Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

C2SMARTER

DISCLAIMER: Please note that the RFI public responses received and posted do not represent the views or opinions of the U.S. Government. We bear no responsibility for the accuracy, legality, or content of the responses and external links included in this document.

Networking and Information Technology Research and Development
Request for Information on Digital Twins Research and Development

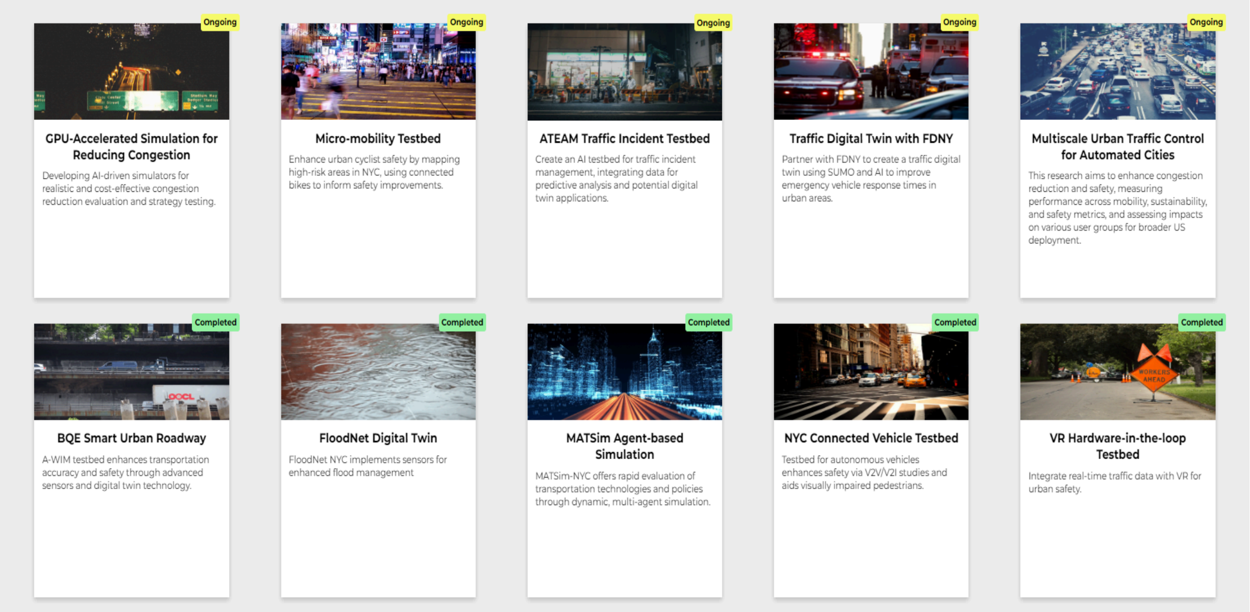
This document respondes to ***Artificial Intelligence (AI):*** **AI and Digital Twins** topic with a focus on **Transportation Digital Twin (TDT).** This response is prepared by Dr. Kaan Ozbay, Director and Professor at ***C2SMARTER Center, New York University (NYU)***, specializing in Intelligent Transportation System, Traffic Safety, Traffic Control, and Dr. Zilin Bian, postdoctoral associate at NYU C2SMARTER center, specializing in AI and systems, and Dr. Jingqin Gao, Assistant Director of Research at C2SMARTER Center, specializing in Intelligent Transportation System, Traffic Management, and Dr. Fan Zuo, postdoctoral associate at NYU C2SMARTER center, specializing in Behavior and Learning theory, Simulation, Cybersecurity.

This document is approved for public dissemination. The document contains no business-proprietary or confidential information. Document contents may be reused by the government in the National Digital Twins R&D Strategic Plan and associated documents without attribution.

Introduction of C2SMARTER

Connected **C**ommunities for **S**mart **M**obility towards **A**ccessible and **R**esilient **T**ransportation for **E**quitably **R**educing *Congestion* (C2SMARTER), is a multi-university U.S. DOT Tier 1 University Transportation Center, uses **cities as living laboratories** to study challenging transportation problems and **find solutions from the unprecedented recent advances** in communication and smart technologies. C2SMARTER is led by New York University (NYU) and is a consortium of seven universities working across fields and geographies. We focus on emerging technologies, operational policies, and their interactions with and impact on transportation and urban systems — including using evidence-based decision making to turn research into transformative solutions that take advantage of recent advances such as artificial intelligence (AI) and digital twins.

C2SMARTER has coordinated and collaborated with other universities and agencies to develop multiple digital twins testbeds, especially transportation digital twins (TDT) for emergency vehicle operations, flooding management, connected and automated vehicles (Figure 1). Leveraging Digital Twins in the transportation sector, significant energy savings can be achieved. Digital Twins enable more efficient traffic management, reducing congestion and optimizing vehicle routing, directly lowering fuel consumption and emissions. In the event of accidents or major catastrophes requiring evacuation, Digital Twins provides real-time data and predictive insights to streamline operations, minimize delays, and ensure energy-efficient responses. This integration not only improves operational efficiency but also supports sustainable urban mobility. Furthermore, Digital Twins are essential for planning and managing multi-modal transportation systems, enhancing the efficiency and coordination of various transport modes such as buses, trains, bikes, and ride-sharing services.



Ongoing

GPU-Accelerated Simulation for Reducing Congestion

Developing AI-driven simulators for realistic and cost-effective congestion reduction evaluation and strategy testing.

Ongoing

Micro-mobility Testbed

Enhance urban cyclist safety by mapping high-risk areas in NYC, using connected bikes to inform safety improvements.

Ongoing

ATEAM Traffic Incident Testbed

Create an AI testbed for traffic incident management, integrating data for predictive analysis and potential digital twin applications.

Ongoing

Traffic Digital Twin with FDNY

Partner with FDNY to create a traffic digital twin using SUMO and AI to improve emergency vehicle response times in urban areas.

Ongoing

Multiscale Urban Traffic Control for Automated Cities

This research aims to enhance congestion reduction and safety, measuring performance across mobility, sustainability, and safety metrics, and assessing impacts on various user groups for broader US deployment.

Completed

BQE Smart Urban Roadway

A-WIM testbed enhances transportation accuracy and safety through advanced sensors and digital twin technology.

Completed

FloodNet Digital Twin

FloodNet NYC implements sensors for enhanced flood management

Completed

MATSim Agent-based Simulation

MATSim-NYC offers rapid evaluation of transportation technologies and policies through dynamic, multi-agent simulation.

Completed

NYC Connected Vehicle Testbed

Testbed for autonomous vehicles enhances safety via V2V/V2I studies and aids visually impaired pedestrians.

Completed

VR Hardware-in-the-loop Testbed

Integrate real-time traffic data with VR for urban safety.

Figure 1. C2SMARTER Digital Twins Testbeds.

Transportation Digital Twin (TDT)

This document adheres to the definition of Digital Twins (DT) as provided by the DOE's Office of Science and Technology Policy (OSTP) and the National Coordination Office for Networking and Information Technology Research and Development (NITRD). According to this definition, a DT 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). It is dynamically updated with data from its physical twin, possesses predictive capabilities, and informs decisions to realize value. The bidirectional interaction between the virtual and the physical is central to the DT concept.

Applying this concept to the transportation domain, a TDT includes three primary stages:

1. **Physical Space**: This includes human beings, vehicles, and transportation infrastructure.
2. **Digital Space**: This involves the creation of digital replicas of the aforementioned physical entities and assets.
3. **Bidirectional Communication**: This stage facilitates continuous, dynamic interaction between the physical and digital spaces, ensuring that the digital twin is consistently updated with real-time data and can influence the physical world.

Transitioning from this foundational understanding, the effectiveness of a TDT is realized through three integral processes: Sensing, Modeling, and Intervening.

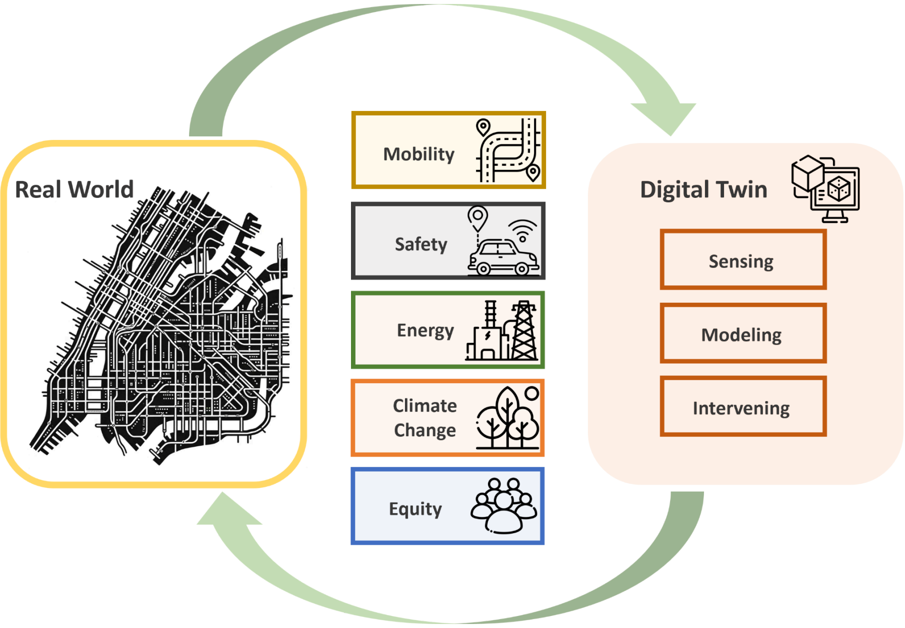


Figure 2. Concept of Transportation Digital Twins.

Sensing

Sensing involves the process of collecting data from the physical world through various sensors and monitoring devices. This data encompasses traffic flow, vehicle speeds, road conditions, and environmental factors. Accurate sensing information ensures that the virtual space remains synchronized and accurately represents the physical space.

Various sensing infrastructures, such as connected vehicles, infrastructure-based surveillance cameras, loop detectors, and probe vehicles, provide varied data types and levels, from individual human or vehicle data to route/network-level information.

Computer vision technology has significantly improved traffic sensing infrastructure, enabling the capture of real-time traffic information through dash-cameras in vehicles and surveillance cameras along roadsides. AI methods such as object detection, sorting/tracking, and re-identification can track trajectories of traffic objects, generating continuous captures across multiple sensing infrastructures. Additionally, AI can facilitate the coordination and cooperation of multiple sensing infrastructures, capturing a broader scale of traffic information through cooperative perception methods that fuse data from vehicle-onboard and roadside devices.

Moreover, augmented reality (AR) and virtual reality (VR) technologies can enhance information capture for DTs. For instance, VR has been used to study work zone workers' interactions with roadside units and connected vehicles, improving their safety and reducing conflicts.

Recent advancements in generative AI (GenAI) present further opportunities for the sensing stage. Technologies such as visual foundation models (VFMs) can accelerate and automate the processing of vast amounts of traffic scene videos, reducing the need for human labor in extracting useful information like congestion and incident data, thereby aiding in the construction of the virtual space in DTs.

Modeling

At the modeling stage, DTs perform two primary tasks: representing and reconstructing the current physical space, and estimating and forecasting the future physical space. Representation and reconstruction ensure that DTs create accurate replicas, while forecasting provides predictive insights and guidance for intervening in the physical space.

Representation/Reconstruction: With data from sensing infrastructures, the virtual space must accurately reconstruct the physical space. This requires robust representation capabilities, whether from the vehicle-end or system-end. For advanced vehicles, such as automated vehicles, real-time environmental reconstruction is crucial. AI methods, such as 3D modeling and occupancy neural networks, convert captured data into digital objects. At the system-end, DTs must calibrate and fine-tune agents in the virtual space to replicate behaviors observed in the physical space, using methods like simultaneous perturbation stochastic approximation (SPSA) to calibrate traffic agents within simulation environments.

Forecasting: Forecasting within DT leverages AI to predict future traffic conditions, enabling proactive interventions and strategic planning. Machine learning models, such as neural networks and gradient boosting machines, analyze historical and real-time traffic data to predict congestion patterns, incident likelihood, and travel demand. AI techniques like graph neural networks combined with temporal methods, such as transformers, can process complex datasets to forecast traffic flow and potential disruptions. GenAI can enhance these predictive capabilities by generating synthetic datasets for training, simulating rare events, and providing advanced analytics to improve model accuracy. These predictive capabilities allow for dynamic adjustments in traffic signal timings, ramp metering rates, and real-time routing suggestions, optimizing traffic flow and minimizing congestion.

Furthermore, modeling within a TDT includes energy consumption simulations, allowing for assessing and optimizing fuel use and emissions. By predicting and managing traffic conditions, TDTs can recommend energy-efficient routes and speeds, reducing fuel consumption and lowering emissions. This aspect is crucial for planning sustainable urban transportation systems and mitigating the environmental impact of vehicular traffic. Additionally, TDTs are crucial in planning and managing multi-modal transportation systems and integrating emerging connected and autonomous vehicles. They also support the development of Mobility as a Service (MaaS) by providing real-time data and predictive analytics to optimize the use of various transport modes, enhancing the efficiency and convenience of urban mobility solutions.

AI-driven forecasting integrates weather data, demographic trends, and economic indicators to enhance the accuracy of predictions. By simulating various scenarios, AI can predict the impact of adverse weather conditions on traffic and the efficiency of public transportation systems. These advanced forecasting methods support long-term infrastructure planning, emergency preparedness, and the integration of emerging technologies like autonomous and electric vehicles, ensuring the resilience and sustainability of transportation networks.

Intervening

Intervening leverages insights from the digital twin model to make informed decisions and take proactive actions in the physical world. This stage includes real-time decision-making, automated control systems, and strategic planning, based on data and simulations provided by the digital twin.

Vehicle-End Intervention: Vehicle-end interventions within DT can leverage AI to enhance the functionality and safety of individual vehicles. AI algorithms, such as those used in adaptive cruise control and automated driving, process real-time data from sensors to optimize trajectory planning, routing, and navigation. Reinforcement learning and spatial-temporal modeling techniques enable vehicles to dynamically adjust their paths, avoid obstacles, and respond to incidents, improving overall traffic flow and safety. Additionally, Vehicle-to-Everything (V2X) communication, powered by AI, facilitates real-time data exchange between vehicles and infrastructure, enhancing situational awareness and coordination.

GenAI can further improve autonomous driving by better identifying and reacting to road risks. Visual Foundation Models (VFMs) and Large Language Models (LLMs) can convert visual information into descriptive contexts, interacting with human-knowledge databases to inform vehicle motion and risk responses. For example, GenAI can enhance trajectory prediction through chain-of-thought reasoning processes tailored to specific traffic scenarios. By leveraging the power of LLMs, semantic annotations can be generated to significantly improve the understanding of complex traffic environments, thereby boosting prediction accuracy and robustness.

System-End Intervention: System-end interventions in DT can utilize AI to optimize and manage complex transportation networks. AI-driven traffic signal control employs reinforcement learning algorithms to dynamically adjust signal timings based on real-time traffic conditions, reducing congestion and improving flow. Traffic camera control systems use computer vision to detect incidents and monitor road conditions, automating responses and maintenance. AI enhances ramp metering by analyzing real-time data to regulate vehicle entry onto highways, balancing demand and capacity to prevent congestion. AI-driven demand management strategies predict travel patterns and suggest optimal routes, influencing travel behavior to reduce congestion. Integrated Transportation Management Systems (ITMS) leverage AI for real-time data analysis and automated control, ensuring coordinated responses to traffic conditions.

Additionally, system-end interventions can significantly contribute to energy savings by optimizing traffic signals to minimize idle times and stop-and-go waves, which are major causes of fuel wastage. AI-driven traffic management can smooth traffic flow, reduce delays, and lower overall fuel consumption, promoting a more sustainable transportation system. Furthermore, TDTs are essential for implementing Mobility as a Service (MaaS), providing a comprehensive platform for decision-makers in both public and private sectors to manage and optimize multi-modal transportation networks, enhancing the user experience and operational efficiency.

Conclusion

This document explores foundational research gaps and opportunities for digital twins in the transportation domain by following the processes of sensing, modeling, and intervening. The integration of AI at each stage enhances the capabilities of DTs, providing accurate representations, predictive insights, and effective interventions to improve transportation systems.

The application of Digital Twins in the transportation sector presents a transformative opportunity to enhance energy efficiency and sustainability. By optimizing traffic management and reducing congestion through real-time data and predictive analytics, DTs can significantly lower fuel consumption and emissions. Furthermore, Digital Twins facilitate more effective responses to accidents and major catastrophes, ensuring efficient evacuation and minimizing delays, which are crucial for saving energy during emergency operations. Incorporating energy consumption simulations within the TDT framework allows for continuous fuel use assessment and optimization, reinforcing the commitment to sustainable urban mobility.

In summary, the strategic deployment of Digital Twins in transportation improves system efficiency and safety. It plays a vital role in reducing the environmental impact and supporting the transition to sustainable urban mobility. Integrating AI and DTs positions us to meet future transportation challenges while advancing energy-saving and sustainability objectives. Additionally, Digital Twins support the planning and operation of multi-modal transportation systems and the integration of connected and autonomous vehicles. They are essential for implementing Mobility as a Service (MaaS), providing a comprehensive tool for decision-makers in both the public and private sectors to enhance the efficiency and user experience of urban mobility solutions.