EXPLORATORY ADVANCED RESEARCH

PREDICTIVE REAL-TIME TRAFFIC MANAGEMENT IN LARGE-SCALE NETWORKS USING MODEL-BASED ARTIFICIAL INTELLIGENCE

February 2024

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Despite decades of research, mitigating traffic congestion due to nonrecurring causes, such as crashes, disabled vehicles, and adverse weather events, remains quite difficult for highway system operations practitioners. This work requires an automated process of accurate, real-time prediction and proactive operational management that currently does not exist. Researchers from Carnegie Mellon University and the University of Washington Seattle, in their project Predictive Real-Time Traffic Management in Large-Scale Networks Using Model-Based Artificial Intelligence, aim to address this issue. The project, sponsored by the Federal Highway Administration's (FHWA) Exploratory Advanced Research (EAR) Program, seeks to fuse prediction strategies, based on artificial intelligence (AI) and machine learning (ML) guided by transportation network flow models, with operational strategies. The researchers want to predict nonrecurrent traffic conditions in large-scale networks up to 30 min ahead of the earliest time an incident is reported and proactively recommend real-time operational management strategies.

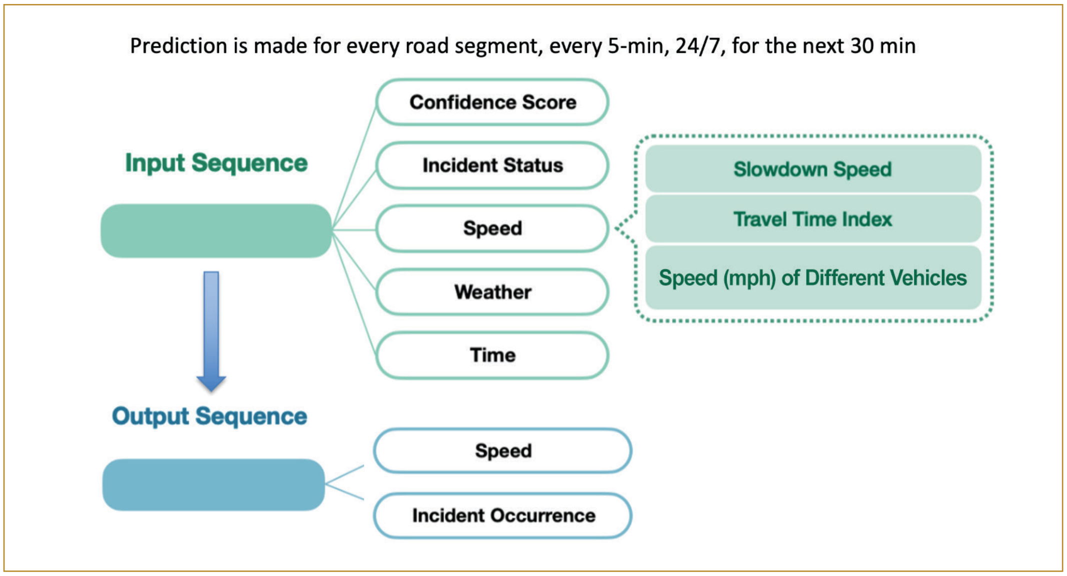

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Figure 1. Traffic management predictive model.

OPERATIONAL MANAGEMENT OF TRANSPORTATION HIGHWAY NETWORKS

Operating transportation highway networks in realtime is challenging. In 2017, American drivers witnessed 8.8 billion h of travel delay and 55 h of delay per car commuter and consumed 3.3 billion extra gallons of fuel.[1, 2] Planned and unplanned incidents (e.g., hazardous weather conditions, accidents, local events) on the highway networks can cause catastrophic mobility and safety impacts. Mitigating nonrecurrent impacts requires accurate and advanced real-time prediction and proactive operational management.

Transportation Systems Management and Operations (TSMO) has emerged as a promising set of practices that maximizes the efficiency, safety, and utility of existing transportation systems without adding capacity.[3] In the past, traffic management centers (TMCs) have developed static and historically generated strategies (e.g., traffic signal timings, traffic signs) to manage day-to-day traffic.

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Unfortunately, TMC staff has little knowledge of how and when to apply those strategies to real-time traffic, especially under nonrecurrent traffic conditions, and are often overwhelmed with data from multiple sources (e.g., sensors and cameras). When operational strategies are employed in response to incident-induced gridlock, they may be too late to improve the traffic. To keep traffic flowing during these nonrecurring traffic incidents requires the following TSMO improvements to deploy a predictive and proactive approach in realtime:

- Identify incidents in the network in realtime, before they are reported.
- Predict potential impacts on network traffic states.
- Take proactive or preventive actions before traffic gridlocks can occur.

Some State and local agencies have already employed some of these methods with promising results:

- Nevada Department of Transportation (DOT) and Florida DOT have developed AI systems that fuse multisource data, e.g., radar, loop detector, and closed-circuit television, and use neural networks to classify scenes as "incidents," "not incidents," or "likely to occur." Both DOTs reported reduced incident detection time up to 12 min.(4)
- Iowa DOT has developed the AI system Traffic Incident Management (TIM) Enabled by Large-Data 9 Innovations, which relies on neural networks and camera inputs to improve incident detection in rural areas.(5) No before-and-after improvements have been reported, but feedback from TMC managers at Iowa DOT has been extremely positive.(6)
- Washington State DOT and California DOT used fuzzy logic methods to meter State-owned ramps for decades. Fuzzy logic is an approach to computing that uses varying degrees of truth to mimic human reasoning and cognition. This approach has performed better than local metering at maintaining reasonable ramp queues in realtime, without substantial heuristic design efforts (i.e., shortcuts to make a decision) and model calibration.(7)

Drawing on these successes, the research team developed AI models that boost TMC network awareness, such as alerting operators to nonrecurring traffic events as soon as possible and illustrating areas of congestion in a given highway system. In addition, the research team developed models that support TMC decisionmaking when a nonrecurring traffic incident is identified. Figure 1 shows an overview of the predictive model.

OVERVIEW OF EAR PROGRAM STUDY

The research team's holistic framework to address the challenges in large-scale predictive TIM can be summarized as interconnecting subtask models that accomplish the following:

- Predict traffic speed.
- Detect traffic anomalies.
- Approximate traffic flow physics.
- Control traffic.
- Estimate network benefits (e.g., mobility, safety, and energy use).

The research team broke the study down into three overall tasks:

- Data collection, data fusion, and infrastructure development and analysis.
- Model design and implementation.
- Model integration, experiments, and case studies.

Data Collection and Infrastructure Development and Analysis

The research team gathered and analyzed an array of historical and real-time data, including probe vehicle speed (i.e., real-time vehicle speed collected on roadways), weather, a Global Positioning System-based smart phone application, State DOTs' incident feed, and traffic counts (i.e., counting how many cars drive on a specific road or intersection during a certain period of time).

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Model Design and Implementation

In this part of the project, the research team developed its prototype to provide predictive analytics and proactive traffic management support through five main modules:

- Unsupervised early anomaly subgraph detection: Finds unusual patterns or structures within a larger network of connected data points. The subgraphs are interconnected groups of data points within a network. Through this module, anomalies among the subgraphs can be found as early as possible.
- Origin-destination estimation: Estimates the amount of time to move people, goods, and vehicles from one place to another in a given area based on the analysis of certain data items.
- Low-rank surrogate models: Approximate subgraph traffic dynamics based on more complex models, capturing the most important patterns and trends.
- Intervention aware traffic prediction: Predicts traffic flow in an area based on previous traffic patterns and real-time interventions, such as road closures, events, or construction.
- Reinforcement learning algorithms: Learn to make ideal decisions based on trial and error. Through regular feedback and training, these algorithms learned to identify optimal proactive TMC interventions that minimize the predicted system cost (e.g., congestion, expected delay).

To support real-time incident detection and traffic prediction, the team also developed a g-transformer ML algorithm and a sequence-to-sequence ML algorithm. The g-transformer ML algorithm uses graph attention (i.e., a way to get a computer to prioritize certain information in a data structure) to find connections and relationships in data, and the sequence-to-sequence ML algorithm takes data input and provides a response.

Model Integration, Experiments, and Case Studies

The research team evaluated its prototype through simulation and case studies. The researchers used the Mobility Data Analytics Center—Prediction, Optimization, and Simulation Toolkit for Transportation Systems to simulate the traffic environment and test the developed reinforcement learning framework for real-time traffic incident management.[8]

The research team completed two case studies to test the project's prototype. One was in the I–70 corridor network in Maryland, and the other was in Cranberry Township, PA's regional network. An example of their work is shown in figure 2. Researchers deployed the proactive TIM framework and analyzed the system performance.

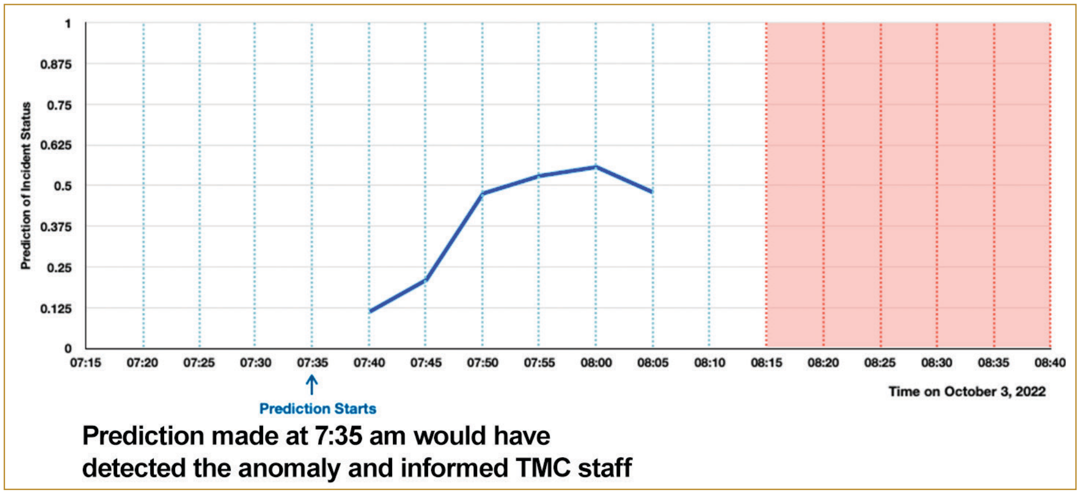

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Figure 2. Traffic management system predicting a traffic anomaly.

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They evaluated the performance of data-driven traffic prediction and subgraph detection against the ground-truth data (i.e., the correct information used to confirm the accuracy of the results) collected in the real-time data streams. The traffic management strategies recommended by the framework were analyzed and reviewed by domain experts in terms of timeliness, feasibility, and soundness of each action.

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The EAR Program supports longer term, higher risk research with the potential for transformative improvements to the U.S. transportation system. The EAR Program seeks to leverage promising expertise and advances in science and engineering to create breakthrough solutions to highway transportation issues.

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To learn more about the EAR Program, visit https://highways.dot.gov/research/exploratory-advanced-research.

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