Workshop 5005: Understanding Digital Twins for Transportation Systems Management

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For the best of reasons

"Digital Twins" of the Past - Using Traffic Simulation for Real-Time Traffic Operations

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TRANSPORTATION RESEARCH BOARD ANNUAL MEETING

Sponsored By Standing Committee on Traffic Simulation

What is a Digital Twin?

- “A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.”

-- Foundational Research Gaps and Future Directions for Digital Twins, National Academies of Sciences, Engineering, and Medicine, 2023

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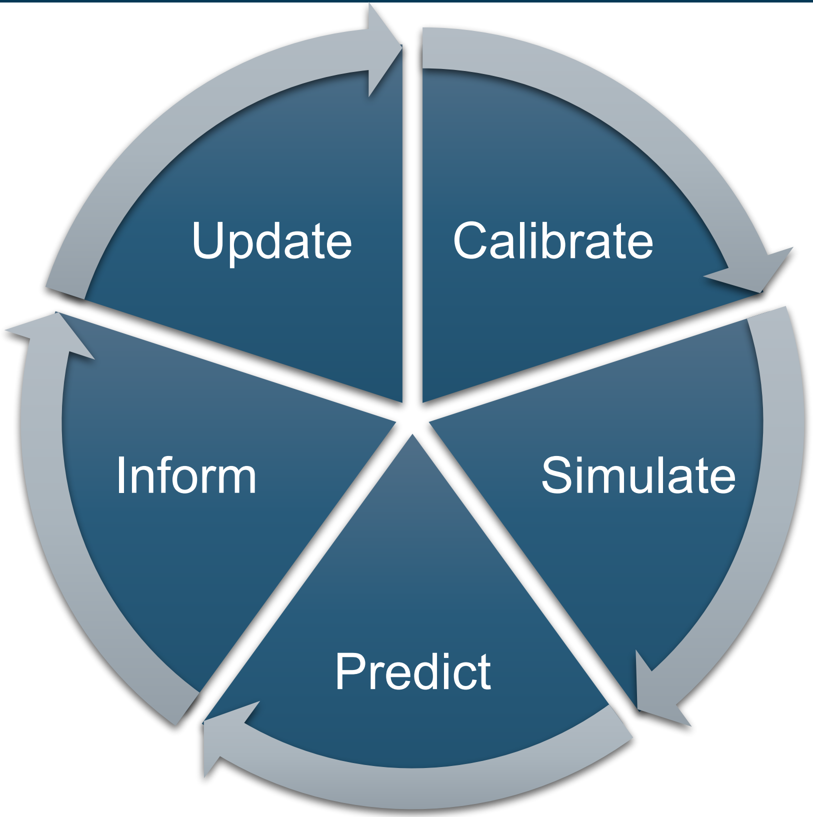
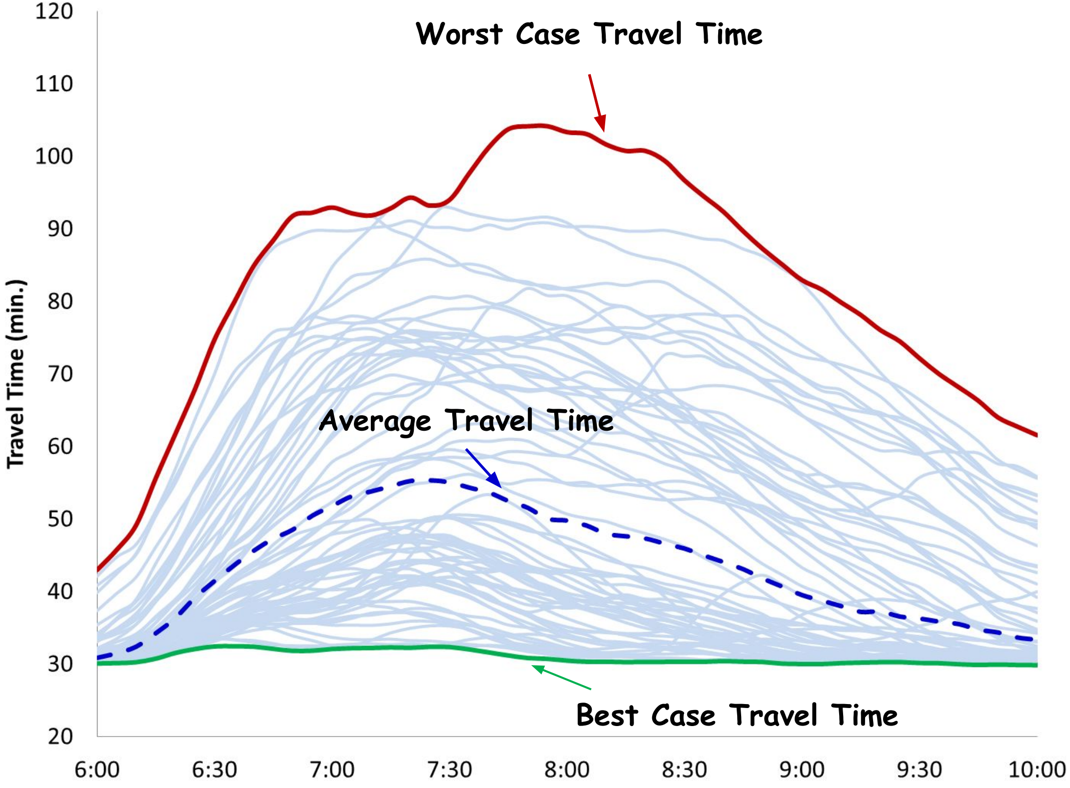
Key Concepts of a Digital Twin



Issues with State of the Practice in Calibration

- Pre-2004, data was scarce, and traffic analysts had to rely on averages
  - Investment planning was historically based on averages biased towards certain investments (like building roads) not managing system reliability
- Now data is more plentiful
  - Travel time data, volume data, weather data, incident data
- BUT general nationwide analytical practice still reliant on averages or use of “synthetic” days
  - Analysts throw out all so-called “abnormal” days and supplement missing data by “stitching in” data taken from different periods, even if there is no logical consistency
- Weaknesses of using these methods
  - Significant effort spent “synthesizing” data rather than analyzing
  - 2/3 or more of days/data ends up being thrown away
  - “Synthetic” (average) days create phantom bottlenecks in the system that cannot be

Average or “Normal” Day Fails to Capture Full Range of Dynamic Travel Conditions



Real systems have good days and bad days.

When we throw out data, and then take an average, we create an artificial day that is not representative of the actual conditions.

A “normal” day based on an average corresponds to no actual day experience in the system.

Source: FHWA Traffic Analysis Toolbox Volume III, 2019 Update to 2004 Version

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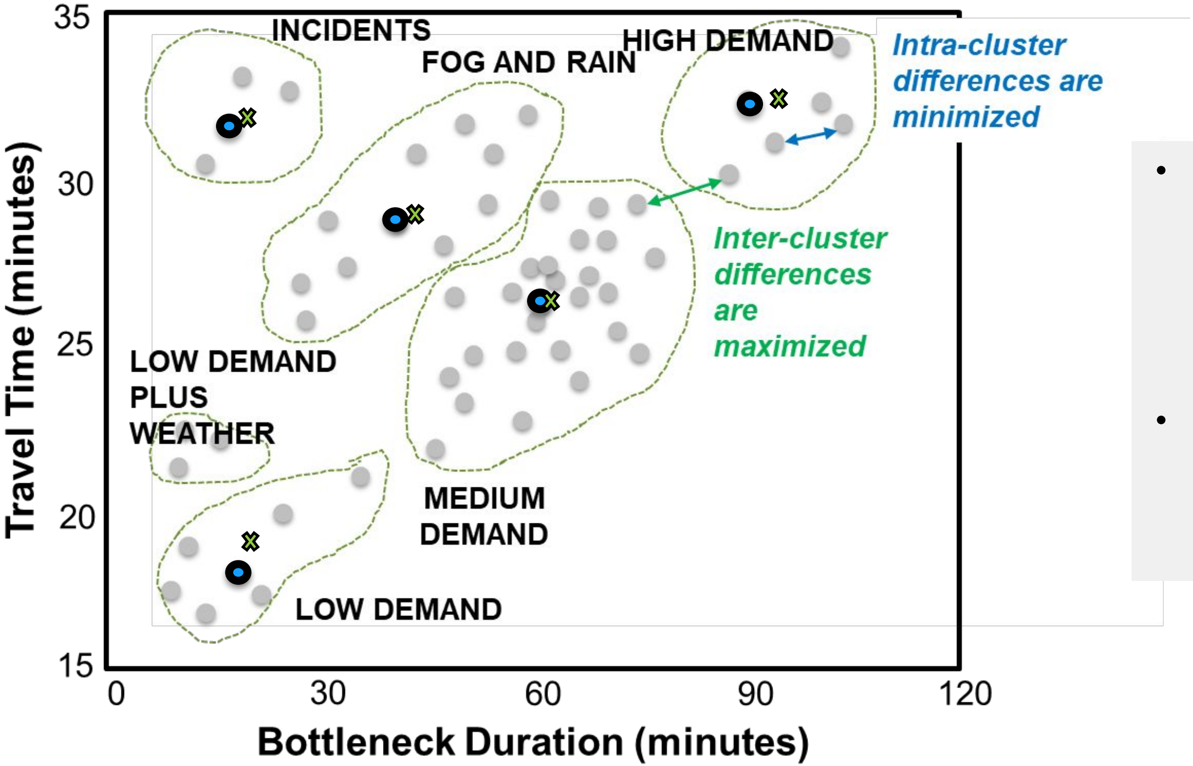
Our Approach: Identify Distinct Travel Conditions



- We group <u>concurrent</u> observed data using cluster analysis to identify distinct travel conditions.
- We find an <u>actual</u> day (i.e., representative day) that is closest to the centroid for each cluster.

Source: FHWA Traffic Analysis Toolbox Volume III, 2019 Update to 2004 Version

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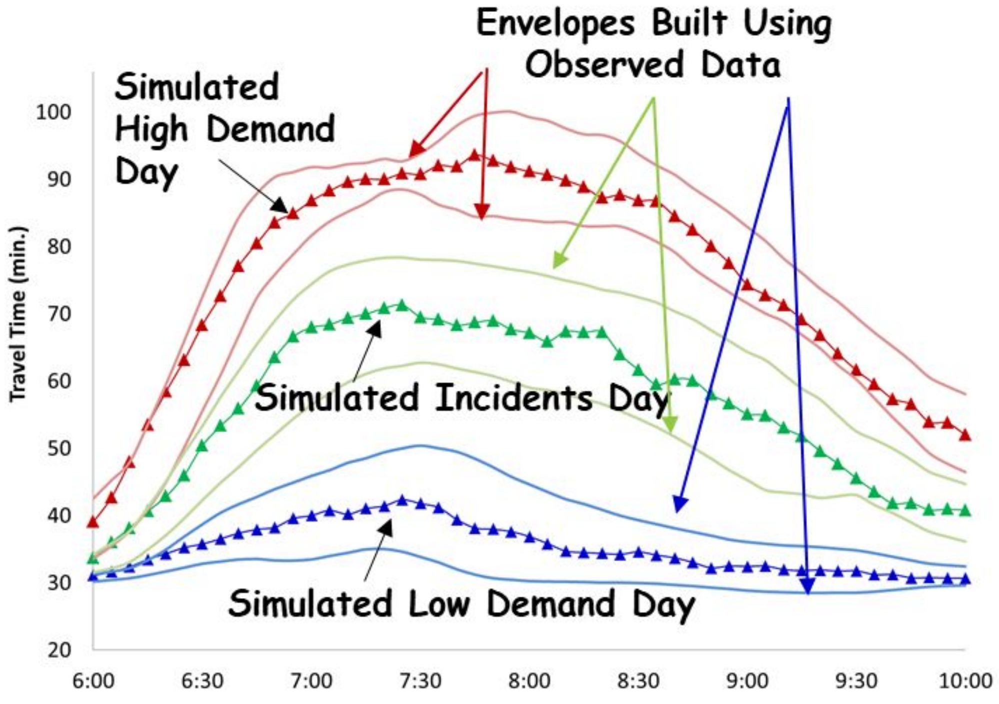
Our Approach: Calibrate Using FHWA's Objective, Data-Driven Criteria

- **Control for maximum number of outliers:**
  - Constrains the number of outliers in simulated results.
- **Control for minimum number of inliers:**
  - Ensures that majority of time-variant simulated results fall close to the representative day.
  - Ensures that during the most congested time periods the simulated results are close to the observed data.
- **Control for bounded average error:**
  - Ensures that on average, simulated results are close to the observed representative day.
- **Control for bounded systematic error:**

Source: FHWA Traffic Analysis Toolbox Volume III, 2019 Update to 2004 Version

Our Approach: Calibrate for Each Travel Condition



- We develop models for representative days in each cluster.
- Then we calibrate each model against four newly-identified calibration criteria.
- If a model meets all four criteria for every measure and associated route/location, then the model is calibrated.

Source: FHWA Traffic Analysis Toolbox Volume III, 2019 Update to 2004 Version

Calibrate: Reproduce Time-Dynamic System Performance

- Make entire process data-driven, repeatable, and automatable (to speed calibration activity).
- Eliminate all subjective criteria and replace with criteria that are statistically valid and derived from observed data.
- Eliminate arbitrary data samples comprising synthetic days, and base simulation analysis on observed travel conditions.

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Issues with State of the Practice in Simulating Basic Safety Messages

- Simplifying assumption on vehicle-to-infrastructure communication protocols (i.e., assumption that vehicles transmit data continuously when in range of an RSU with no loss).

- Simplifying assumption of persistent vehicle identifiers (discounts J2735 requirement to protect privacy).

- Limited consideration of sensor/equipment failures or incomplete/erroneous BSM data.

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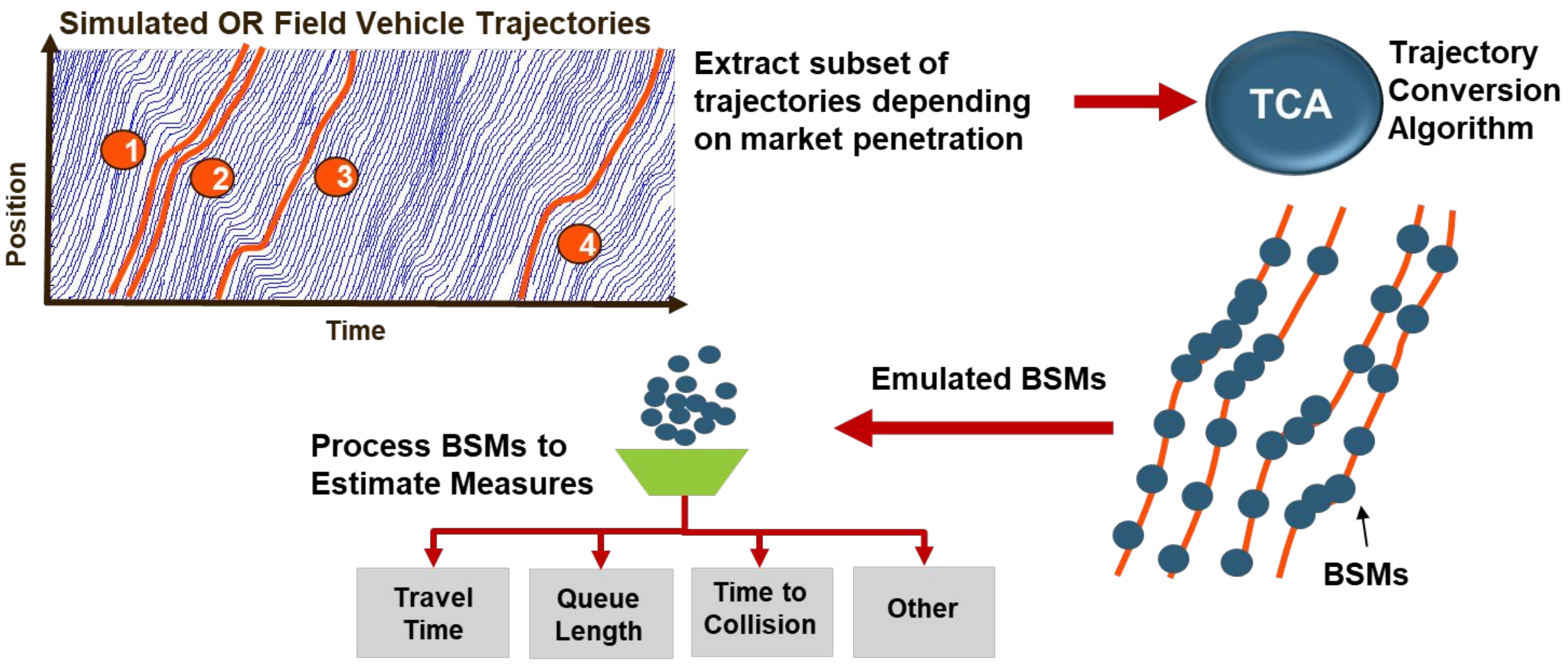
Our Approach: Emulate Basic Safety Messages Per SAE J2735 Standards



Source: NCHRP Research Report 997 - Algorithms to Convert Basic Safety Messages into Traffic Measures

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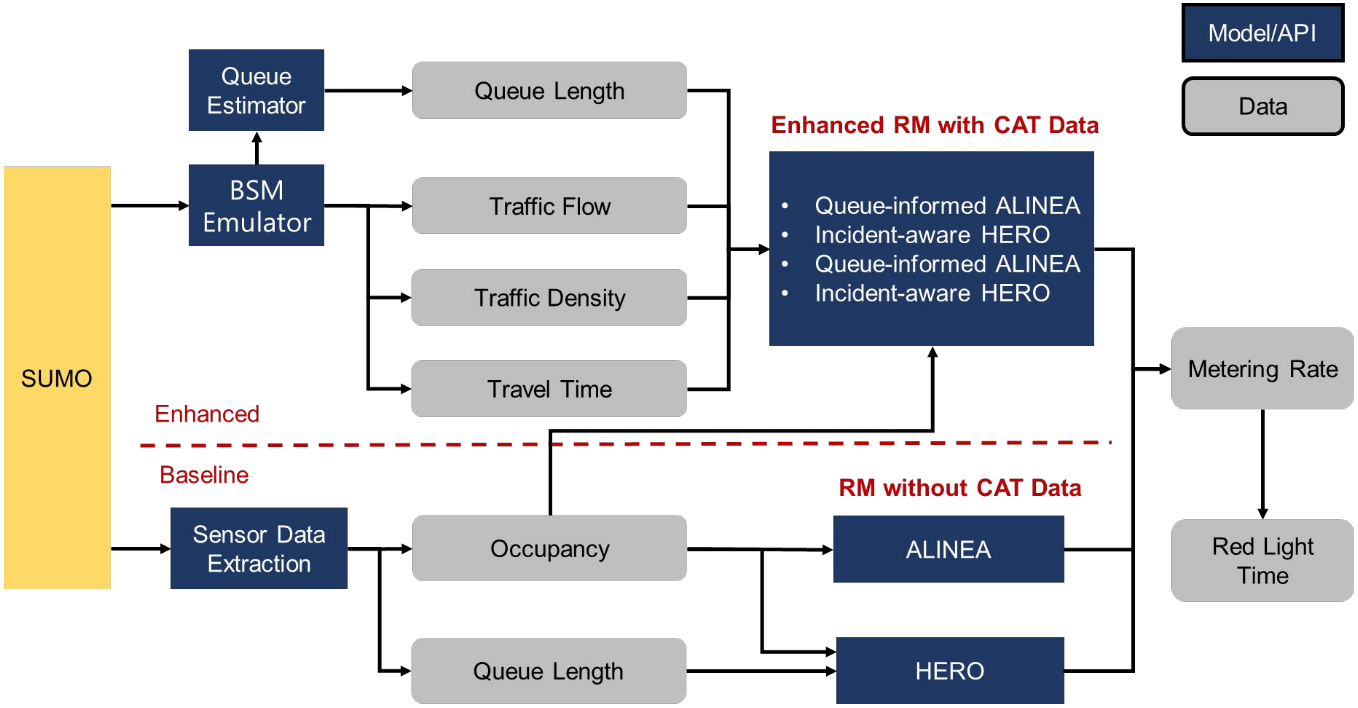
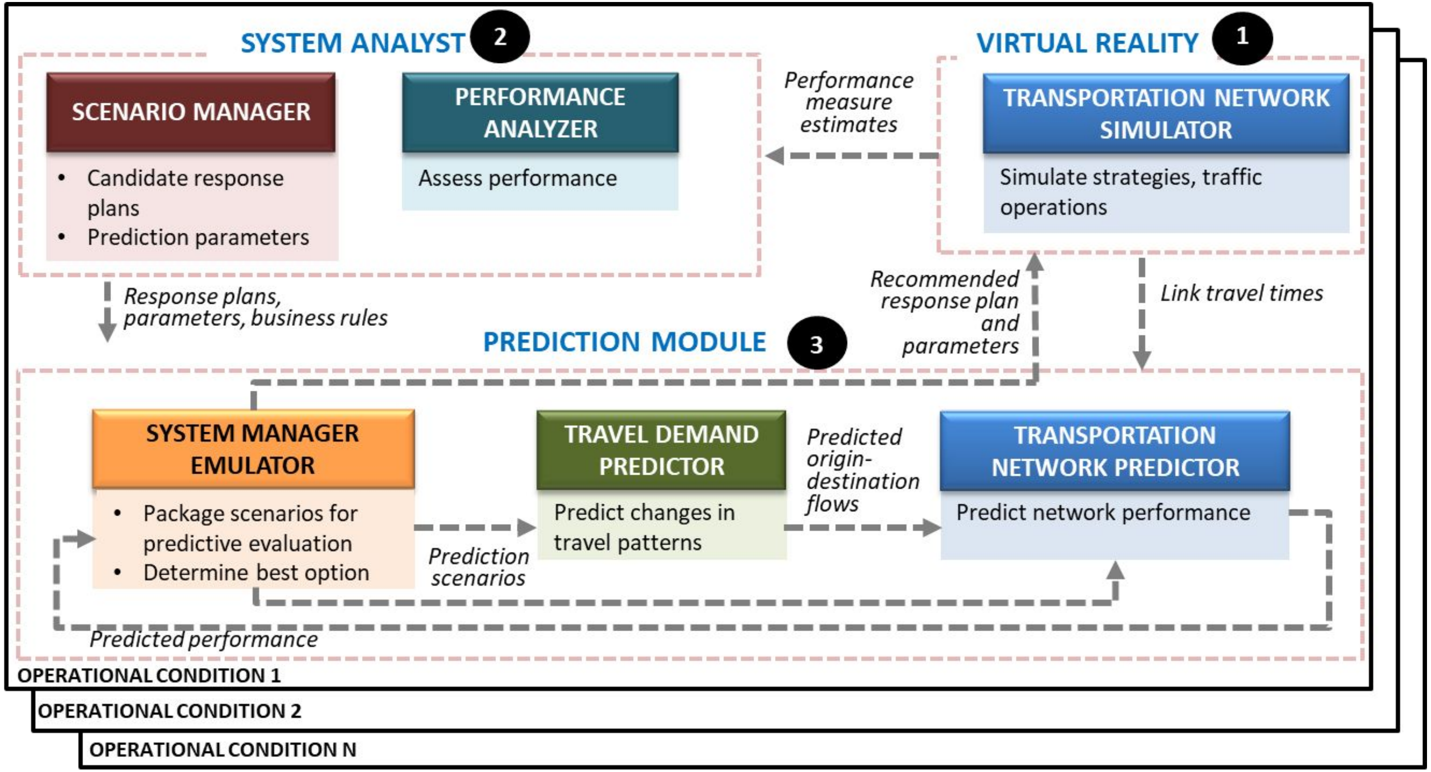
Our Approach: Integrate BSM Emulator within Simulation



- A SUMO model was built and calibrated for EB I-210 to assess impacts of using data from CAV messages for ramp metering.
- Multiple APIs were built and integrated into SUMO for: sensor data extraction, BSM emulation, queue estimation, and ramp metering algorithms.

Source: NCHRP 08-145; Final Report forthcoming; Collaborative effort between Noblis and NYU

Digital Twin: Example Framework for Active and Integrated Management



Source: FHWA Training on Using AMS for More Active and Integrated TSMO

Next Steps

- Model the entire transportation system:
  - Communication system and protocols, including losses, errors, and privacy constraints.
  - Power grid, and related driver decisions, and interactions between the vehicle and the grid.
  - Vulnerable road users.
- Improve data collection, processing, and fusion speed – so that information is relevant and reliable.
- Continuously re-calibrate and synchronize the Digital Twin – to consistently replicate reality.