Integrated Modeling for Road Condition Prediction

Final Report

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December 31, 2017
FHWA-JPO-18-631

U.S. Department of Transportation

Produced under Contract DTFH61-12-D-00045, Support Services for the Office of Operations (HOP) Transportation Operations (HOTO) and Transportation Management (HOTM) Operations Group 2 Operations and Intelligent Transportation Systems (O&ITS)
U.S. Department of Transportation
Office of the Assistant Secretary for Research and Technology, Intelligent Transportation Systems Joint Program Office
Federal Highway Administration, Office of Operations

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-JPO-18-631		

4. Title and Subtitle	5. Report Date
Integrated Modeling for Road Condition Prediction	December 31, 2017
	6. Performing Organization Code
7. Author(s) J. Kyle Garrett; Hani Mahmassani; Deepak Gopalakrishna; Bryan Krueger; Jiaqi Ma; Fang Zhou; Zihan Hong; Marija Ostojic; Nayel Urena Serulle	8. Performing Organization Report No.
9. Performing Organization Name and Address Leidos 11951 Freedom Drive Reston, VA 20190	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTFH61-12-D-00045
12. Sponsoring Agency Name and Address ITS Joint Program Office Office of the Assistant Secretary for Research and Technology U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington D.C., 20590	13. Type of Report and Period Covered Technical Report, September 8, 2015 - December 31, 2017
	14. Sponsoring Agency Code ITS JPO

15. Supplementary Notes

The Contracting Officer's Technical Representative (COTR): Gabriel Guevara

16. Abstract

Transportation Systems Management and Operations (TSMO) is at a critical point in its development due to an explosion in data availability and analytics. Intelligent transportation systems (ITS) gathering data about weather and traffic conditions coupled with the imminent deployment of connected vehicles will bring an increase in data availability to power traffic and road condition predictions. This convergence of opportunities has led the Federal Highway Administration's (FHWA) Road Weather Management Program (RWMP) to initiate research into integrated modeling for road condition prediction (IMRCP) to investigate and capture that potential.

The product of this IMRCP research is a prototype system and demonstration deployment that provides a framework for the integration of road condition monitoring and forecast data to support decisions by travelers, transportation operators, and maintenance providers. The system collects and integrates environmental and transportation operations data; collects forecast weather data; initiates road weather and traffic forecasts; generates advisories and warnings; and provides the results to other applications and systems.

This Final Report describes the development and deployment of the demonstration prototype, including the concept of operations and system requirements, stakeholder engagement, system architecture, system design, system development, test, deployment, and evaluation.

17. Keywords	18. Distribution Statement
road condition prediction, road weather management program, RWMP, TSMO	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	62	N/A

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

Acknowledgements

This report was developed by a Leidos team with Synesis Partners LLC, the Northwestern University Transportation Center (NUTC), and ICF under the sponsorship of the United States (U.S.) Department of Transportation (DOT) Federal Highway Administration (FHWA). The authors would like to thank the numerous representatives and staff members of USDOT, state and local transportation agencies participating as stakeholders, and especially the personnel from KC Scout, the Missouri DOT, the Kansas DOT, the Mid-America Regional Council, the City of Kansas City, Missouri, and the City of Overland Park, Kansas, for their support in the development and review of materials in this report.

Aaron Cherney, Synesis Partners
Amy Stevinson, Missouri Department of Transportation
Barry Viss, Mid-America Regional Council
Brenda Boyce, Booz Allen Hamilton
Bryan Krueger, Synesis Partners
Cary Vick, Leidos
Cedrick C. Owens, Sr., Missouri Department of Transportation
Deepak Gopalakrishna, ICF
Denise Markow, I-95 Corridor Coalition
Dennis Mitchell, Oregon Department of Transportation
Doug Laird, U.S. Department of Transportation
Eileen Yang, Mid-America Regional Council
Fang Zhou, Leidos
Gabriel Guevara, U.S. Department of Transportation
Gary Covey, Kansas City Scout
Haleh Ale Ahmad, Northwestern University Transporation Center
Hani Mahmassani, Northwestern University Transportation Center
Jakin Koll, Minnesota Department of Transportation
James Shannon, Missouri Department of Transportation
James Sturrock, U.S. Department of Transportation
Jessica Silliman, Synesis Partners
Jiaqi Ma, Leidos
John Halkias, U.S. Department of Transportation
John Obenberger, U.S. Department of Transportation
Kyle Garrett, Synesis Partners
Lindsay Harris, Kansas City Scout
Lisa Miller, Utah Department of Transportation
Lynelle Luther, Missouri Department of Transportation
Marija Ostojic, Northwestern University Transporation Center
Mark Taylor, Utah Department of Transportation
Medha Jannat, Leidos
Melissa Lance, Virginia Department of Transportation
Michael Flory, Kansas Department of Transportation
Michelle Neuner, Leidos
Nancy Powell, Missouri Department of Transportation
Nayel Urena Serulle, ICF

Paul Pisano, U.S. Department of Transporation
Paul Wlodkowski, ICF
Peter Koonce, City of Portland, Oregon
Radha Neelakantan, ICF
Randy Johnson, Kansas City Scout
Ray Webb, Mid-America Regional Council
Ron Achelpohl, Mid-America Regional Council
Shawn Gotfredson, City of Overland Park, Kansas
Tina Greenfield-Huitt, Iowa Department of Transportation
Vince Garcia, Wyoming Department of Transportation
Xuesong Zhou, Arizona State University
Zihan Hong, Northwestern University Transportation Center

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Executive Summary

Transportation Systems Management and Operations (TSMO) is at a critical point in its development due to an explosion in data availability and analytics. Intelligent transportation systems (ITS) gathering data about weather and traffic conditions coupled with the imminent deployment of connected vehicles will bring an increase in data availability to power traffic and road condition predictions. This convergence of opportunities has led the Federal Highway Administration's (FHWA) Road Weather Management Program (RWMP) to initiate research into Integrated Modeling for Road Condition Prediction (IMRCP) to investigate and capture that potential.

The purpose of the IMRCP is to integrate weather, traffic, and other operations data sources with analytical methods to effectively predict road and travel conditions. Research, development, and operations stakeholders have been involved in every part of the IMRCP effort. Identification of system functions and interfaces is driven by stakeholders in operations, who also provide feedback on the usefulness of the model results. The model could ultimately become a practical tool for transportation agencies to support traveler advisories, maintenance plans, and operational decisions at both strategic and tactical levels.

This effort has included a survey of available and imminent weather, hydrological, traffic, and related transportation management models; development of a concept of operations and fundamental system requirements; development of a system architecture and system design; implementation of a foundational system; and deployment of the system with an operating transportation agency to evaluate its effectiveness.

The IMRCP system provides an integrated view of forecast road weather and traffic conditions for a given road network. The IMRCP model draws input from traffic, weather, and hydrological data sources to generate estimates of current conditions and forecasts of future conditions. Forecast outputs are available through a web interface on maps, in reports, and in subscriptions.

Traffic data sources such as advanced transportation management systems (ATMS) provide volumes and speeds, freeway control and traffic signal operations data, incident reports, and plans for work zones and special events. Current and forecast atmospheric and hydrological conditions are drawn from National Weather Service sources. State and local agencies provide specialized road weather conditions such as pavement temperatures. Data collected from the various sources are indexed, stored, and archived in a heterogeneous data store.

While atmospheric and hydrological forecasts, work zones, and special events data are taken from external sources, the IMRCP synthesizes road weather and traffic condition predictions with embedded best-in-class forecast models. In the current implementation, road weather conditions are estimated across the network using field measurements of conditions and predicted from atmospheric forecast conditions using the METRo model. Current traffic conditions are similarly estimated from detector stations and demand models and are predicted from road weather, incident, and demand forecasts using the TrEPS/DYNASMART model.

A portion of the Kansas City metro area along a congested interstate corridor and surrounding arterials has been used for a demonstration study and evaluation area. The Kansas City area is subject to highly variable weather conditions and local recurring congestion typical of U.S. urban/suburban settings. The

I-435 corridor along the southern part of the metro carries heavy commuter traffic in both directions and for much of its length runs along a streamway with historically significant flood risk. The corridor is well-instrumented for traffic, weather, and hydrology.

An evaluation of the IMRCP demonstration deployment was conducted with the staff of the Kansas City Scout traffic management center. Overall, the evaluation provided positive but mixed results. While the IMRCP tool provides a good foundation for merging and harmonizing weather forecast data for operators to use within a single system, the assessment shows that the traffic predictions do not always reflect the expected changes from forecasted weather conditions. Statistically across the network, the model's traffic prediction capability provides a robust simulation of typical traffic patterns. However, on a case-by-case basis, the model exhibits shortcomings in capturing some non-recurring variations in traffic behavior.

Pavement condition predictions were found to be working as intended, but their use in the real world was limited by the timing of the evaluation, which did not include winter months. One of the key findings of the assessment is that more operational experience with the model in real-time, adverse weather conditions (e.g., snow, ice, and thunderstorms) is needed, as this would better calibrate the tool and allow it to demonstrate its full potential regarding weather-related traffic predictions.

The core objectives of the IMRCP study have been met. The concept of integrated modeling for road condition prediction has been successfully developed, demonstrated, and validated in an evaluation with transportation operations stakeholders. The demonstation system provides an efficient integration of operational data with user tools that increase operator awareness of forecast, current, and past road network conditions.

Opportunities for future research and demonstration could include applications focused on specific management and operations challenges, exchange of data with other TSMO-supporting systems, advanced forecast methods for traffic and weather predictions, automation of some modeling tasks, and enhancement of the IMRCP system interfaces to improve the user experience.

Chapter 1. Introduction

Background

Transportation systems management and operations (TSMO) is at a critical point in its development due to an explosion in data availability and analytics. New approaches in road weather management are bringing together meteorology, traffic management, law enforcement, maintenance, and traveler information to support agency decision making and influence travel behavior. Through these operational efforts and private sector innovations, travelers today have higher expectations for their travel experience. Travelers now participate in generating and validating information as well as consuming it. This trend will accelerate with deployment of connected vehicle (CV) systems. Within this context, the role of prediction and forecasting will become more important to the travel and activity choices made by travelers, as well as to agency decisions in transportation operations. Freight carriers and logistics providers will also benefit in planning routes, times and delivery schedules.

Development and adoption of traffic prediction approaches by operating agencies have been limited, however, even with a growing body of research. While this is partly attributable to limited data, available predictive tools have been narrowly focused and have not taken full advantage of developments in related disciplines and domains. As a result, the use of predictive methods in support of operational decisions continues to be limited.

Recent efforts to incorporate forecast weather conditions in traffic predictions have shown considerable promise. Factoring in reported conditions from environmental sensor stations, vehicle fleets, and citizen-reported conditions could improve estimation of the current system state from which predictions are developed. The utility of traffic predictions could be further enhanced by augmenting the forecast weather conditions with known and likely capacity constraints such as work zones and incidents. Current and planned road treatment approaches, snowplow routing, parking restrictions, and maintenance decisions could be included as well.

Based on these opportunities, the Federal Highway Administration (FHWA) has undertaken the investigation, development, and demonstration deployment of an Integrated Model for Road Condition Prediction (IMRCP). This effort has included a survey of available and imminent weather, hydrological, traffic, and related transportation management models; development of a concept of operations and fundamental system requirements; development of a system architecture and system design; implementation of a foundational system; and deployment of the system with an operating transportation agency to evaluate its effectiveness. Research, development, and operations stakeholders have been involved in every part of the IMRCP effort.

Purpose

The purpose of the IMRCP is to integrate weather, traffic, and other operations data sources with analytical methods to effectively predict road and travel conditions. Identification of system functions and interfaces is driven by stakeholders in operations, who also provide feedback on the usefulness of the model results. The model could ultimately become a practical tool for transportation agencies to support traveler advisories, maintenance plans, and operational decisions at both strategic and tactical levels.

This Final Report describes the development, demonstration deployment, evaluation, and assessment of the IMRCP. It provides a summary description of the development processes and demonstation results, including the ConOps and system requirements, stakeholder engagement, system architecture, system design, system development, test, deployment and evaluation.

Scope

The IMRCP provides a framework for the integration of road condition monitoring and forecast data to support tactical and strategic decisions by travelers, transportation operators and maintenance providers. The system:

- Collects and integrates environmental observations and transportation operations data;
- Collects forecast environmental and operations data when available;
- Initiates road weather and traffic forecasts based on the collected data;
- Generates travel and operational advisories and warnings from the collected real-time and forecast data; and
- Provides the road condition data, forecasts, advisories and warnings to other applications and systems.

Road condition and operations data and forecasts integrated into the prediction, as available, include:

- Atmospheric weather;
- Road (surface) weather;
- Small stream, river, and coastal water levels;
- Road network capacity;
- Road network demand;
- Traffic conditions and forecasts;
- Traffic control states;
- Work zones;
- Maintenance activities and plans; and
- Emergency preparedness and operations.

Document Overview

Chapter 1, Introduction (this section), provides an overview of the background, purpose, and scope of the project and this document.

Chapter 2. Project Description, describes the overall IMRCP project including the methodology and approach, project tasks and deliverables, and stakeholder engagement.

Chapter 3. Implementation and Deployment, describes the process of implementing and deploying the IMRCP including the vision and objectives, user needs, application scenarios, system description, study area description and modeling, traffic model calibration, system deployment and operations, and open source work product.

Chapter 4. Evaluation, describes the evaluation of the IMRCP project.

Chapter 5. Analysis, Conclusions, and Recommendations for Further Study, describes the end results of this phase of the IMRCP. This section includes case studies and applications, lessons learned and limitations, deployment considerations, conclusions, and recommendations for further study.

Chapter 2. Project Description

The multi-disciplinary nature of TSMO can be exemplified in strategies and practices in road weather management that bring together meteorology, traffic management, law enforcement, maintenance and traveler information to support agency decision making and influence travel behavior. Similar needs are present in work zone managment, traffic incident management, and active traffic management strategies, all of which seek to provide actionable information to travelers, enabling them to make better choices for safe and reliable travel, and to agencies, enabling them to minimize and mitigate the impact of disruptions. Initiatives across all of these disciplines have been working toward developing similar frameworks and methodologies.

Through these efforts, and through innovations in the private sector related to the gathering, processing and mobile dissemination of information, travelers today have higher expectations for their travel experience. From being passive consumers of information with unknown accuracy, travelers are now vital players in generating and validating information. This trend will accelerate with deployment of Connected Vehicle systems, which will create a powerful new platform for collecting and sharing information. Within this context, the role of prediction and forecasting will become more important to the travel and activity choices made by travelers, as well as to agency decisions in the active management of surface transportation operations. Economic imperatives require freight carriers and logistics providers to factor in a variety of traffic conditions for planning routes, times, and delivery schedules.

While a wide variety of approaches have been proposed in the scientific literature for predicting traffic conditions, development, application, and adoption of these approaches by operating agencies have been limited. Part of the reason has been limited data availability, a situation that is changing rapidly. Another reason is that available tools have been too narrowly focused and have not taken full advantage of developments in related disciplines and domains. As a result, the use of predictive strategies in TSMO remains nascent, and decisions continue to be largely reactive.

To support proactive operations, higher quality predictions are needed for incorporating factors beyond the fundamental traffic models into the analysis. Recent developments incorporating forecast weather conditions in traffic predictions (e.g., UDOT TrEPS[1] in an FHWA project led by Northwestern University and Leidos) have shown considerable promise in improving the relevance and usefulness of traffic predictions for agency decision making related to incoming weather. However, the richness and usefulness of traffic predictions can be enhanced by augmenting the forecast weather condition during the prediction window with known and likely capacity constraints (both planned like work-zones or snow-route restrictions, and probabilistic like incidents). Additional fidelity may result from factoring in reported conditions from environmental sensor stations (ESS), mobile observations from fleets, and citizen reports.

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[1] Federal Highway Administration, *Implementation of a Weather Responsive Traffic Estimation and Prediction System (TrEPS) for Signal Timing at Utah DOT*, FHWA-JPO-14-140 (Washington, DC: FHWA, 2014). http://ntl.bts.gov/lib/52000/52600/52623/FHWA-JPO-14-140_v2.pdf

Current and planned road treatment approaches, snowplow routing, parking restrictions, and maintenance decisions might be factored in as well.

This IMRCP demonstration project provides an opportunity to develop, deploy, and evaluate an integrated model for predicting road conditions that incorporates transportation and non-transportation data, deterministic and probabilistic data, and measured and reported data into a framework for agency decision making and traveler information. The model provides a practical tool for State DOTs to support traveler advisories and maintenance and operational decisions at both strategic and tactical levels.

Methodology and Approach

One of the main challenges in this project is accounting for the different latencies, qualities, and levels of certainty in source data and methods to generate consistent, accurate and useful results. For example, in Utah DOT, citizen and maintenance personnel reports of road conditions are subjectively weighted in decision making based on the timing of the report and the nature of the decision. The in-house meteorologists weigh all the observed conditions along with ensemble weather forecasts to make a call on the road condition forecast. Creating a framework and methods to accommodate those considerations is a significant undertaking.

As a second step, the model needs to translate road segment-based information into meaningful impacts and actionable information within a corridor and across the network. This is where the ability to understand the traffic impacts of road conditions is critical. Building off of concepts explored in TrEPS and the second Strategic Highway Research Program’s L04 project entitled *Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools*, translating road weather conditions to traffic impacts will inform the route, mode, and time choices of travelers. This also calls for integrating recent developments in utilizing probabilistic information and forecasts in optimal decision processes as new information becomes available. For example, optimal routing in dynamic stochastic systems for both individuals and service vehicles (package delivery, repair vehicles, etc.) requires different algorithms than are typically used in deterministic conditions.

The recommendations provided by such algorithms must be conveyed in simple, understandable terms to the end user and enable querying the system for additional information. For example, using probabilistic models requires communicating probabilities to the traveler, a concept traditionally avoided by DOTs but common in meteorology.

The products of this project are the IMRCP system software and documentation, a demonstration deployment, an evaluation of the demonstration, and analysis of the experience. To facilitate use by State and local agencies, including those involved in the demonstration deployment, the model has had to be easy to use, rely on available data sources, integrate with existing legacy systems, generate timely predictions, and ultimately provide decision support in a manner useful to operators and travelers.

Project Tasks and Deliverables

Phase 1 of this project identified user needs and set broad requirements for a demonstration IMRCP capability. It surveyed the existing field of predictive models, engaged a broad stakeholder community, and developed a concept of operations and requirements for an integrated model for predicting road conditions that incorporates transportation and non-transportation data, deterministic and probabilistic data, and measured and reported data.

Phase 2 of this project started with follow-on efforts to develop a system architecture and design with input from the IMRCP project stakeholders. A foundational system was then implemented and deployed in a suburban Kansas City study area in cooperation with the KC Scout transportation management center (TMC), which is itself operated cooperatively by the Missouri DOT (MoDOT) and the Kansas DOT (KDOT). The effectiveness of the system’s ability to incorporate real-time and archived data and results from an ensemble of forecast and probabilistic models to predict the current and future overall road/travel conditions was then evaluated.

The first task in Phase 1 of the project was to analyze existing and imminent models. This included identifying weather, pavement, and traffic models and developing analysis criteria for considering the dimensions of each model. Weather, traffic, and hydrological models were then analyzed to determine how the different models might be integrated into a framework that provides predictive capabilities, and the results were summarized in a Model Analysis.

This model analysis then led to development of the Concept of Operations. The Concept of Operations (ConOps):

- Described the objectives and context for the program;
- Captured the user needs and use cases;
- Described the concept as it was to be developed into the downstream projects;
- Developed scenarios describing potential uses of the system; described its potential impacts on stakeholders and their processes; and
- Provided an analysis of its eventual benefits, advantages, limitations and disadvantages relative to the current state.

The system requirements were developed based on the user needs in the ConOps and supplemented by requirements from reference documents for other road weather and connected vehicle projects. The requirements were then vetted by stakeholders. The Requirements Specification was structured around the standard functional, interface, performance, security, data, and reliability requirements categories.

Phase 2 of the project began with the identification of additional stakeholders and the creation of the stakeholder engagement plan for system development. The engagement plan identified the stakeholders, the schedule for engagement, webinar formats and approach, and main outcomes expected from each engagement with the group. The plan was used to guide stakeholder interactions throughout the project lifecycle. Specific stakeholder interactions are discussed further in the Stakeholder Engagement section of this document.

A study area for which to demonstrate the IMRCP system was also selected as part of setting up the Phase 2 implementation. Local agencies became key stakeholders in the demonstration system configuration, deployment, and subsequent evaluation. The development team worked closely with the involved agencies to understand and access their systems while minimizing the impact on their resources.

The next tasks were to create a system architecture and design for implementation. In the first of these, the system concept from the ConOps was expanded, and the system interfaces were specified. The prototype deployment environment characteristics were also identified. The deliverable for this task was the System Architecture Description. Development of the Systems Design Document grew from the architecture document and focused on the implementation of the components themselves—their interfaces and internal functions. The system design process had multiple opportunities for interaction between the development team, USDOT, and system stakeholders.

The system and software development process incorporated building, configuring, and testing the system. Building the system involved an iterative implementation of the intended system design, which was confirmed to meet the system requirements through ongoing unit, component, and integration testing. Configuring the system models to accurately and completely capture the environmental, traffic, and operational behaviors was a significant part of the deployment effort. An Acceptance Test Plan was created and executed against the completed system.

An evaluation plan that provided a clear framework for assessing the potential benefits of this system was based on the original ConOps and was developed independently of the system implementation. The evaluation plan identified how the system enhanced the agency's ability to make improved operational decisions and provide more actionable traveler information. Agency users were given access to the implemented system, along with documentation and training resources, and were encouraged to explore its potential applications. Technical support was provided throughout the course of the deployment and evaluation.

Final deliverables from the project include this report on the project and a Software Distribution Kit (SDK) containing the application software and configuration files for the demonstration deployment.[2] In addition to the final report, a master presentation and flyer describing the IMRCP were developed. These products provide a high-level overview of the project and system development process for transportation agencies that may be interested in future deployment of such a system.

Stakeholder Engagement

Stakeholder involvement in the IMRCP project was needed to understand user needs and potential modeling and data constraints. Meteorologists helped in understanding forecast models and ensemble methods. Traffic researchers and modelers assisted in understanding current and emerging models and predictive capabilities. DOT maintenance workers and DOT traffic operations personnel were needed for gathering user needs, including use of modeling and prediction in operational decision making. Third-party information provider and traveler needs were collected from DOT traveler information managers.

Stakeholder input was critical to user needs and system concept development. Stakeholders addressed what operational and system needs the IMRCP should address and provided insight into what an effective and usable system would look like. The ConOps and Requirements documents captured those stakeholder needs. Subject matter experts were involved in identifying (and eventually resolving) modeling issues and constraints.

Agencies associated with the demonstration study area deployment in the southern part of the Kansas City metropolitan area (described further in Chapter 3) were key stakeholders in system development, implementation, and evaluation. Staff personnel at KC Scout, the Missouri DOT, the Kansas DOT, the Mid-America Regional Council, the City of Kansas City, MO, and the City of Overland Park, KS were

[2] The SDK is available on the USDOT's Open Source Application Development Portal at https://www.itsforge.net/.

members of this key stakeholder group. These stakeholders participated in stakeholder engagement and activities with other IMRCP stakeholders, supported the development team with data and access to their transportation management systems, used the demonstration IMRCP alongside their TMC systems, and provided input to the evaluation.

Specific stakeholder meetings and webinars included:

Presentation to Transportation Research Board (TRB) Winter Maintenance Committee – January 12, 2015

This presentation introduced the IMRCP project, scope, and objectives and described stakeholder participation opportunities.

Initial Stakeholder Meeting, Project Overview and Needs Gathering – July 27, 2015

Stakeholders were introduced to the IMRCP project, scope, and objectives. Stakeholder participation opportunities were also described. Stakeholder participants identified gaps in current weather and road condition data, IMRCP concepts, and operational scenarios

Weather Responsive Traffic Management (WRTM) Stakeholder Meeting – October 20, 2015

This presentation introduced the IMRCP project, scope, and objectives to the WRTM Stakeholder group. Potential opportunities for change and example application scenarios were shared with the group.

Core Working Group Review of ConOps and Project Status – February 2, 2016

This presentation described stakeholder engagement opportunities and provided an update on project progress. Stakeholders provided feedback on the concept. The development plan and next steps were also described.

Road Weather Management Stakeholder Meeting – June 30, 2016

The project objectives, tasks, scenarios, and system architecture were described during this presentation. Stakeholder engagement and next steps were also described.

Project Background with KC Scout/MARC – July 15, 2016

The project background meeting with Kansas City stakeholders allowed the team to describe the model inputs, outputs, and data needs. The stakeholders identified data sources and contacts as well as operational interests.

Kansas City Stakeholder Deployment Model Update Webinar – November 30, 2016

The Kansas City stakeholder deployment model update webinar allowed the team to provide a first look at preliminary output. Stakeholders gave feedback on the system interface and application concepts. Stakeholders identified the need for a notification feature for notifying users of unusual conditions.

Kansas City Stakeholder Webinar System Demonstration – April 25, 2017

The team gave Kansas City stakeholders a user interface tour and introduced evaluation perspectives at the Kansas City Stakeholder webinar system demonstration.

Kansas City Stakeholder Notification Demonstration – August 3, 2017

The team introduced the notification feature at the Kansas City Stakeholder notification demonstration, and the Kansas City stakeholders provided feedback on the feature.

Chapter 3. Implementation and Deployment

Development of IMRCP capabilities presents a diverse set of challenges. The interdisciplinary nature of the concept necessitates a broad group of stakeholders with particular operational needs, leading to an equally broad set of application scenarios. The variety of data types needed to support the scenarios necessitates identification, access to, and development of components for data collection from a wide variety of sources. The spectrum of data conditions, quality, and attributes across those sources then necessitates a flexible and extensible data repository and data processing capability to synthesize the input needed by all of the component forecast methods. And the system and user interfaces have to be able to represent the original data and forecasts results in consistent, easy-to-use presentations that provide spatial and past-present-future temporal contexts.

Vision and Objectives

TSMO strategies and practice are on the cusp of dramatic changes due to increased availability of data and sophistication of models and systems supporting those operations. Intelligent transportation systems (ITS) are widely deployed and gather data about weather and traffic conditions from across the road networks. The imminent deployment of connected vehicles will bring an order-of-magnitude increase in data availability. Traffic and road condition predictions need and are powered by these data, and the accuracy and reliability of the models improve with the increase. This convergence of opportunities presents potential for operational improvements in safety and mobility. The FHWA RWMP initiated this research into an IMRCP to investigate and capture that potential.

Transportation agencies currently have a variety of ITS collecting information to support TSMO, but the integration of the data into operations support systems is selective. Predictive capabilities are typically limited to generalized weather forecasts and traffic predictions based on historical patterns. Impacts of other factors—hydrology, incidents, and work zones, for example—are even less likely to be routinely integrated with operational forecasts and plans. Winter maintenance teams in many cases do have access to maintenance decision support systems (MDSS) based on forecast conditions, but these are not generally shared with traffic operations. TMC operations typically have strategies for dealing with abnormal events as they occur, but generally do not explicitly consider forecast conditions. Unusual and exceptional events (e.g., small stream flooding or coastal storm surge) are responded to, but not necessarily anticipated. Traveler information presents a distillation of current information, but seldom provides the end users with travel decision support.

In light of these developments and system limitations, it is clear that providing an integrated model and prediction capability is open to further research and prototype development. ITS, connected vehicle, and ancillary data sources are increasingly plentiful. Traffic prediction and weather forecast capabilities have grown beyond mechanistic models to include sophisticated statistical and ensemble methodologies. User needs for better operational data and forecasts cut across all the traditional transportation disciplines and stakeholder perspectives—operations, maintenance, meteorology, emergency response, transit, commercial operations, and the traveling public. An integrated modeling capability to address needs and opportunities entails making changes across the involved disciplines, including systematizing network and event models, coordinating data collection and normalization across the forecast domain, reviewing and potentially modifying traffic and operations forecast models, standardizing interfaces between model components, testing and tuning the predictions, and formulating decision-enabling advisories and warnings based on these predictions.

The scope of capabilities needed to operate an IMRCP system cover a range of functions across multiple disciplines. The integrated system includes the fundamental underlying physical and operational models, the planning and strategic components, operations and plan execution, monitoring operations, generating alerts based on monitoring, forecasts of future conditions, and generating decision support information. These functions are all active to varying degrees in disciplines such as meteorology, pavement maintenance, traffic studies, work zone management, and traveler information. Some of these discipline-specific functions are unique to the IMRCP system, but many either are or could be provided by services outside the IMRCP.

IMRCP capabilities will have downstream impacts on future research and operational considerations. From a research perspective, an integrated predictive capability requires deployment and testing that enable continuous improvement of the models, further evaluation of non-traditional (e.g., crowd-sourced) road condition information, additional analysis of coupling between underlying discipline-specific models, assessment of using predictive data in operations centers, and evaluation of traveler behaviors in response to prediction-based operational strategies and messaging. From an operational perspective, the IMRCP creates a need for real-time operational data not readily available (in work zones, for example); systematizing operational strategies and interactions with the predictive models; providing decision-centric data for traveler information systems; and public education and outreach on interpreting probabilistic road condition information.

User Needs

To understand the capabilities required of the IMRCP, it is important to understand the needs of the various types of potential users of the IMRCP, who range from travelers to transportation operators to maintenance managers to consulting meteorologists to emergency planners. This broad pool of interested stakeholders prefigures the wide range of functions to be required of the IMRCP.

Users need information to help them make appropriate travel and traffic management decisions. Information about conditions on the road ahead of them is useful; on the road they might take at the next decision point only slightly less so; on the road behind them, not so much. Too much information outside a user’s context may distract the user from more immediate and relevant information. Potential road condition predictions are useful only if they are relevant to the traveler’s temporal and spatial context. This has significant ramifications for predictive capabilities. Traffic information provided to managers and travelers has, to this point, been limited to observed conditions, but predictions have more dramatic decision implications. Information must be timely enough to facilitate effective decisions based on anticipated conditions. Telling someone in the middle of a one-hour commute that severe congestion is likely for the next 30 minutes is much less effective than having issued the advisory 90 minutes earlier.

Users need to have road condition predictions expressed in clear terms consistent with other similar contexts that help their decision-making processes. Traffic information and signage already provides some information of this type; travelers understand what an “icy road ahead” or a “deer crossing” sign means. Signs like these are used to express likelihood and provide an advisory appropriate to the traveler's immediate decision context. Predictive capabilities expand this concept to more specific times and potentially provide quantified likelihoods. The public is generally aware of how probabilities are expressed in weather forecasting, and a traffic forecast could be understood similarly if expressed in similar terms. It might even in some contexts be appropriate to describe the level of confidence for the prediction.

Users need to have access to predictions through existing interfaces providing similar traffic and weather information. Providing additional information of familiar types through existing channels is more effective in the near-term than establishing new channels specific to the additional information. Consumers of traffic and weather condition information already have access to traditional media, websites, and social media; it would be more efficient to supplement those channels with predictive capabilities than to develop new apps for publishing road condition predictions.

User needs for decision support are not, however, directly changed by the availability of road condition predictions. A traveler, for example, might look for routing guidance in travel planning. Road condition predictions are an input to the guidance, not the reason for initially seeking it. As such, the "users" of the predictions are in this case the routing system rather than the end user. Road weather MDSS demonstrate this in practice; the precipitation and icing forecasts are embedded in the analysis of decision-support planning.

Application Scenarios

The potential users of the IMRCP face a diverse set of challenges related to traffic, weather, and hydrology. The IMRCP system functions can conceptualy assist users in meeting these challenges.

Variable Speed Limits

TSMO practitioners may use the IMRCP to create proactive situations rather than operating on a purely reactive basis. Dynamic or variable speed limits (VSL) can enhance network performance during peak demand periods, when congestion and delay are often exacerbated by bad weather; reduce traffic shocks and incidents; and delay or prevent flow breakdown, thus maintaining optimal throughput. The posted speed limit, which could also consider visibility, friction, and traffic conditions, may be adjusted based on a combination of prevailing and predicted weather conditions.

Enhanced Motorist Advisories and Warnings

Road weather information such as en-route weather warning and route conditions can be disseminated through radio, internet, mobile devices, roadside dynamic message signs (DMS), and other similar means. Travel time predictions for alternative routes and times would enable users to select the best route and departure time for their particular travel need, including the impacts of inclement weather or work zones. Travelers could therefore choose their departure time and/or route based on the predictive information.

Enhanced Intelligent Signal Controls

The IMRCP integrates weather forecasts with traffic predictions, the results of which could form a basis for selecting traffic signal control interventions in a systematic, continuous process. To achieve this, the signal control interventions would be linked to the predicted weather and traffic conditions based on measured conditions. Real-time traffic data feeds are used as a basis for the traffic state estimation and prediction within the IMRCP and could be obtained directly from the sensors for signal controls in a corridor.

Maintenance

The IMRCP system enhances the ability to support strategic and tactical maintenance decision making at an agency. The IMRCP could complement the current use of MDSS at an agency by integrating traffic and roadway characteristics into a single predictive view of conditions. Using this integrated forecast would enable agencies to make better strategic and tactical decisions relating to winter maintenance. The IMRCP would similarly provide non-winter maintenance personnel with the capability of including weather and traffic forecasting in day-to-day decisions on maintenance scheduling.

Freight

IMRCP capabilities can help freight managers, dispatchers, and operators/contractors make better decisions in pursuit of higher customer satisfaction at a lower overall cost. Once a truck is on the road for a long-haul move, whether for a truckload delivery or as part of a less-than-truckload (LTL) network move, predictive IMRCP information could help the driver select the route that best meets their travel time and travel time reliability objectives. Better route planning with an IMRCP could then improve load planning by operators as well.

Work Zones

For work zone personnel, the IMRCP offers the ability to provide segment-level alerts for monitoring work zones. The tool complements the ability of Smart Work Zones and Work Zone ITS to provide more actionable information to travelers. Potential scenarios could also include near-term work zone support and coordination, where the work zone impacts can be assessed based on current conditions and imminent operations plans.

Travelers

Commuters, as end-user beneficiaries of the IMRCP capabilities, will have access to forecasts of traffic conditions that parallel the access they already have to weather forecasts. Commuters also would have access to predicted conditions resulting from planned (forecast) work zones, special events, or localized flooding.

IMRCP applications could offer tourists the ability to plan long trips on unfamiliar roadway networks. Tourists would have access to traffic forecasting services in the IMRCP that provide data for the entire trip planning horizon, predicting likely conditions based on archived and real-time traffic conditions and atmospheric and road weather forecast conditions.

Emergency Response

Just as the IMRCP can facilitate predictive route planning for freight and individual travelers, it could also assist emergency response planning for either responders or evacuees. The model's predictions of traffic and roadway conditions in consideration of weather and hydrology could improve both safety and mobility during both incidents and, potentially, extreme weather events.

System Description

In order for the IMRCP to meet the needs of the user, the user must be able to see into the system. The IMRCP user interface provides a view of the system through an interactive map and reporting features. The data that populate these user interface features are kept in a data store that contains both collected data and data generated through forecasting components. Forecast data are generated within the IMRCP context for traffic and road weather conditions and are obtained from sources outside the system for atmospheric weather, hydrology, work zone plans, and known special events. Current traffic and incident conditions come from an advanced transportation management system (ATMS). Current environmental conditions are collected primarily from the National Weather Service (NWS) and other government agencies.

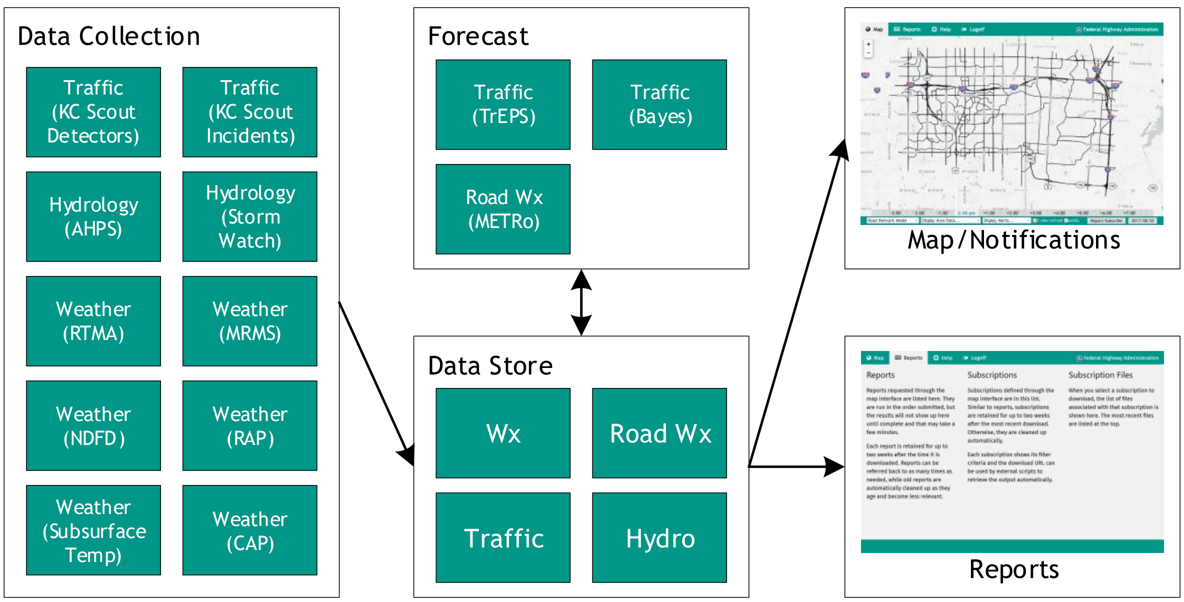


Figure 1. IMRCP System Functions.

Data Collection

The integration of diverse sets of data requires a diverse set of data collectors. Traffic, hydrology, and weather data relevant to a deployment area are collected from numerous sources.

Current air temperature, wind speed, surface pressure, and humidity observations are collected from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Research (NCEP) Real-Time Mesoscale Analysis (RTMA). These weather observations are used as input to the traffic model for generating traffic predictions and to the road weather model for road weather predictions. They can be viewed on the map or through reports.

Atmospheric weather forecasts are collected from the NOAA National Weather Service's (NWS) National Digital Forecast Database (NDFD). These forecasts are displayed on the user interface and shared through the reporting and subscription feature. They are also used in traffic and road weather predictions.

The NOAA/NCEP Rapid Refresh (RAP) is used as the source for forecasted surface pressure, precipitation amount and precipitation type. Forecasted weather data is used for traffic and road weather predictions as well as providing users with information.

The NOAA National Severe Storms Laboratory (NSSL) Multiple Radar/Multiple Sensor System (MRMS) provides radar and precipitation rate and type observations for the IMRCP. This weather data can be viewed on the map or through reports and is used as input for the traffic model and road weather prediction model.

Current hydrological conditions and forecasts are collected from the NOAA/NWS Advanced Hydrologic Prediction Service (AHPS) when new data becomes available at any of the AHPS stations in the study area. The values are used to determine the flood depth on road network links based on inundation mapping provided by AHPS. Additional hydrological conditions and forecasts for small streams can also be collected from other sources, when available.

The current pavement and subsurface temperatures can be collected from a Road Weather Information System (RWIS) station or FHWA's Weather Data Environment (WxDE) for use in road weather predictions. These values are used in initiating road state and road temperature predictions with the Model of the Environment and Temperature of Roads (METRo).

Alerts, watches, and warnings are collected from NWS using the Common Alerting Protocol (CAP) and are available for IMRCP users to view.

Current traffic conditions are collected from traffic detectors maintained by the road network infrastructure owner/operator (in this case, KC Scout for the highway network). Speed, volume, and occupancy data from these detectors are provided by an ATMS to the IMRCP system for predicting traffic across the network.

Incident and work zone data are also collected from an ATMS (again, KC Scout in this case). The location, estimated time frame, lane closures, and type of event are used to feed the traffic model for predictions and to display on the map.

Forecast Model Components

The IMRCP system forecasts traffic and road weather conditions using current and forecast atmospheric and hydrologic condition data from the data store, collected from the sources described previously.

The TrEPS model estimates and predicts the traffic demand and network states at the zone-to-zone (origin-destination) level. After an appropriate off-line calibration based on traffic data archives for the network of interest, the TrEPS on-line component is capable of interacting continuously with multiple sources of current "real-time" traffic data, such as from loop detectors, roadside sensors, and vehicle probes, which it integrates with its own model-based representation of the network traffic state. TrEPS also considers and integrates current road weather conditions, incident status, and work zone plans into its estimation and prediction of network link speed, volume, occupancy, and travel times. For this IMRCP integration, detector, incident, work zone, and weather data input are provided from the core IMRCP data store.

The Bayesian traffic model can be used to estimate and predict traffic on the network, particularly for longer-term prediction of “typical” network conditions. Traffic, weather, incident, and work zone data are all used as input to this model to predict the speed, volume, and occupancy on network links for which sufficient historical data are available to train the model.

The METRo model estimates and predicts pavement conditions on roadways within the network of interest. The model computes pavement temperatures and surface conditions on network pavement segments and bridges using current condition data from RWIS and mobile sensors (when available), atmospheric weather forecasts, and pavement configuration data.

Data Store

All data collected and computed by the system are kept in its integrated data store. Data collected by the system directly from external sources are kept in their original formats. Data generated by the system in data digest and forecasting components are stored in compatible file structures. All data kept by the system are indexed to location and temporal contexts. All other system components work from data within the store for forecasting, presentation, and reporting.

User Interface

The IMRCP user interface provides forecasted traffic and road weather conditions on maps and in ad hoc and subscribed reports. The map interface can be used to view conditions on roadways, over regions of a deployment area for alerts, in combinations. As a live system, the map can be set to view a single point in time or to automatically refresh as new data become available. Notifications of current events and predicted conditions can be pushed to the user view over the map. Time controls on the map enable users to view forecasted and recent past conditions or to access archives and “replay” past events. Reports can be created from the map view and retrieved when complete. An example of an IMRCP map layer for traffic conditions is shown in Figure 2.

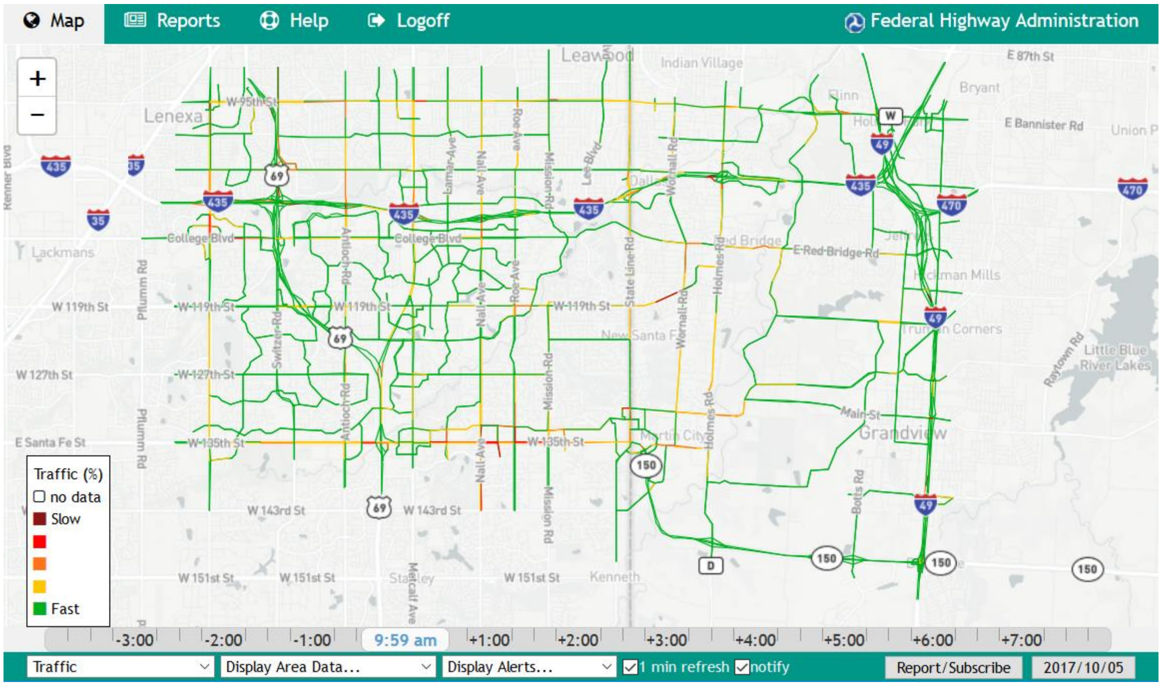


Figure 2. User Interface Map.

Study Area Description and Modeling

The study area for the IMRCP was selected from among several candidate locations in the United States in order to demonstrate a broad range of capabilities. The Kansas City region is subject to highly variable weather conditions, typical urban congestion patterns, and interesting hydrological characteristics. A set of corridors in the Kansas City metropolitan area was chosen because of the range of data available and the working relationship between and with the local agencies. A planning model for the city was available from the Mid-America Regional Council (MARC), the regional metropolitan planning organization (MPO), and was used as a basis for the road network model in the IMRCP.

The specific study area within the metro area was chosen based on a combination of characteristics, including congested traffic, alternative routes, weather sensors, and hydrologically challenging areas (there are several streams subject to severe flooding within the study area). The I-435 corridor is well-instrumented for traffic, weather, and hydrology, and the extended study area contains I-435 from Quivira Road in Kansas to I-49 in Missouri, portions of I-470, US-69, US-71, and MO-150. Data availability and sensor types within the study area are illustrated in Figure 3.

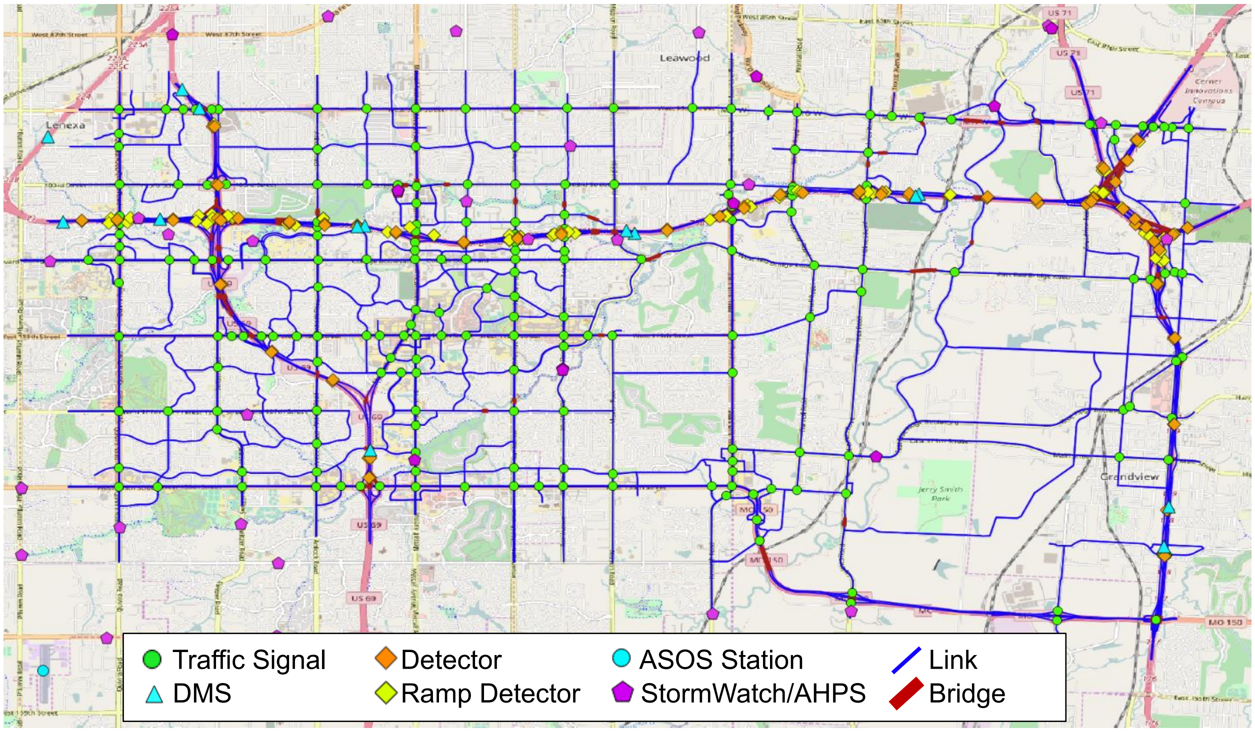


Figure 3. IMRCP Study Area Features.

The study area model uses 2,006 roadway network links, 870 nodes, and 188 bridge segments to represent the study area road network. The model includes 205 traffic signals, 150 traffic detectors, 53 ramp detectors, 15 DMS, 20 StormWatch hydrological stations, 5 AHPS stations, and an NOAA Automated Surface Observing System (ASOS) station.

Traffic signal configuration data was provided by local agencies including the City of Overland Park and Operation Green Light. The configuration data included timing plans for each of the 205 traffic signals for each day and time of the week and was formatted to the TrEPS model specifications.

KC Scout is the primary operational stakeholder for the IMRCP demonstration deployment. Staff personnel from the KC Scout TMC, MoDOT, and KDOT supported the modeling effort and provided evaluation input for the IMRCP system after the deployment of the system. Real-time and archive data for the highway network were provided through KC Scout's TransSuite® data portals. Incident and work zone were collected from KC Scout's event feed once per minute, and traffic detector data consisting of speed, volume, and lane occupancy were collected from KC Scout's detector feed, also once per minute.

Weather and hydrological data for the study area were gathered primarily from the NOAA sources described earlier, but were supplemented with local sources such as the StormWatch system operated by the City of Overland Park. Atmospheric weather forecasts are updated and retrieved once per hour. Hydrological systems generally update their data feeds only when the data change, but the IMRCP is configured to check those feeds at least once every 10 minutes to capture potential flash flooding events.

Based on these data availabilities, METRo road weather condition forecasts are re-computed once per hour. Those updates are provided with the 1-minute traffic data updates to TrEPS, which then re-computes a 2-hour traffic condition forecast once every 15 minutes.

TrEPS Traffic Model Calibration

Calibration of the TrEPS traffic model for the study area is a critical and significant component of the integrated model deployment. This section summarizes the results of the model calibration effort. It provides a comparison between the model estimation results and the corresponding real-world observations.

Traffic Flow Model

The primary sources of traffic information were radar-based detectors installed along each of the three freeways, i.e., I-435, US-69, and I-49 (Figure 4). Initial traffic flow model calibration was based on the 2015/2016 archived detector data provided by KC Scout. Detector-retrieved traffic parameters—including volume, speed, and occupancy—defined freeway traffic conditions in 5-minute intervals. The daily 24-hour traffic flow demand profile was described in a vector, which included 288 5-minute intervals of flow volume, speed, and occupancy. Five-minute aggregated values were used to estimate link-level speed-density relationships for each available detector.

Due to reliability, consistency, and availability issues, 69 detectors were adopted for the traffic flow model calibration. The archived data used to verify the relation between speed and density consisted of 5-minute and 1-minute aggregated historical detector data collected during 2017. The final list accounted for 69 reliable detectors (Figure 4) for which individual traffic flow model parameters are presented in Table 1.[3] Speed-density relationships were calibrated using the time-varying traffic data records: density and speed at 5-minute measurement intervals. A two-regime traffic flow model form is used for traffic flow on freeways, while a single regime model form is used for arterials. Traffic flow model parameters include: breakpoint density (k_{bp}), speed-intercept (v_f), minimum speed (v_0), jam density (k_{jam}), and the shape parameter (α).

[3] Please refer to *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs. Calibration Report – Chicago*. FHWA-JPO-16-381. October 2016, for more detail.

Table 1. Calibrated Parameters for Traffic Flow Model.

Detector ID	Station	Facility Type	Link ID	K_{bp}	V_i	V_0	V_f	K_{jam}	Alpha	RMSE
8081	US-69 N @ 103rd Street	Mainline	155-5016	13.5	72	2	67	245	1.33	4.14112
7793	I-435 W @ AFTER HWY 69	Mainline	317-321	10.3	70	2	66	190	1.38	7.17599
8269	I-435 E @ Quivira road	Mainline	322-324	19.4	94	2	65	245	4.92	7.58841
8271	I-435 E @ Past Quivira road	Mainline	324-171	21	97	2	61	245	5.73	30.79274
7640	I-435 E @ ANTIOCH RD	Mainline	328-2169	18.1	129	2	63	245	10.24	37.7912
7362	I-435 E @ WORNALL RD OR	Ramp	604-14785	1.2	42	2	41	245	6.78	9.14489
7412	I-435 E @ METCALF OR	Ramp	608-2331	1.7	52	2	50	180	4.39	15.9175
8270	I-435 W @ Quivira road	Mainline	609-11657	18	71	2	69	185	0.6	5.65783
7604	I-435 E @ 104TH STREET OR	Ramp	648-649	10.4	45	2	35	200	5.17	19.61551
7534	I-435 W @ WEST OF 104TH ST	Mainline	651-14723	28.7	141	2	70	245	6.46	4.25121
7532	I-435 W @ WEST OF HOLMES RD	Mainline	653-11559	21.4	105	2	70	245	4.99	3.75397
7700	I-435 E @ ANTIOCH	Mainline	2169-2274	11.2	80	2	68	245	3.8	31.83561
8412	I-435 EB @ METCALF Mainline	Mainline	2274-2331	9.2	72	2	65	245	2.86	14.72253
8295	I-435 EB @ Lamar Avenue	Mainline	2469-2543	18.6	101	2	69	185	4.03	5.89083
8072	US-69 N @ I-435	Mainline	2520-2533	16	66	2	56	245	2.95	4.24129
7289	I-435 E @ NALL AVE CD	Dir Ramp	2598-2615	9.2	58	2	48	195	4.22	22.16141
7459	I-435 E @ NALL AVE FR	Ramp	2598-11748	0.5	48	2	49	245	6.14	21.40012
7297	I-435 W @ NALL AVE CD	Dir Ramp	2599-2593	5.7	63	2	55	200	4.15	4.24129
7295	I-435 W @ NALL AVE FR	Ramp	2599-11739	5.7	63	2	55	200	4.15	5.79682
8400	I-435 EB@ East of HWY 69	Mainline	2655-326	22.8	123	2	65	245	7.37	31.36644
7303	I-435 W @ ROE AVE CD	Dir Ramp	2676-2672	4.6	65	2	60	135	2.35	12.02707
8272	I-435 E @ LEE BLVD	Mainline	2719-14794	19.1	111	2	71	205	5.19	4.49326
8091	US-69 S @ College	Mainline	5738-5805	13	116	2	72	235	9	5.50624
7775	I-435 S @ BANNISTER ROAD OR	F-F Ramp	11186-11462	0.4	61	2	60	180	5.35	34.26032
7773	I-435 E @ S OF BANNISTER RD	F-F Ramp	11410-14712	17	78	2	68	245	2.08	5.79682
7965	I-49 S @ I-470	F-F Ramp	11464-14763	10.9	97	2	72	245	6.82	10.04384
8082	US-69 S @ 103rd Street	Mainline	11509-2538	19.7	73	2	68	245	0.86	5.49859
7971	I-49 S @ I-435 SB Freeway to Freeway	Ramp	11578-14763	10.5	115	2	77	245	9.88	7.707
7772	I-435 E @ GRANDVIEW RD	Mainline	11581-14692	17.1	86	2	68	200	2.91	4.81822
7530	I-435 W @ STATE LINE RD	Mainline	11625-11640	25.1	146	2	69	240	7.67	4.29111
8273	I-435 W @ LEE BLVD	Mainline	11640-11707	20.8	127	2	71	245	7.43	4.76225
7578	I-435 W @ ANTIOCH RD	Mainline	11706-14190	2.8	69	2	68	240	1.57	12.60568
8238	I-435 W @ ROE AVE	Mainline	11707-11709	17.7	139	2	71	245	9.94	5.25124
7311	I-435 E @ ROE AVE OR	Ramp	11712-605	5	54	2	48	230	5.56	14.02355
8237	I-435 E @ Roe Blvd	Mainline	11718-2719	14.9	173	2	69	245	16.01	20.74929
7411	I-435 W @ METCALF OR	Ramp	11734-11706	11.1	61	2	60	165	0.3	22.46856
8413	I-435 WB @ Metcalf Ave mainline	Mainline	11735-11706	10.2	77	2	64	245	4.44	13.10776
7292	I-435 E @ NALL AVE OR	Ramp	11748-607	3.3	65	2	59	245	8.1	19.22139
8296	I-435 WB @ Lamar Avenue	Mainline	11759-11735	15.7	104	2	68	245	7.02	7.49434
7762	I-49 N @ I470/I435 CD	F-F Ramp	11853-14749	7	62	2	58	200	3.81	40.05499
8106	I-49 N @ Red Bridge Road	Mainline	11878-11853	18	130	2	70	190	7.01	3.90121
8090	US-69 N @ College	Mainline	12030-11913	24.1	118	2	70	245	5.67	5.31224
8067	US-69 S @ 135th Street	Mainline	12365-14051	18.6	110	2	71	160	4.06	6.65664
8338	US-69 N @ 135th Street Directional Ramp	Dir Ramp	12564-12458	20.4	98	2	69	245	4.49	4.45611
7449	I-435 W @ ANTIOCH RD	Mainline	14190-313	23	158	2	62	205	8.94	29.01118
7966	US-71 N @ Before Bannister Road	F-F Ramp	14702-14691	13.6	88	2	63	175	4.63	5.98596
7469	I-435 W @ GRANDVIEW RD	Mainline	14722-650	16.6	101	2	71	235	5.27	4.69472
7533	I-435 W @ EAST OF HOLMES RD	Mainline	14723-11575	18.7	96	2	70	245	4.3	5.34986
7790	I-470 W @ I-435NB/US71 FF	F-F Ramp	14725-11664	1.1	73	2	71	240	5.21	15.69007
7791	I-470 W @ HILLCREST RD	F-F Ramp	14725-14726	1.8	75	2	72	175	2.67	18.15634
7766	I-49 S @ I470WB TO US71SB FF	F-F Ramp	14747-14750	0.6	63	2	62	150	4.93	21.25441
8116	I-49 S @ Hickman Mills Drive	Mainline	14755-15214	11.1	73	2	69	245	1.32	3.34481
8117	I-49 S @ Red Bridge Road	Mainline	14756-14755	11.1	73	2	69	245	1.32	3.34481
7698	I-49 S @ RED BRIDGE FR	F-F Ramp	14764-14746	1.8	79	2	76	205	3.75	46.40221
7786	I-470 E @ W OF 71NB TO 470EB F	F-F Ramp	14765-14724	18.8	107	2	63	245	7.36	22.60902
7527	I-435 E @ WEST OF HOLMES RD	Mainline	14776-14782	22.2	107	2	68	245	5.38	4.75511
7454	I-435 E @ WEST OF 104TH ST	Mainline	14779-649	22.3	103	2	69	245	4.69	5.33992
7580	I-435 E @ HOLMES RD OR	Ramp	14780-655	2.9	38	2	37	195	1.67	6.85058
7394	I-435 E @ HOLMES RD OR	Ramp	14781-14782	2.9	28	2	26	245	5.64	5.76567
7528	I-435 E @ EAST OF HOLMES RD	Mainline	14782-14779	17.3	93	2	68	245	4.65	5.85965
7418	I-435 W @ HOLMES RD OR	Ramp	14783-11575	6.5	34	2	31	170	2.04	6.09865
7531	I-435 W @ WEST OF WORNALL RD	Mainline	14786-11573	22.9	104	2	66	245	5.28	3.88908
7526	I-435 E @ EAST OF WORNALL RD	Mainline	14788-14785	20.9	112	2	72	245	5.5	4.64028
7525	I-435 E @ STATE LINE RD	Mainline	14796-14793	18	103	2	68	220	5.345	26.40614
8105	I-49 N @ Hickman Mills Drive	Mainline	15217-15210	22.8	123	2	65	180	5.83	2.83254
8115	I-49 S @ Harry S Truman Drive	Mainline	15222-15232	20.2	110	2	66	245	6.61	4.0673
8114	I-49 S @ 135th Street	Mainline	15238-15239	16.8	110	2	68	245	7.43	3.95762
8113	I-49 S @ 140th Street	Mainline	15239-15242	17.1	115	2	71	245	7.31	5.75373
8102	I-49 N @ 140th Street	Mainline	15241-12766	19.8	129	2	69	245	8.21	4.04419

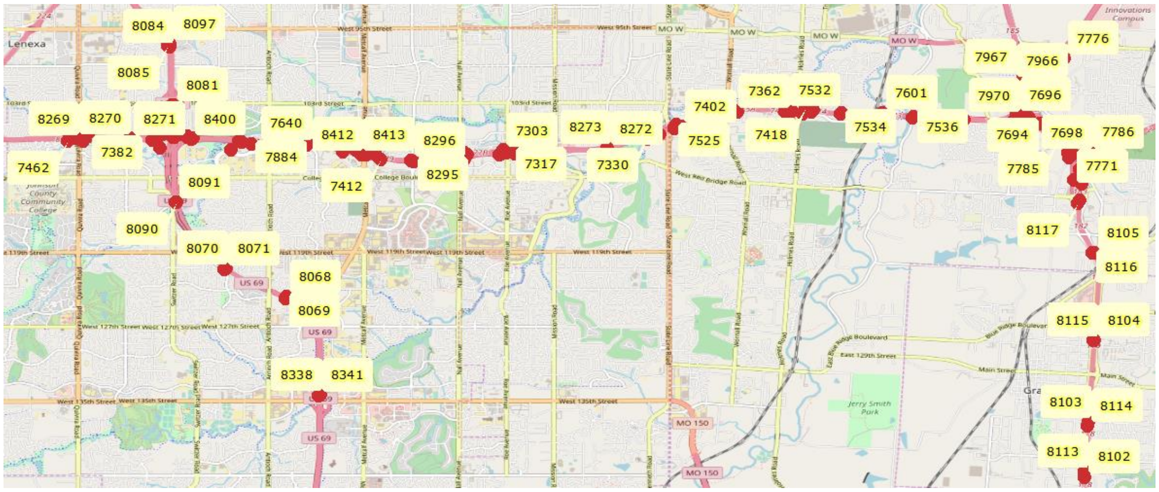


Figure 4. Selected Detectors for Traffic Flow Model Calibration, by ID Code.

Freeway traffic flow models were divided into sections, depending on the freeway type of facility (i.e., mainline, on ramp, off ramp, or freeway-to-freeway ramp), direction of traffic, and free flow speed characteristics. The calibrated speed-density curves for the network are presented in Figures 5 and 6. The graphs below represent typical example freeway links for which the observations were available, grouped by type of section they belong to.

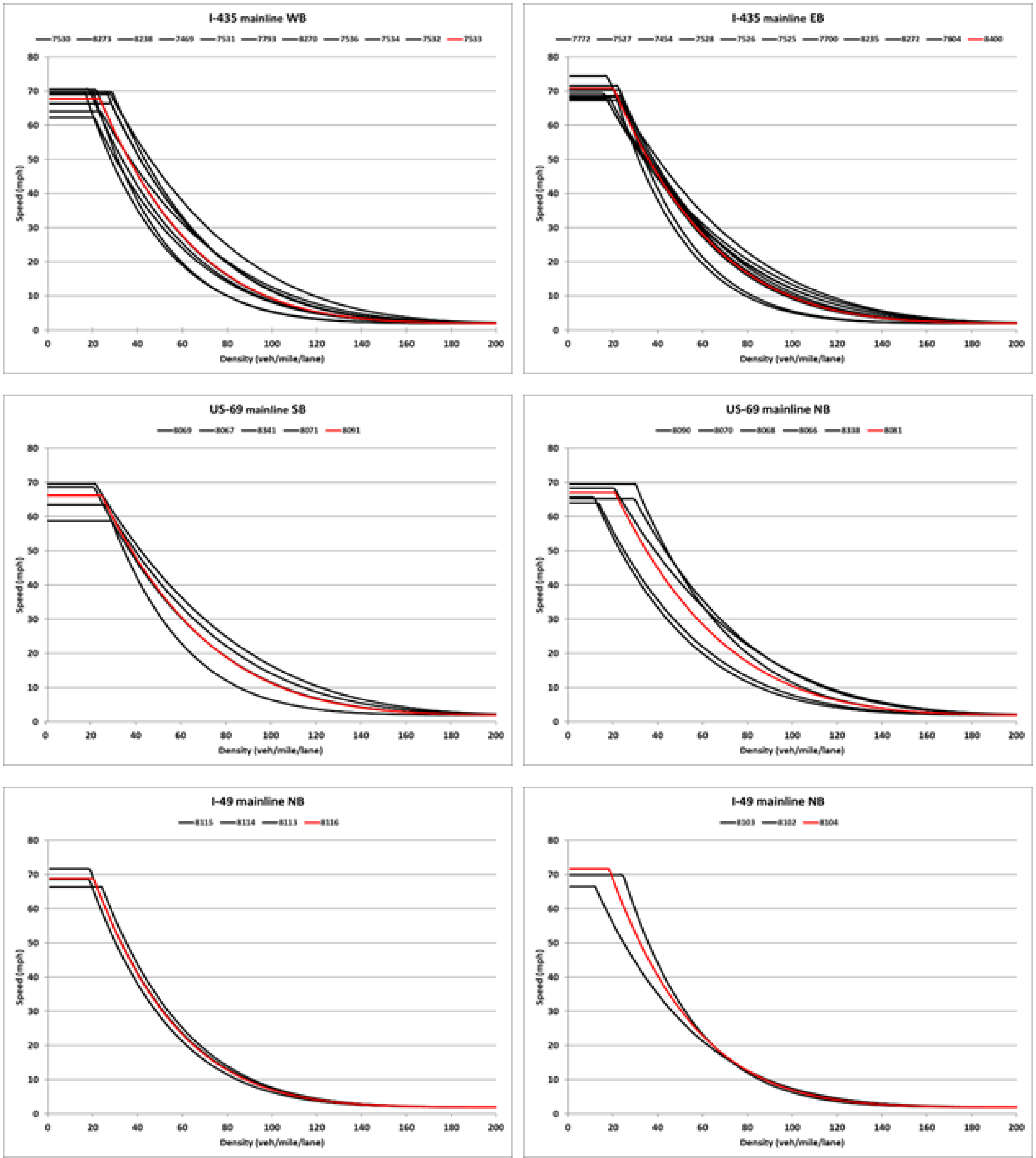


Figure 5. Calibrated Speed-density Curves for Representative Detector Locations.

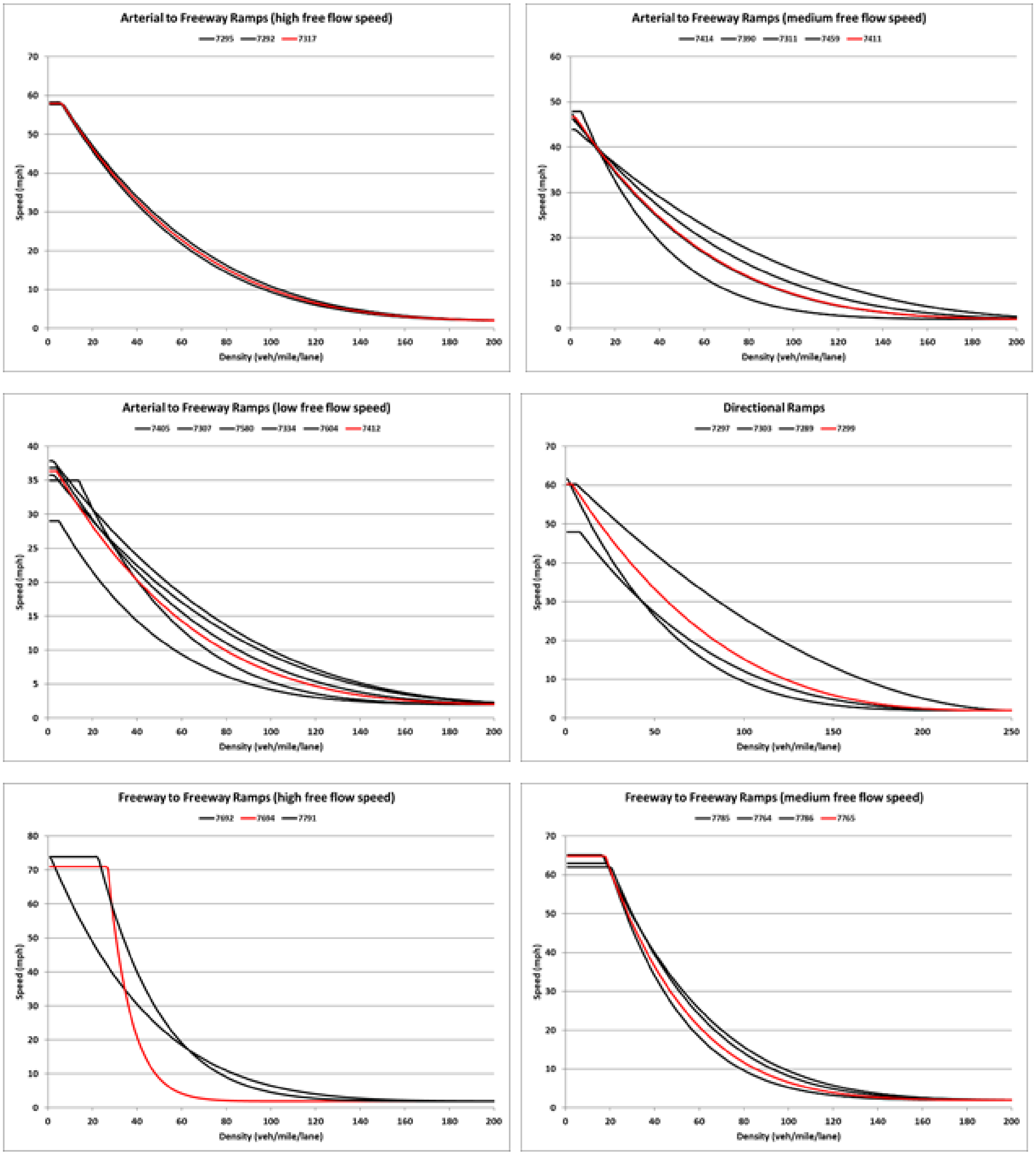
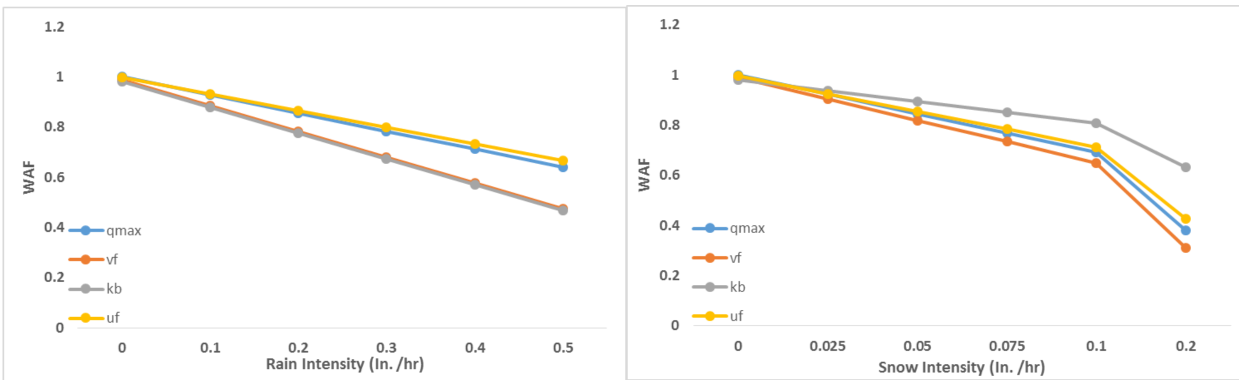


Figure 6. Calibrated Speed-density Curves for Representative Detector Locations.

Weather Adjustment Factors

Relevant literature findings[4] demonstrated that the traffic flow model parameters—the maximum service flow rate (qmax), shape parameter (α), and free flow speed (uf)—are sensitive to both rain and snow intensities. As the rain or snow intensity increases, maximum flow rate, speed intercept and free flow speed are reduced. The effects of the rain intensity and the snow intensity on different traffic flow model parameters are presented in Figure 7.



SOURCE: FHWA.

Figure 7. Effect of Rain and Snow Intensity on Weather Adjustment Factors.

An historical weather dataset obtained from KC Scout and NWS sources for the period from May through December of 2016 provided sufficient detail relative to visibility and precipitation intensity levels for calibration. However, lack of adverse weather data within the archived dataset, particularly a representative number of rain and snow days with associated parameters, coupled with the necessity of examining the traffic model's prediction quality for adverse weather conditions motivated the use of previously calibrated values for a greater Chicago area network.[5] Since heavy rain and snow conditions appeared very rarely (i.e., was not recorded in the archived dataset with great enough level of detail for weather adjustment factors to be calibrated), the detectors did not provide enough data for traffic flow model calibration for heavy rain/snow weather conditions.

Time-dependent Origin-Destination Matrix

Joint estimation of the entire 24-hour time-dependent origin-destination (TDOD) demand pattern was used in this study. Most previous dynamic traffic assignment (DTA) applications are limited to estimating peak-period demands. The 24-hour demand was generated by extrapolating the estimated origin-destination (OD) demand from the peak period to an overall daily pattern. The static/historical demand matrix retrieved from the 2010 MARC transportation planning model, along with time-dependent traffic

[4] (Ibrahim and Hall, 1994; Rakha et al., 2008, Yelchuru et al., 2016)
[5] Federal Highway Administration, *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs. Calibration Report – Chicago*. FHWA-JPO-16-381 (Washington, DC: FHWA, October 2016).

counts on selected observation links, was used to develop time-dependent OD matrices over the time horizon with a chosen time interval (five minutes).

The static/historical OD demand matrix for Kansas City subnetwork was retrieved from a much larger 2010 MARC transportation planning model, which consisted of 981 zones and was developed for a peak period. The demand for the study area subnetwork (69 zones) was estimated by first extracting from the larger model and then calibrating to the available detector data.

For the OD extraction for the sub-area under study, four types of trips relative to the sub area were observed: Internal–Internal (I-I), External-Internal (E-I), Internal-External (I-E), and External-External (E-E). I-I trips could be easily extracted from the original OD matrix. However, the effects of E-I and I-E on the sub-area network also needed to be considered. To do so, a simulation of the entire network in NeXTA had been performed to retrieve vehicles' trajectory, and the number of vehicles entering or existing the subarea had been added to the I-I trips with their corresponding zones. After the procedure was completed, total demand for the subarea was 1,438,515.

Offline Calibration of the OD Matrix

The demand extracted in the previous section needed to be calibrated based on the archived detector data. This section discusses the detector data, demand calibration, and the results.

Data Sources

The time-dependent link counts on selected observation links within the Kansas City network were used with dynamic traffic assignment models for calibrating time-dependent OD matrix. The characteristics of traffic count data used in this project are shown in Table 2. Out of 148 detectors available in archive data, 79 were excluded for reasons such as unreliable daily counts, inconsistencies in mass balance, or uncharacteristic speed-density relationships. The remaining 69 detectors were used for offline demand calibration.

Table 2. Characteristics of Traffic Count Data.

Facility Type	Freeway (I-435, I-49, and I-69)
Data Source	Kansas City Scout
Resolution	5 minutes
Data Contents	Flow, Speed, Occupancy

Demand Calibration

The demand calibration was based on minimizing the weighted distance between historical OD and detectors values, with weights of *w* and (1-*w*), respectively. Additionally, time weights and links weights were devised to impose more control over time and individual link calibration.

In each DTA simulation, a number of iterations of the User Equilibrium algorithm were applied to reach an equilibrium state in the network. Initially, a sensitivity analysis on parameter *w* was conducted to select the optimal weights in the objective function corresponding to the deviation from historical demand and link counts. The sensitivity analysis includes two ranges of values for the parameter *w*. The first range includes 0.1 to 0.9, with increments of 0.1, for the deviation from historical demand. The second range includes the following values: 0.99, 0.999, and 0.9999. Figure 8 shows deviations from observations and the deviation from the target demand under different weight selections in the first iteration of the basic solution method. By comparison, *w* = 0.9 gives a decent compromise between two deviation terms in the objective function and is selected for numerical experiments. The link weights have been carefully selected so that the simulation better matches the observation. The time weights of the 288 intervals (total of 24 hours) of demand may vary from period to period.

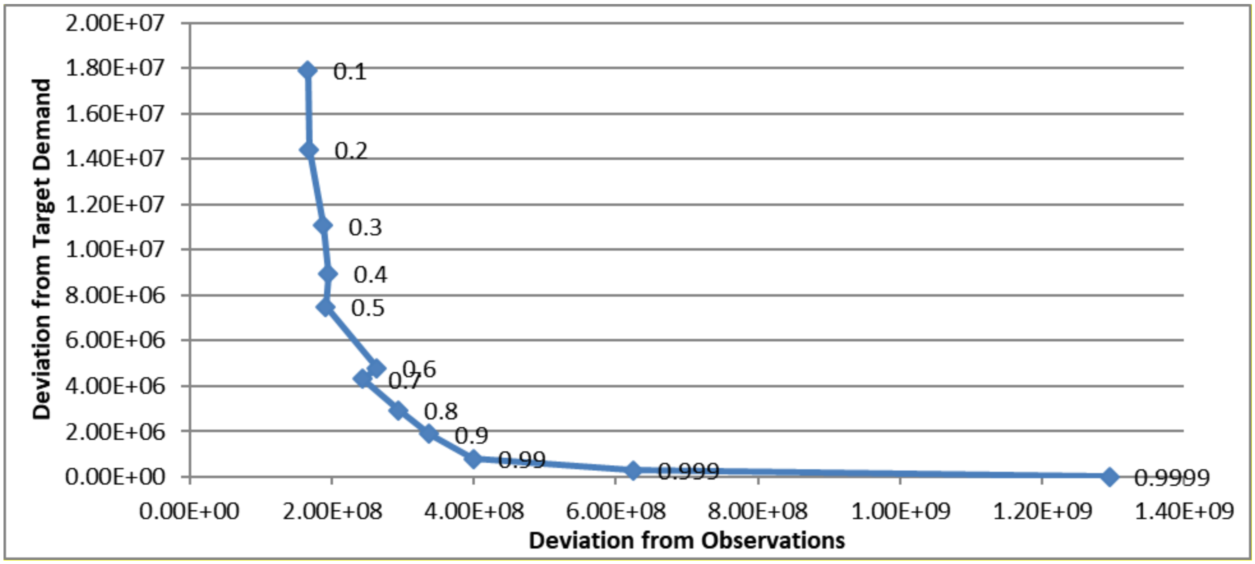


Figure 8. Sensitivity Analysis of Different Weights.

Calibration Results Evaluation/Validation

The TDOD estimation was first validated on a link-level basis, and then the overall calibration results, including the traffic flow model, WAF and TDOD were taken into DYNASMART-X and verified by the comparison between simulation data and historical observation data.

First, the simulated and observed link counts are compared for each link. Simulation results based on the estimated time-dependent OD matrix are compared with the actual observations. Figure 9 shows the 5-minute vehicle counts for 3 selected links before (left) and after (right) calibration.

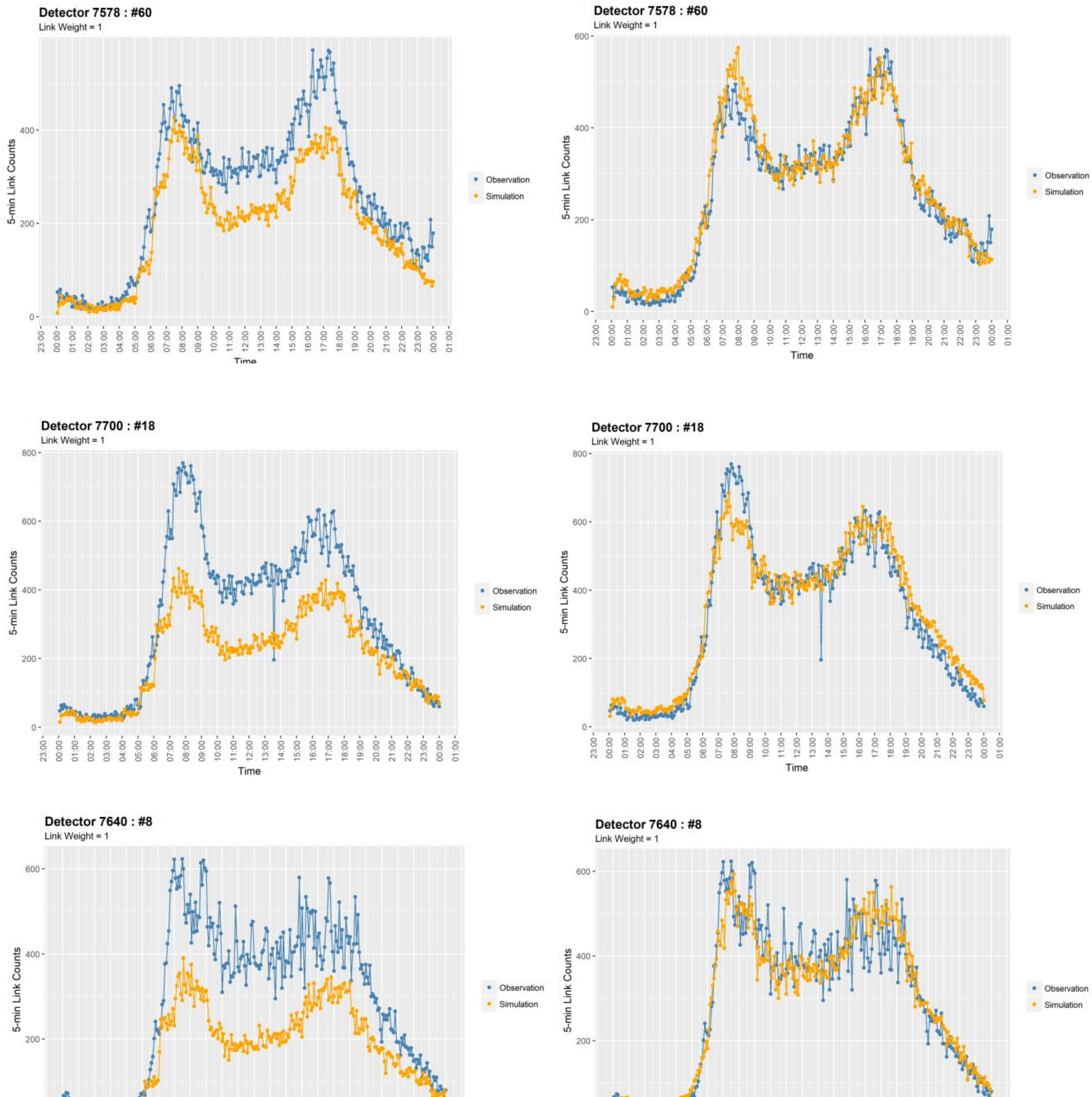


Figure 9. Five-minute Vehicle Counts Before (Left) and After (Right) Calibration.

Figure 10 shows the cumulative vehicle counts on the selected links before (left) and after (right) calibration.

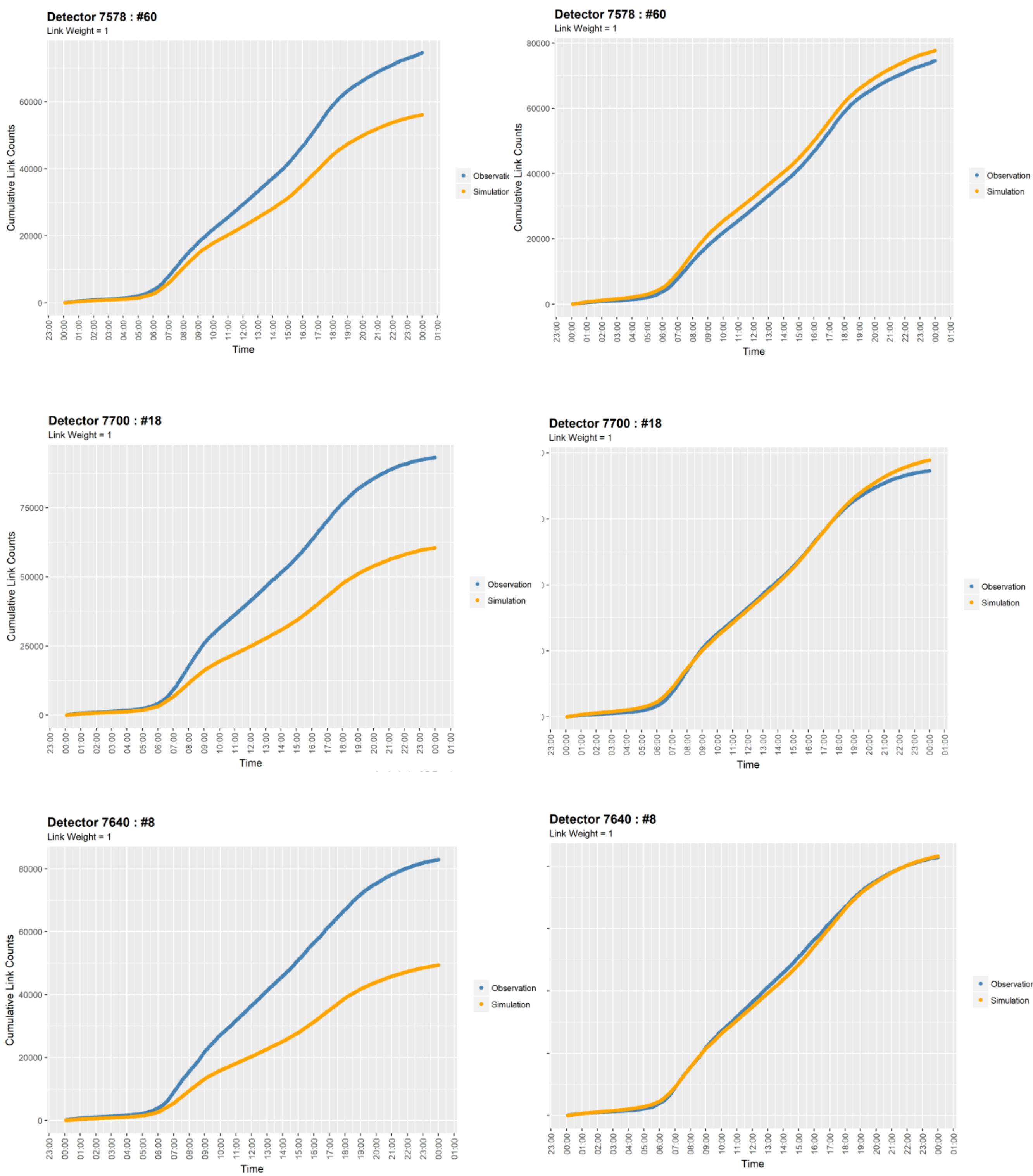


Figure 10. Cumulative Vehicle Counts Before (Left) and After (Right) Calibration.

System Deployment and Operations

This deployment of the IMRCP is a system development prototype. As such, the focus is on development, and it is desirable to simplify the deployment in order to minimize system management overhead. To that end, the prototype is deployed to a two-component computing environment—the main IMRCP and the TrEPS components—and provides distributed user access for the development team, the review team, and the partner prototype agency. The IMRCP core data services and computational services are closely linked and benefit from co-location to reduce latencies and remote network calls. The demonstration deployment of the TrEPS model, however, requires significant set-up and calibration and needs to be co-located with its development subteam.

Figure 11 shows the IMRCP system deployment for the Kansas City area demonstration. The IMRCP system software, database and file services, and the Tomcat Web server are deployed on a common server with a high-bandwidth connection to the Internet to access data contributors and to provide access to IMRCP forecast products for stakeholders and systems. The IMRCP and TrEPS servers exchange data remotely, but could alternatively have been deployed to a common local network.

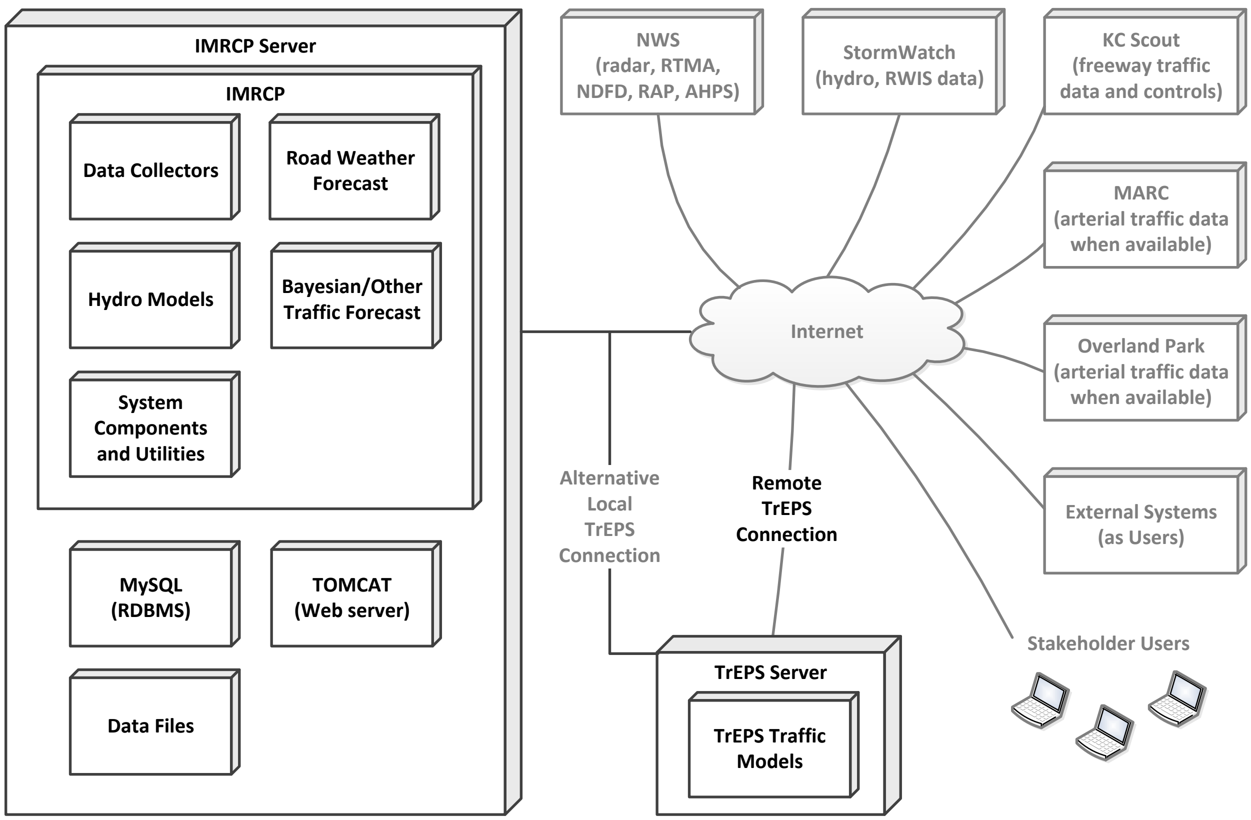


Figure 11. IMRCP System Deployment Diagram for the Kansas City Area Demonstration.

Chapter 4. Evaluation

Introduction

The IMRCP will provide a framework for the integration of road condition monitoring and forecast data to support tactical and strategic decisions by travelers, transportation operators, and maintenance providers. The system collects and integrate environmental observations and transportation operations data; collects forecast environmental and operations data when available; initiates road weather and traffic forecasts based on the collected data; generates travel and operational advisories and warnings from the collected real-time and forecast data; and provides the road condition data, forecasts, advisories and warnings to other applications and systems. Road condition and operations data and forecasts to be integrated into the prediction may include atmospheric weather; road (surface) weather; small stream, river, and coastal water levels; road network capacity; road network demand; traffic conditions and forecasts; traffic control states; work zones; maintenance activities and plans; and emergency preparedness and operations.

This model is moving from prototype development to a testing phase and is currently being demonstrated for a study area in the Kansas City region. The primary objective of this implementation project is to test the validity and value of integrated predicted information for TMC operations. In this sense, this test seeks to understand: 1) if the tool was able to adequately provide advance warning of traffic and weather conditions, and 2) whether forecast conditions (of weather, road conditions, and traffic) enable TMC operations staff to make better decisions, such as more proactive implementation of weather responsive traffic management strategies.

It is important to note the small window of opportunity to evaluate the tool. This was a key limitation of this assessment process, which translated to a limited number of events (weather, work zones, and incidents) to calibrate the traffic model within IMRCP and assess the tool. Additionally, most adverse weather events during the evaluation period of September through November occurred either on weekends or during late hours of the night—times for which the prediction model has not been explicity calibrated. Furthermore, as of late November, there have not been any winter storms (i.e., with snow and ice) to analyze. Therefore, there has not been any opportunity to assess the full potential of the tool's weather-related traffic prediction capabilities.

While a robust system, the IMRCP is constrained by the following aspects:

- The overall accuracy of predictions is contingent on the component models. Since a "true" ensemble forecast where different models are weighted to provide a unified and integrated forecast is not yet built and tested, there is a significant burden on the user to understand the relative value of the different forecasts. Currently, the system shares different predictive outputs with the user, who then has to evaluate them based on their knowledge and experience in making related decisions.

- As a research product, the IMRCP tool is not integrated with TMC operating processes or systems. This implies that currently operators are not required to make decisions based on tool outputs, nor is it integrated with the ATMS used by the TMC.
- The IMRCP system is also currently limited to a small network of road segments in the Kansas City area.
- The quality of the IMRCP system's output is directly dependent on the input provided from the traffic management centers. If the quality or the timeliness of the input is suspect, the resulting predictions may be unreliable.

This summary provides an evaluation of the IMRCP system in a real-world context within the limitations of the implementation.

Summary of Impacts

The following impacts and findings were observed during the evaluation time period.

- The IMRCP tool lends itself as a good foundation for merging and harmonizing weather data for operators to use within a single system, demonstrating that it can successfully integrate externally generated weather forecast data into its interface.
- Statistically, across the network, the TrEPS traffic prediction capability in IMRCP provides a robust model of reality for the network. While calibration was conducted only for the weekday periods, the model performs satisfactorily in capturing the normal variations in traffic in the network. Detailed statistical analyses are presented in the full evaluation report.
- Pavement conditions and pavement temperature features were assessed as working as intended but their use in the real-world was limited by the timing of the evaluation which did not include winter months.
- The evaluation looked at several days/events to assess the IMRCP tool performance from an operator's perspective. In the selected day-to-day examples, the IMRCP tool showed mixed performance in incorporating weather forecasts into traffic predictions. Two examples are highlighted here to illustrate the results. In the first scenario, a particular segment's real-time traffic speed was compared to its predicted / simulated traffic speed on a day when there was a short burst of heavy rainfall in the afternoon. In the second scenario, the same approach was applied on a day when there was predicted snowfall (which, incidentally, never occurred).
    - In the first scenario (seen in Figure 12), the TrEPS data (traffic speed predictions, updated every 15 minutes) was overlayed on the historical, real-time traffic speed data derived from KC Scout on Tuesday, October 10th, when heavy evening rainfall occurred. The model yielded what appears to be normal, evening-time congestion, and that it did not predict the late-afternoon speed drop due to the rainfall—despite the fact that the IMRCP interface showed that heavy rainfall was occurring at 3:50 p.m. There are three possible reasons for this:

        1. The limitation of receiving weather forecast data only once per hour could have limited the tool's ability to adapt to rapidly changing weather conditions.
        2. While this was "heavy" rainfall, it only occurred during a short spike around 3:50 p.m. and did not have a substantial impact on traffic (as seen in the historical KC Scout data).
        3. Related to the previous point, weather adjustment factors are not yet fully calibrated due to the fact that there have not been many peak-time adverse

weather conditions to work with—and therefore the detectors did not provide enough data for traffic flow model calibration of heavy rain / snow weather.

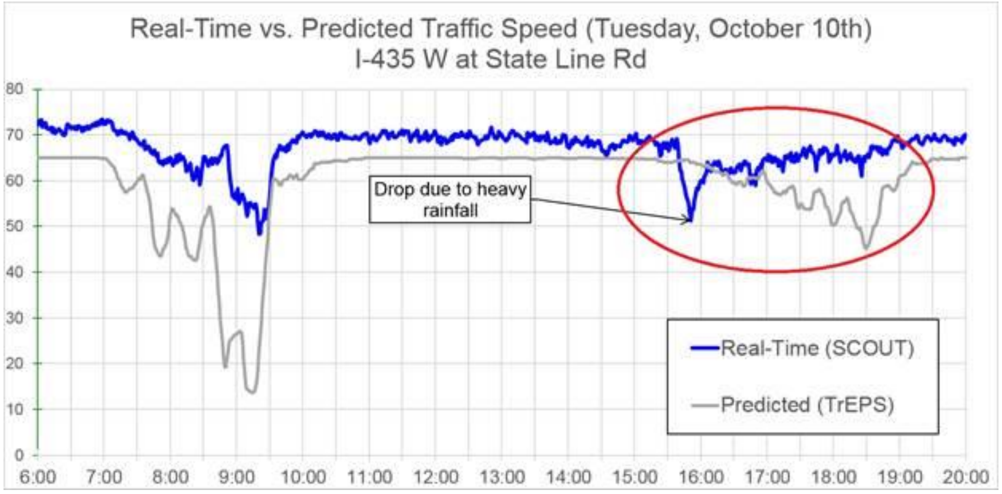


Figure 12. TrEPS Prediction Model Results Relative to Heavy Rainfall Event

- The second scenario, tested whether TrEPS is capable of adapting its speed predictions based on snowy weather that was predicted in the region for the afternoon of Tuesday, October 31st (Figure 13). The results from this second scenario illustrate that TrEPS is responding to the predicted adverse weather (i.e., indicated by the drop at 3:00 p.m.). The difference between the predicted and ground truth data can be explained by the fact that, as confirmed by MoDOT, there was no precipitation on that day in the study corridor; nevertheless, the National Weather Service had *still predicted* snow at that time due to an approaching cold front from the northwest. While the snowfall did not ultimately occur, these results extracted from the tool prove to be promising. The IMRCP was able to display future traffic conditions according to weather forecast data, and the model was able to adjust its prediction accordingly.

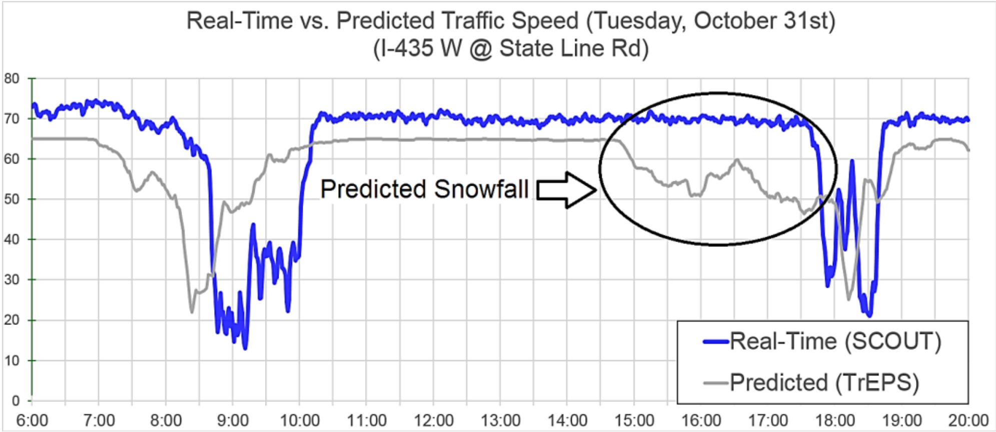


Figure 13. TrEPS Prediction Model Anticipating the Impact on Traffic Due to the 3:00 p.m. Snowfall.

- Work zone-related examples were evaluated as well and revealed some ongoing model limitations. The model is currently not set up to assign multiple work zones on a link, which a real-world example highlighted. Short term work zones can be overridden by the presence of a long-term work zone activity leading to the traffic impact not being adequately captured.

Scout Operators Assessment

As part of the evaluation process, two separate conversations were held with Scout operators to determine their perspective of the IMRCP tool. The conversations gathered information from the early morning / day shift and the evening shift operators. Unfortunately, the night operators were not available at the time of these conversations; they might have provided a different perspective from the day- and evening-shift operators, as the available traffic cameras are not as effective during night/dark hours. The key viewpoints are summarized below:

- A key benefit of the tool is its potential to provide information from sources that do not share information with KC Scout. For instance, there were some instances during late evening / early night hours within the study period where the IMRCP notified the operator of light rain that was not forecasted by NWS. However, they do note that the very low number of weather events did not allow them to fully grasp the potential of this tool.
- While the tool is able to integrate information from a number of different sources, it can become redundant when the TMC (or host agency) is one of the main sources/providers of the information. The operators felt that the tool provided no added value to traffic congestion monitoring and incidents, since KC Scout is the original source of these notifications.
- Related to the previous statement, the operators felt that their current (modern) ATMS tool provided more meaningful notifications of current traffic events, making the IMRCP tool redundant for current traffic conditions. The advantage of IMRCP is its forecasting capability; however, the operators noted that they were not notified of any potential/forecasted traffic related event during the evaluation period and therefore are not able to comment on the usefulness of this feature.
- There is a belief that this will be the “Holy Grail” for weather management. For maintenance specifically, the ability to see into the future (i.e., “scroll to the right”) is significant given that they currently receive forecast information only twice a day and it is not route-specific. Hence, as a snow-forecasting tool, it would provide much needed information to the maintenance crews (e.g., what specific routes need attention, at what time is a storm expected to hit a specific location).

The operators also suggested the following improvements to the user interface to make the tool easier to use:

- Bookmarks and/or user-tailored search criteria could improve the interaction with the user interface. As it is currently operating, the user of the tool has to always go back and select the criteria/parameters he/she wants to show every time they log in (or when they move away from their preferred standpoint).
- It would be useful to provide some way to suppress recurring notifications of updates to existing alerts. The operators felt that these notifications were too frequent, and most of the time the update was not meaningful to warrant such notification.
- In the cases where they are the main providers of information, it would be useful to put incident detection in the background and just focus on forecasted impacts of weather events and changes in traffic volumes.

- Operators usually have many windows opened at the same time, minimizing and changing their sizes as they need to in order to see the best information available to them. The current setup of the interface does not allow users to hide the legend of the variables/parameters that are being shown. While this is useful for new users of the tool, more experienced ones do not need this level of detail and would benefit from the ability to hide the legend, instead of it being constantly displayed and blocking the map where the information is being presented (especially when the operators reduce the size of the window).

Lessons Learned

The IMRCP system is a unique research effort that brings together different transportation operations disciplines together to achieve a lofty goal of providing integrated predictions of road conditions to operators. Bringing together weather, road temperature, and traffic models together in real-time requires a complex data integration architecture coupled with big data management and effective visualization. The evaluation approach and findings (more fully detailed in Chapters 4 and 5 of the Evaluation Report) describe not only the successes in meeting the lofty goal but also the continuing efforts that are needed to bring IMRCP to a stable operational use. This section summarizes the key lessons learned with a focus on future implementation sites that might be considering the use of systems like IMRCP.

- **The quality of IMRCP results is dependent on foundational systems at the TMC**. The IMRCP tool is based on a foundation of traffic data available at a TMC. These include detector data and event data typically available as part of an ATMS suite. In addition, IMRCP requires a representation of the network that is easily available. If there is an existing micro/meso simulation, verified detector data and robust tracking of events at the TMC, the set-up of IMRCP is greatly simplified. However, in the absence of verified foundational data, the start-up hurdles of setting up IMRCP can seem daunting. However, it is important to note that agencies can (and likely take) a piecemeal approach to IMRCP integration starting with the easily available sources of data and slowly building up capabilities of this modular system.
- **Expand focus beyond the workday**. A key lesson learned from the evaluation was the need for the IMRCP system to be set up to account for the “unusual” since those conditions are where operators greatly value the improved situational awareness. Traditional model development focuses typically on calibrating for the frequent, predictable workday conditions. Counter-intuitively, this is when operators feel that they can manage the event using their existing tools. Weekends, special events, and nights are often times when non-recurring congestion (and associated impacts) occur that are not as well monitored by current TMC systems.
- **Invest in Calibration and Testing.** While calibration and testing were a core element of the project, the evaluation revealed the need for more robust approaches to calibration and testing before operational deployment. In essence, as the first generation of the tool, the evaluation period served more as a “shakedown” period with many errors and limitations coming to light as operators, evaluators, and system deployment teams started looking more at the output results. While the test plans focused on component level testing, additional end-to-end testing could have revealed some of the issues earlier.
- **Reporting Exceptions Rather than the Norm.** The IMRCP tool was also a first in figuring out how to assemble the various data and model compenents in the system for use by a TMC operator. As the evaluation progressed, it became clear that “less is more” in terms of the information provided to the operator. For systems like IMRCP, reporting the “exception from the norm” is particularly important. For example, the notification feature added by the system

development team was well received by the TMC operators. Additional effort is needed to enhance the notification of exceptions including multiple exception handling, prioritization and user interface displays. It is important to note that, as a research tool, the IMRCP project was only scoped to develop a functional user interface rather than spend resources on a polished user interface. (See the following lesson for additional detail.)

- **Encourage Direct Integration of IMRCP Outputs into ATMS**. Fundamentally, the IMRCP is a decision support tool that ingests data and provides notifications of current and forecast conditions. While a separate user interface was developed for this project, the more realistic use case is to build a data interface directly into the ATMS. Data feeds from the IMRCP can directly feed into event notification systems at the TMC and operators can be made aware of a change in conditions directly on their screen as opposed to having another browser open with this information. Once the interface is built, additional capabilities become possible such as direct dissemination to travel information systems or to support messaging/paging of TMC/maintenance staff when alert thresholds are met.
- **Develop Scenarios of Use for Traffic Prediction**. Lastly, the use of weather forecasts in decision-making is intuitive. In fact, people use weather forecasts in their daily lives. Road weather information such as pavement condition and pavement temperatures are also well-understood by the maintenance community and they are able to adequately adjust their strategy and tactics based on forecasts of such information. On the other hand, the role of traffic prediction in TMC operations is still emerging. Most TMCs rely only on current data for decision-making. To adequately integrate predictions into the TMC set up, additional work is needed to establish scenario managers that translate the traffic prediction to more meaningful actions for the TMC. For example, a variable speed limit scenario manager might take into account traffic predictions and alert the operator that a speed change might be needed in 15 minutes.

Chapter 5. Analysis, Conclusions, and Recommendations for Further Study

Having developed and demonstrated a capability for providing integrated traffic and road condition prediction, this section offers some potential applications for the IMRCP, summarizes lessons learned and deployment considerations, draws conclusions from the demonstration, and recommends topics for further study.

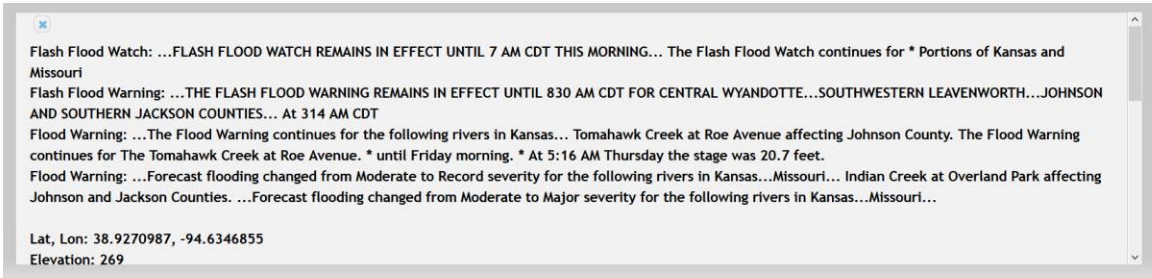
Potential Applications

Flooding Event

The IMRCP system may be able to monitor hydrological data during flooding events for potential impacts on transportation infrastructure. The Kansas City demonstration study area was chosen in part because of its urban small-stream, flash-flood challenges. Transportation system operators and emergency services personnel can use the IMRCP system to view predictions for flooded roads or to look back at the behaviors of a hydrological event.

The small-stream flooding of July 27, 2017, proved to be a challenging hydrological event for the Kansas City study area. Several roads in the study area experienced flooding and closures. This event can be reconstructed on the map using a combination of various layers and the date/time feature. In the case illustrated in Figure 14, the date/time feature has been set to July 27, 2017, at 6:00 a.m. The pavement flood depth layer and NWS alert layer have been selected in Figure 15. The Pavement Flood Depth layer displays the roads that registered as flooded according to the IMRCP, with pavement flood depths above 12 inches coded in dark blue. The NWS Alert layer displays several blue polygon overlays in the study area to represent flood-related NWS alerts. The overlays are darker in some areas to indicate multiple overlays on top of one another.

The time slider can be moved backward or forward to view the changes in the flood depths of the roads and the NWS Alert overlays. When a link is selected on the map, a pop-up box displays the flood depth calculated for the link at the time indicated on the time slider. When an area is selected on the map, all overlays that intersect with that point are listed in the pop-up box (Figure 16) at the time indicated by the time slider.



Flash Flood Watch: ...FLASH FLOOD WATCH REMAINS IN EFFECT UNTIL 7 AM CDT THIS MORNING... The Flash Flood Watch continues for * Portions of Kansas and Missouri
Flash Flood Warning: ...THE FLASH FLOOD WARNING REMAINS IN EFFECT UNTIL 830 AM CDT FOR CENTRAL WYANDOTTE...SOUTHWESTERN LEAVENWORTH...JOHNSON AND SOUTHERN JACKSON COUNTIES... At 314 AM CDT
Flood Warning: ...The Flood Warning continues for the following rivers in Kansas... Tomahawk Creek at Roe Avenue affecting Johnson County. The Flood Warning continues for The Tomahawk Creek at Roe Avenue. * until Friday morning. * At 5:16 AM Thursday the stage was 20.7 feet.
Flood Warning: ...Forecast flooding changed from Moderate to Record severity for the following rivers in Kansas...Missouri... Indian Creek at Overland Park affecting Johnson and Jackson Counties. ...Forecast flooding changed from Moderate to Major severity for the following rivers in Kansas...Missouri...

Lat, Lon: 38.9270987, -94.6346855
Elevation: 269

Figure 14. Kansas City Hydrological Event Alert for July 27, 2017.

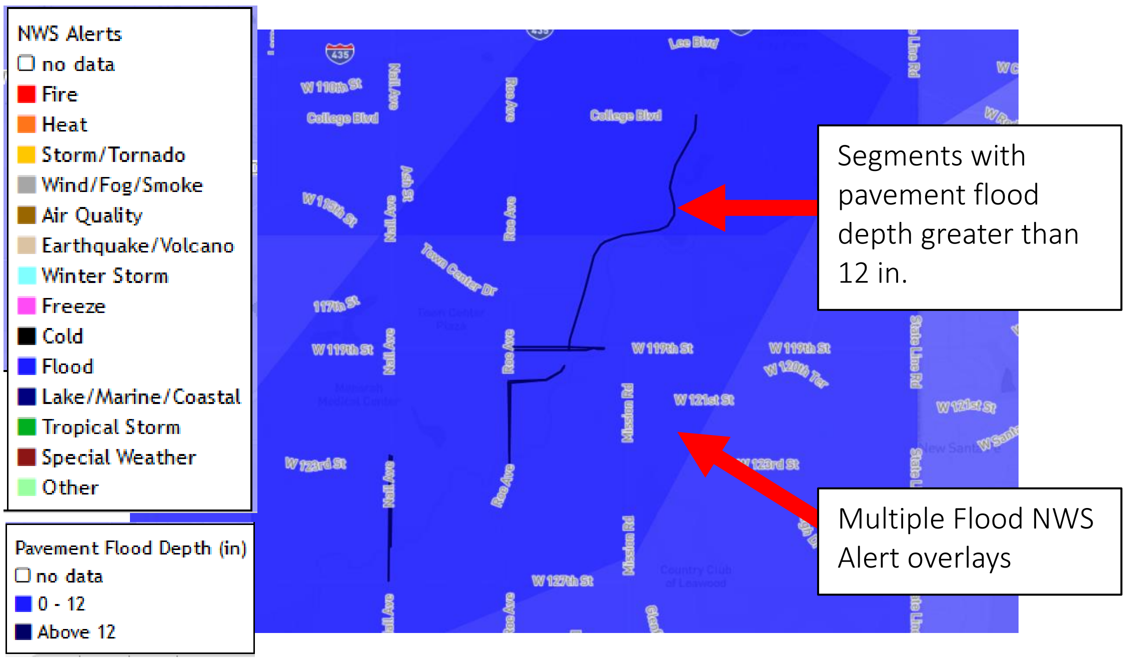
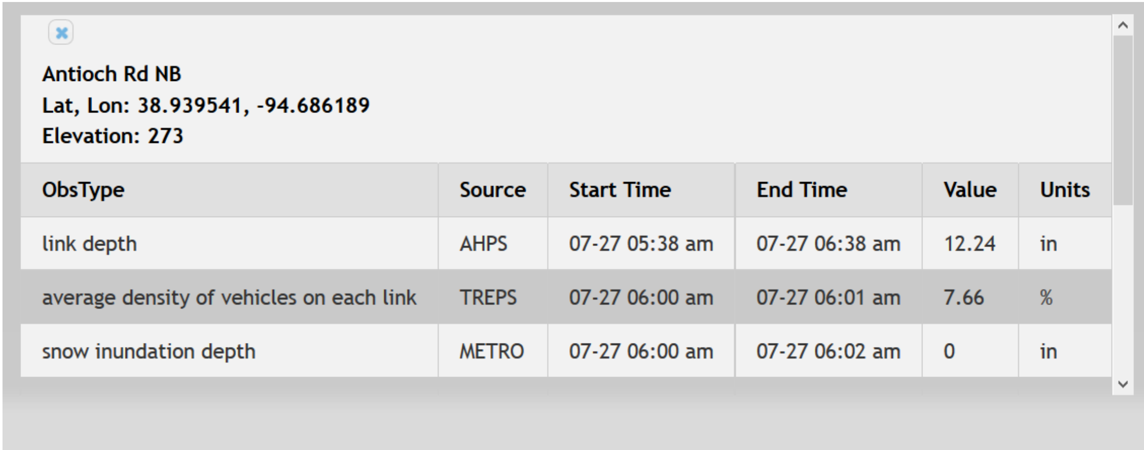


Figure 15. Kansas City Hydrological Event Map for July 27, 2017.



Antioch Rd NB
Lat, Lon: 38.939541, -94.686189
Elevation: 273

ObsType	Source	Start Time	End Time	Value	Units
link depth	AHPS	07-27 05:38 am	07-27 06:38 am	12.24	in
average density of vehicles on each link	TREPS	07-27 06:00 am	07-27 06:01 am	7.66	%
snow inundation depth	METRO	07-27 06:00 am	07-27 06:02 am	0	in

Figure 16. Kansas City Hydrological Event Link Data for July 27, 2017.

Pavement State Prediction

Monitoring pavement state predictions as a weather event approaches is essential to prudent traffic operations, especially during peak traffic hours. Early predictions of wet or icy roads enable operators to provide traveler notification of inclement conditions. The IMRCP system map and reporting features can be used to view these predictions and their potential impacts on traffic.

To view pavement state predictions on the map, users can set the date/time function to “Now” and select the “pavement state” road data layer. The user can move the time selector ahead in time to see the unfolding forecast. The color of the segments on the map indicates the pavement state prediction, as coded in the legend. Users can zoom in and out of the map to view different parts of the study area, and segments on the map can be selected to confirm the pavement state through the detailed pop-up box. The 1-minute refresh option enables the map to update with new predictions as they become available. Figure 17 shows the pavement state predictions at 3:30 p.m. for the study area, as forecast at 11:00 a.m. on 10/31/2017. The map indicates that water/snow is predicted on the pavement over part of the region, while other areas remain dry.[6]

[6] As it turned out, the approaching weather event did not result in any measurable precipitation on area roadways, although it did appear on weather radar images.

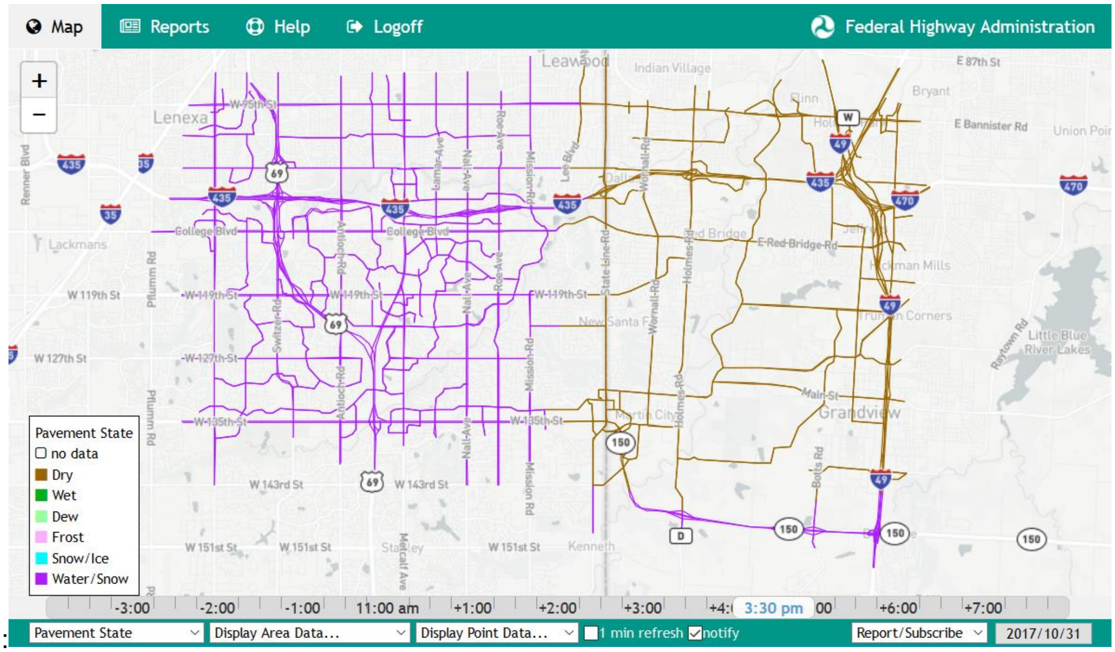


Figure 17. Pavement State Prediction Example.

To get predictions from the system in report form, the report/subscription function can be used to draw a box around the study area or a portion of the study area. The user should set the report conditions to an observation type of STPVT (pavement state) and to the Report radio button. The reference time should be set to the current time and the offset should be set to 0:00 so that only predictions will be returned in the report. The duration should be set to the amount of time until the end of peak traffic hours. For example, Figure 18 shows the report/subscription wizard for a report with a reference time of 11:00 a.m. on 10/31/17, an offset of 0:00, and a duration of 6:00 hours. This will return a report for pavement-state predictions between 11:00 a.m. and 5:00 p.m. on 10/31/17.

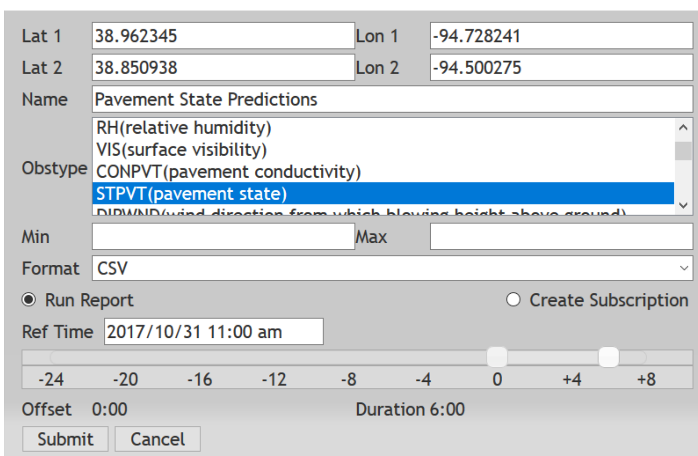


Figure 18. Report/Subscription Wizard for Pavement State Predictions.

Travel Time Predictions

The IMRCP predicts travel times for specific routes within the deployment area based on the traffic forecast model. As at KC Scout, travel times may be posted on roadside dynamic message signs and otherwise provided to travelers to adjust their expectations or departure times for their daily commute, especially in inclement weather. For instance, a user who works at Overland Park Regional Medical Center near I-435 and Quivira and lives near Three Trails Crossing could check to see if the approaching thunder storm will affect their usual evening commute home.

The user can select the Routes layer from the road data layer drop-down box on the map interface. This layer shows routes with available travel times in black on the map. Each of the routes can be selected and the travel time will be displayed in the pop-up box. It may also be beneficial to display the "precipitation rate & type" to view the forecasted precipitation over the near future. The "routes" and "precipitation rate & type" layers have been selected in Figure 19 and are displayed for the current time. Figure 20 shows that the travel time for the I-435 EB before Quivira to I-470 route is 13.4 minutes.

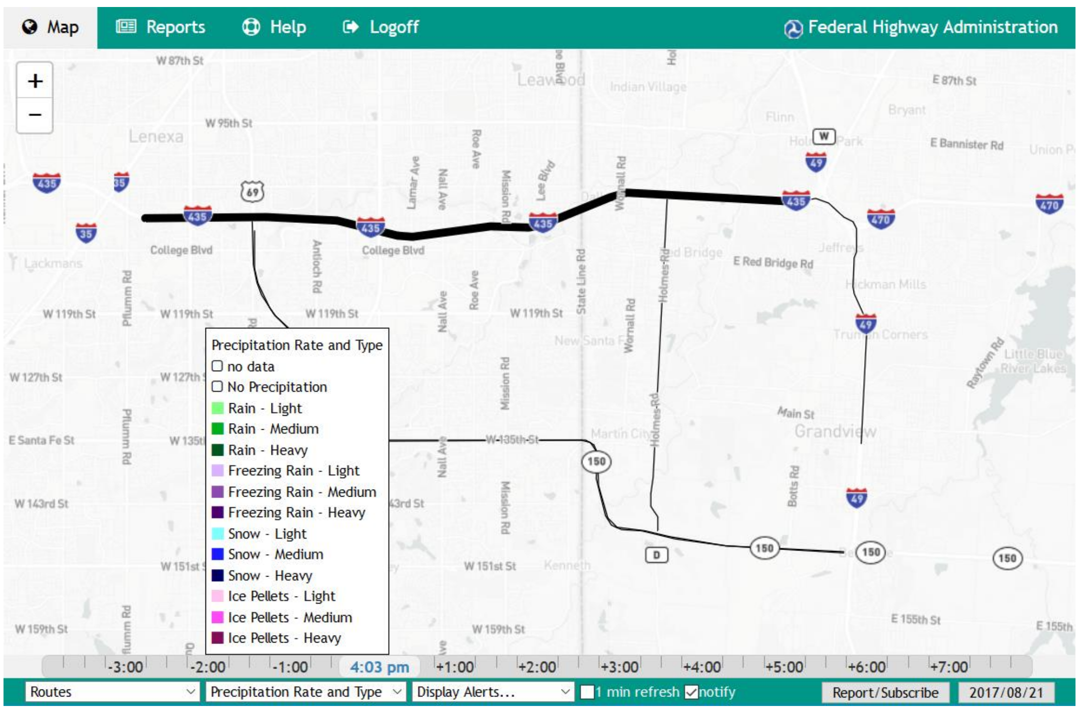


Figure 19. Routes and Precipitation Rate and Type Layers Prior to Rain Event.

I-435 EB before Quivira to I-470
Lat, Lon: 38.932520, -94.639502
Elevation: 265

ObsType	Source	Start Time	End Time	Value	Units
route time	TREPS	08-21 04:03 pm	08-21 04:04 pm	13.4	min

Figure 20. Route Travel Time Data Prior to Rain Event.

The user can slide the time selector into the future to examine future route travel time predictions. The user may see that precipitation is predicted at their usual commute time of 4:30 p.m. The travel time for I-435 eastbound before Quivira to I-470 at the user's usual commute time is 15.2 minutes. This travel time is slightly longer than the current travel time. The user can then make a more informed decision about their departure time based on this information.

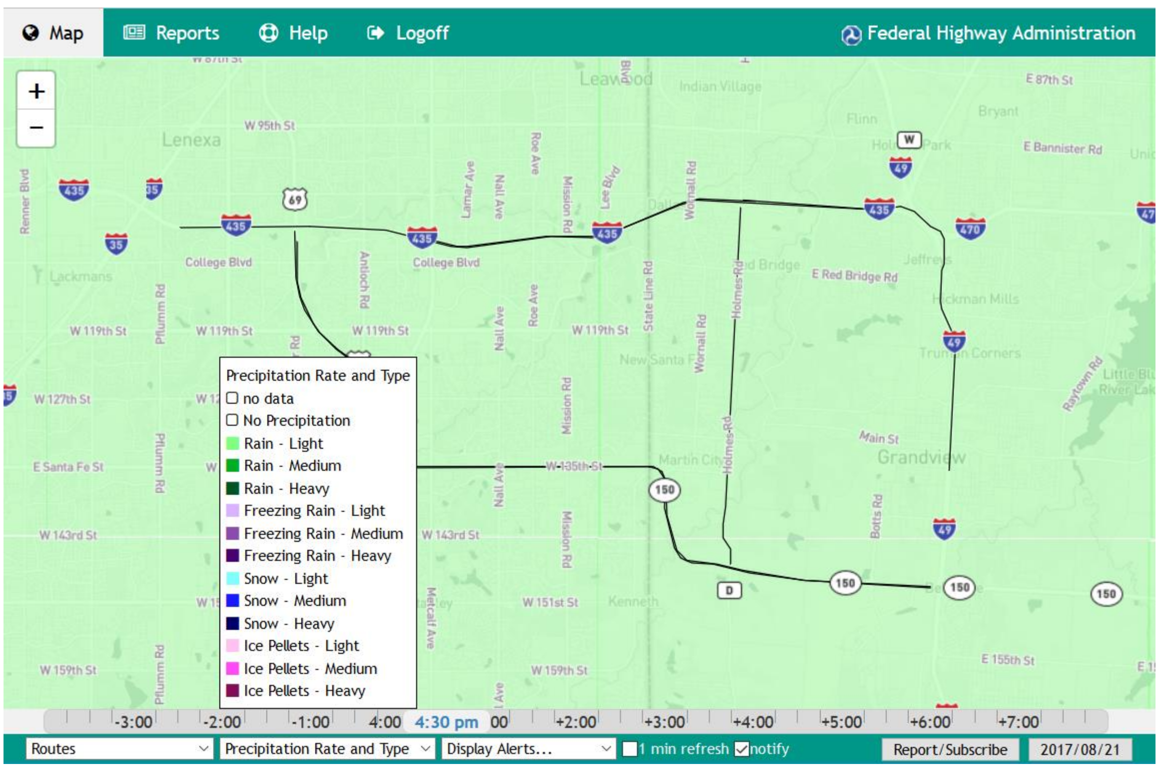
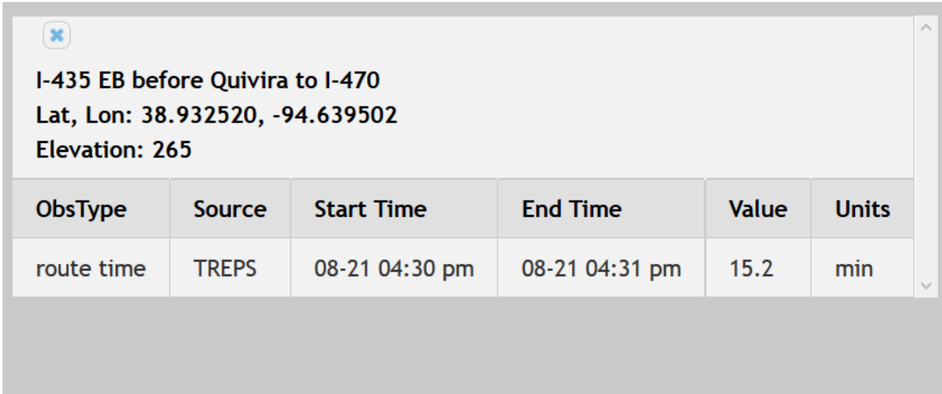


Figure 21. Predicted Routes and Precipitation Rate & Type Layers during Rain Event.


I-435 EB before Quivira to I-470
Lat, Lon: 38.932520, -94.639502
Elevation: 265

ObsType	Source	Start Time	End Time	Value	Units
route time	TREPS	08-21 04:30 pm	08-21 04:31 pm	15.2	min

Figure 22. Route Travel Time Forecast during Rain Event.

Deployment Considerations

One intent of this study was to investigate the potential for interested agencies to develop their own deployments of an IMRCP system. This section briefly describes some of the relevant considerations in a localized IMRCP deployment.

The IMRCP system, its components, and documentation have been developed under USDOT sponsorship and are available to interested parties on the Open Source Application Development Portal (OSADP). Software components are open-source licensed, except for some TrEPS components that are nonetheless available for download as executables. Other server components used in this IMRCP integration also use an open-source license. The database server is an open-source MariaDB Server, and Apache Tomcat 8 software is used for the application/web server. Java Runtime Environment 1.8 must be installed on the server.

Much of the data presented to users through the IMRCP is mapped to the road network of the study area. Definition of the area to be modeled needs to consider the potential applications, the extent of the network, the availability of data from traffic monitoring and control systems, and the effort needed to acquire the data and model the network. For example, creating the road network for the IMRCP study area was a critical and time-consuming process. In particular, getting the traffic signal configuration data within the demonstration study area was complex, and real-time monitoring of signal state was not needed for the TrEPS model. In practice, the arterial links and traffic signal components of the model were not used by the highway system TMC operators. Although a certain level of arterial detail was needed to assure the integrity of the demand model relative to the highway model calibration, in hindsight the network model for arterials was more complex and time consuming to build than was warranted by the end-user applications.

The IMRCP uses many local data sources that are specific to the study area. The ease of access to and the quality of data available for the deployment site are important considerations that may not themselves determine the relative value of a deployment, but may nonetheless affect its applications and utility. Relative to the demonstration deployment, the study area uses data from traffic detectors that are maintained by KC Scout, but the traffic model calibration found that data availability from some detectors was not reliable enough to use in training the system. System metadata (such as the location of the traffic sensors on the network links) presented similar challenges with availability and precision.

The accuracy of IMRCP predictions is directly related not just to the physical model of the road network, weather, and hydrology, but also to the operations and event data within the modeled region. TMC operators and ATMS software generally excel at identification and management of incidents and ITS traffic controls. Work zone management and winter maintenance operations may not, however, be integrated with those ATMS systems. Operational awareness of special events may be similarly limited. This is especially challenging in an area like the Kansas City study area, which has multiple State and local operating agencies. Identifying and entering data for work zones in the area, beyond those provided directly by the automated ATMS data feed, involved going to two State and multiple county/municipal data sources for work zone locations and schedules, with an IMRCP system manager entering the work zones data manually.

Conclusions

The core objectives of the IMRCP study have been met. The demonstration deployment provides predictions of traffic and road conditions in real-time that incorporate data on atmospheric and road weather conditions, traffic, incidents, hydrological conditions, work zones, winter maintenance operations, and special events, when such data are available. The predictions are made available to system users, operators, and maintainers in user-friendly maps and reports. The underlying IMRCP system provides a scalable framework for deployment in other areas, is extensible to other types and sources of data, and can support additional application-specific user interfaces as needed.

The level of effort needed to deploy and maintain the IMRCP depends on the extent and detail of the road network model, which in turn depends on the intended applications. As such, a practical deployment will consider and be based on an analysis of the specific applications to be supported. The models for arterial signal system management will likely differ from those for a freeway TMC/ATMS or a statewide deployment.

Data availability is critical to completeness and accuracy of the models, particularly for evaluating the impact of real-time events. The best possible forecast models will be upset by events from outside the domain of the forecast models. Incidents will disrupt traffic flows and forecasts, but their impacts can be evaluated if the relevant event data can be captured and fed into the next forecast cycle. Storms that intensify rapidly, more so than indicated by earlier forecasts, can be factored into subsequent computations if and when the data are available. Roadway flooding can be predicted only if hydrological profiles, precipitation rates, and stream levels are known and monitored.

Atmospheric weather forecast models are mature and reliable for large-scale events, but are less accurate for very near-term needs at road network link levels. Current atmospheric forecast products from the NWS used in this demonstration provide 1-hour temporal resolution and 3-kilometer or greater spatial resolution. This temporal resolution, in particular, leads to operational uncertainty as to when particular links might be impacted by weather fronts. Higher-resolution forecast models could improve the accuracy of forecasts for key points on the road network.

The variabilities seen in traffic predictions suggest that an ensemble approach might improve the reliability of and confidence in traffic predictions. While improvements are undoubtedly to be made to any particular model and its calibration, the underlying physical, statistical, and data models may constrain the adaptability and accuracy of each model. The best meteorological methods recognize these limitations and have evolved ensemble approaches of diverse methods to improve the accuracy of forecasts.

Recommendations for Further Study

Having demonstrated the integration of data and basic predictive capabilities, the next step in IMRCP development should be to provide applications for predictive capability to drive operational enhancements directed at safety, mobility, environmental, and operational cost improvement. TSMO programs have and are continuing to identify strategies for addressing operational needs, and the IMRCP provides data integration and a predictive view of conditions that can better inform those strategies. The goal would not be to replace existing TSMO programs, strategies, and systems, but to provide more complete, timely, and proactive views and analysis of system conditions from recent past to near future.

Use cases for an enhanced IMRCP could address many aspects of and strategies for TSMO. IMRCP capabilities could support further development of WRTM strategies that would take advantage of information and guidance specific to measured and anticipated conditions. Traffic condition forecasts could be used to refine traveler information to mitigate congestion and decrease likelihood of related incidents. An IMRCP framework could support, investigate, and prototype work zone management strategies to take advantage of information and guidance specific to anticipated conditions. A deployed IMRCP system could enable winter maintenance operations to better consider impacts on predicted traffic conditions. Agencies could pre-position emergency response and maintenance assets in anticipation of conditions like localized flooding.

Stakeholder and application needs derived from these use cases can identify functional enhancement priorities. As in the work done to date, the emphasis would be on the integration and exchange of data with other types of models. For example, closer integration with ATMS might enable the exchange of travel time forecasts and traveler information messages. Integration with MDSS models and systems could enhance both operations and maintenance perspectives. Exchange with work zone management system models would improve the reliability of forecasts around those locations and times.

Other research priorities might be driven by the demonstration experience. For example, the lack of real-time traffic data on arterials could be alleviated by alternative sources of traffic data (e.g., connected vehicle probe data). Traffic data quality checking could improve the reliability of the real-time data feeds. For new deployment areas, automating road network model generation could reduce the level of effort needed and enhance the quality of the model. Integration of the weather and traffic models might be tightened by identifying and developing (or obtaining) weather products with higher temporal and spatial resolution.

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Appendix A. Glossary

AHPS	Advanced Hydrologic Prediction Service
ASOS	Automated Surface Observing System
CAP	common alerting protocol
ConOps	concept of operations
COR	Contract Officer's Representative
CV	connected vehicle
DMS	dynamic message signs
DOT	Department of Transportation
FHWA	Federal Highway Administration
GTM	Government Task Manager
IMRCP	integrated model for road condition prediction
IT	information technology
ITS	intelligent transportation systems
LTL	less-than-truckload
MARC	Mid-America Regional Council
MDSS	maintenance decision support system
METRo	Model of the Environment and Temperature of Roads
MRMS	Multiple Radar/Multiple Sensor
NDFD	National Digital Forecast Database
NOAA	National Oceanic and Atmospheric Administration
NUTC	Northwestern University Transportation Center
NWS	National Weather Service
OD	origin-destination
PMP	project management plan
RAP	Rapid Refresh
RTMA	Real-Time Model Assessment
RWIS	road weather information system
RWMP	Road Weather Management Program
SSD	solid-state disk drive
TDOD	time-dependent origin-destination
TMC	transportation management center
TRB	Transportation Research Board
TrEPS	Traffic Estimation and Prediction System
TSMO	transportation systems management and operations
USDOT	United States Department of Transportation
WRTM	weather responsive traffic management

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