Interstate 24 MOTION open road testbed

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Abstract

We describe the I-24 MOTION open road testbed led by the Tennessee Department of Transportation on Interstate 24 near Nashville, TN. The purpose of the testbed is to provide an open road experimental facility for testing traffic management and automated vehicle technologies in real freeway traffic. The testbed consists of pole-mounted 4K resolution video cameras providing uninterrupted coverage of the roadway. Video data is processed in real time into vehicle trajectories for all vehicles passing through the testbed. The current length of the testbed is approximately 1600 feet and upon its completion will stretch 6 miles. Testbed specifications, hardware, and design decisions are discussed, as well as the future of the testbed construction.

Keywords: open road testbed; traffic dataset; integrated corridor management

1 Introduction

The transportation landscape is undergoing a significant shift in which increasingly automated vehicles are being developed and deployed on roadways, changing the fundamental properties of traffic flow. Understanding and modeling traffic dynamics and the impacts of automated vehicles in traffic streams is an issue that cuts across various domains, including traffic management and connected and autonomous vehicle development. In this work, we introduce the I-24 MOTION open-road testbed, which is explicitly designed to provide new experimental facilities and datasets to advance research and development in these areas.

Our team – a partnership between the Tennessee Department of Transportation (TDOT), Gresham Smith, Vanderbilt University, and a growing consortium of other universities -– is building a camera network on Interstate 24 in Nashville, TN. When completed, the testbed will produce continuous streams of traffic data in the form of 200 million vehicle-miles of trajectories annually. Trajectory datasets (i.e., the sequence of timestamped positions of the vehicles as they pass through the instrument), such as the famous FHWA-sponsored NGSIM datasets cite, are considered as the gold standard for traffic science.

An overview of the development timeline – past, present, and future – is provided in Figure 1. When completed, the testbed will provide a continuous field of view of six miles on the 8-lane I-24 freeway. Pole mounted cameras are connected via fiber network to a computing hub, where computer vision tracking algorithms extract vehicle trajectories (time space path of each vehicle through the testbed), which are then available for analysis. A total of approximately 300 4K resolution cameras will be mounted on up to sixty 110 ft poles spaced every 500-600 ft along the freeway. The poles provide an overhead vantage point of the road to avoid occlusion, with overlapping fields of view. As of March 2021, three poles have been constructed forming the "Validation System" (Figure 2), with the remainder in the design phase.

The main contribution of this article is the introduction of testbed, a discussion of the goals for its development, and its expected beneficiaries and user base. We describe the specifications of the overall testbed, the hardware and configuration supporting the testbed, and some of the design decisions that were made during conceptualization and planning.

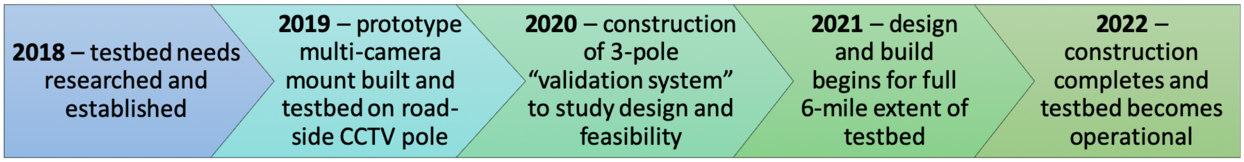


Figure 1: Broad timeline of testbed conceptualization, design, and construction.

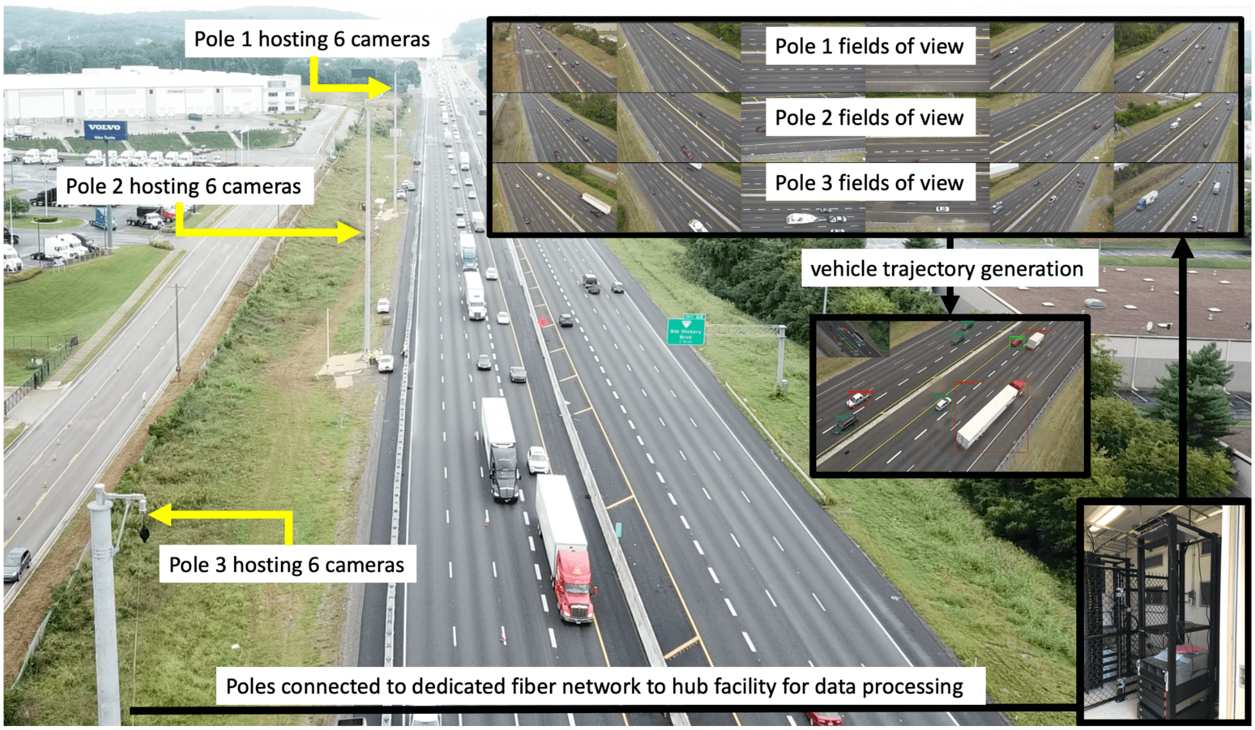


Figure 2: Testbed overview. Poles spaced approximately 500-600 ft host multiple 4K resolution cameras to capture an overlapping and continuous field of view of the roadway. Video is streamed to a hub facility for data processing, where the video is converted to trajectory data for analysis.

The remainder of this article is as follows. In Section 2 we discuss research literature relevant to the envisioned testbed capabilities, alternative approaches to achieving the needs for the testbed, and other existing testing grounds with distinct capabilities to what is planned on I-24. In Section 3 we describe the research needs motivating the testbed and how they will benefit from the capabilities of the testbed. Section 4 describes the testbed hardware and design decisions for the testbed. Section 5 lays out considerations and plans for expanding from the current validation system to the full testbed build out. Finally, Section 6 concludes the article.

2 Literature review and existing facilities

In this section we review research and development efforts related to the generation of vehicle trajectory data, the applications of this data, and testbed facilities related to I-24 MOTION.

Existing vehicle trajectory datasets and sensing technologies to generate them

Trajectory data from individual vehicles has proven instrumental in research areas related to traffic science. Arguably the most influential are the NGSIM datasets. Collected at multiple sites, the I-80 dataset contains approximately 1,800 vehicle-miles of data over a 45 minute data collection window [1]. The new highD drone-collected dataset [16] contains 25,000 vehicle-miles of data from German highways. There are other sources of vehicle-level data from car following experiments; however, combined, they represent only a few hours of traffic from a few short sections of roadway. Greater coverage of traffic is needed in terms of temporal coverage, spatial coverage, variety of traffic conditions, and observation of rare events.

In terms of technologies to extract individual vehicle trajectories, the dominant sensor source is video imagery. Radar and LiDAR sensors are also used to generate trajectories, however cameras with computer vision algorithms allow better extensibility, e.g., to determine fleet mix useful in estimating energy consumption of traffic. Fixed position cameras from high vantage points can achieve a good visibility of the roadway, but must be deployed in multiple locations to cover a long section. While camera-equipped drones are viable for short term data collection and offer better visual coverage due to their flying height, they do not allow continuous monitoring over extended time horizons and multiple must still be deployed simultaneously to cover an extended area of roadway. The proposed testbed design leverages fixed position cameras to support vehicle trajectory data generation on a much larger spatial and temporal scale than is available today.

Other technologies to collect traffic data provide complementary information. For example, high fidelity data is available on highly-instrumented experimental vehicle platforms, but these represent a small fraction of cars on the road. GPS data from vehicles is more widely available to commercial companies, but raw data is difficult to acquire in open research settings. Roadway sensors such as radar units and inductive loops provide aggregate data that does not allow detailed understanding of the spatiotemporal dynamics of individual vehicles. The envisioned testbed is also distinct from standard CCTV camera systems used for traffic management, since those systems are not typically deployed at the height or density required to support a testbed.

New applications of trajectory data

Adding a large and perpetual vehicle trajectory data source will have a large impact on traffic research across multiple domains. Our understanding of traffic jams that spontaneously due to human driver behavior will be improved [24], and it will advance research in eliminating inefficient stop-and-go oscillatory behavior [19, 23]. Addressing congestion through integrated corridor management (ICM) strategies, such as ramp metering, variable speed limits, and driver messaging, will be enhanced with the new data streams and other ICM infrastructure available on the testbed [7, 20].

The testbed will also provide the opportunity to collect high-fidelity data required for understanding the secondary effects of deploying automated vehicle technologies in real traffic [25]. These technologies have the opportunity to improve congestion-related traffic effects [13], as well as the potential to create difficulties or abnormal behaviors for human drivers [6].

Similar testbed facilities with other capabilities

There are existing closed course and open road testbeds that address some of the research needs [9]. Closed course testbeds, such as the American Center for Mobility [2], MCity [5], GoMentum Station [8], and Suntrax [15], have the distinct advantage of being capable of hosting experiments and data collection for cutting edge technologies and techniques including those under active research and development. By testing in highly controlled settings, they can assure safety and eliminate externalities such as unpredictable drivers and road conditions that can confound experiments. Because of the motivating objectives of closed course testbeds, they can be limited in their ability to test in real traffic conditions with regular drivers encountered on public roads.

Open road testbeds exist in many forms on a variety of road types; examples include the Minnesota Traffic Observatory [21], The Ray [22], the California Connected Vehicle Test Bed [10], Ann Arbor Connected Vehicle Test Environment [26], and Providentia [17]. They support experiments in live traffic, similar to the I-24 testbed. The collection of high-fidelity trajectory data on each and every vehicle on the roadway is not an existing capability in the United States; although, the Lower Saxony testbed supports these objectives in Germany. This degree of data collection is required for modeling, analytics, and experiments that rely on the behavior and/or response at the individual vehicle level. It is in this landscape of existing facilities that the I-24 testbed will add value and new research and experimental capabilities.

3 Needs and benefits

In this section we define the needs that the testbed fulfills, related to operations, research, and development. The overall design of the system as a dense network of cameras, arose specifically to meet these needs. Rationale for specific design elements can be found in Section 4. The needs met by the testbed span operations, development and research.

Need 1 – Operations: The I-24 corridor is a major limited access facility within Tennessee for commuters and freight. This corridor was selected for the state's first Integrated Corridor Management (ICM) project, called the I-24 SMART Corridor, which operates on the route between Nashville and Murfreesboro. The corridor includes Interstate 24, the parallel arterial route SR 1, and connector routes between I-24 and SR 1. The ICM project has deployed an upgraded communications network and Intelligent Transportation System (ITS) devices for increased operational management of the corridor. High resolution sensing provided by the testbed in this area will allow TDOT to better leverage the existing ICM infrastructure investments for refining operational strategies beyond the limited-fidelity decision making capabilities using aggregate sensing technologies.

Need 2 – Development: Currently, most test facilities used by industry for vehicle and vehicle technologies development are closed-course environments that enable safe testing of experimental technologies. Due to the intended purpose of the closed course testbeds, it is however very challenging to understand how the proven technologies will operate and interact in real world environments. The variability of traffic conditions and the unique human driver behavior inherent to a real roadway are challenging conditions for new technologies, but necessary barriers to overcome. This project will be a novel testing facility that will allow TDOT and third-parties the ability to gather data on new transportation technologies through real world testing. The capabilities of the testbed provide the unique ability to collect data from every vehicle on the roadway to evaluate direct and indirect effects amongst the entire traffic stream.

Need 3 – Research: Producing vehicle trajectory data allows features of traffic flow related to individual vehicle behavior to be explained. Such data at the level of individual vehicles is more important than ever due to increasing autonomy on individual vehicles, which are beginning to influence traffic flow via their interactions with conventional vehicles. The testbed's 6-mile length allows for observing complex multi-vehicle interactions such as the creation of phantom traffic jams. The testbed will generate over 200,000,000 vehicle-miles of trajectory data annually, assuming an 80% uptime. The testbed location exhibits a wide range of traffic conditions from free-flow to heavy congestion and bottlenecks.

4 Testbed design elements

Recognizing the needs driving the development of the testbed and the lack of existing facilities in the US to meet those needs, we next describe our design considerations of the testbed.

As discussed in Section 2, camera-based sensing is advantageous for observing the entire roadway; and a dense deployment of cameras, such that their views overlap and observe vehicles continuously, is necessary for providing end-to-end coverage through the testbed. Installing this infrastructure in a permanent capacity provides the temporal coverage of data that is needed for many research applications, and provides a location that is always available for testing technologies or running experiments.

In 2020, TDOT and partners set out to study the feasibility of this dense camera infrastructure approach on I-24. A 3-pole, 18-camera system was designed, constructed, and commissioned (Figure 2, Figure 3). As is intended with the full testbed, cameras are connected via fiber to a hub building that houses servers for real time trajectory extraction. The prototype was strategically sized to inform meaningful scalability and design considerations, thereby determining if the full testbed scope was attainable with the same design strategy.

The following describe design elements of the 3-pole validation system, effectively allowing us to pilot each technology and strategy for inclusion in the full system.

- Pole & foundation design. The validation system has cameras mounted on 110-foot tall poles (Figure 3 Left). To observe all vehicles on the roadway with minimize occlusion, the poles are significantly taller than the standard 30-50 ft poles used on many other CCTV systems. New poles and corresponding foundations were designed and built with total deflection of less than 1.5 inches in 30 mph wind.

Figure 3: Validation system construction. Left: 110-foot poles are raised adjacent to the freeway; middle: Multi-camera mount holds 6 4K PTZ cameras; right: cameras are elevated to the top of the pole.

- Fiber network. The poles are connected on a fiber backbone to a hub building capable of hosting compute and storage equipment. As part of a larger infrastructure and technology upgrade by TDOT known as the I-24 SMART Corridor, the freeway fiber network is complete and has dark fiber available for use by the testbed.

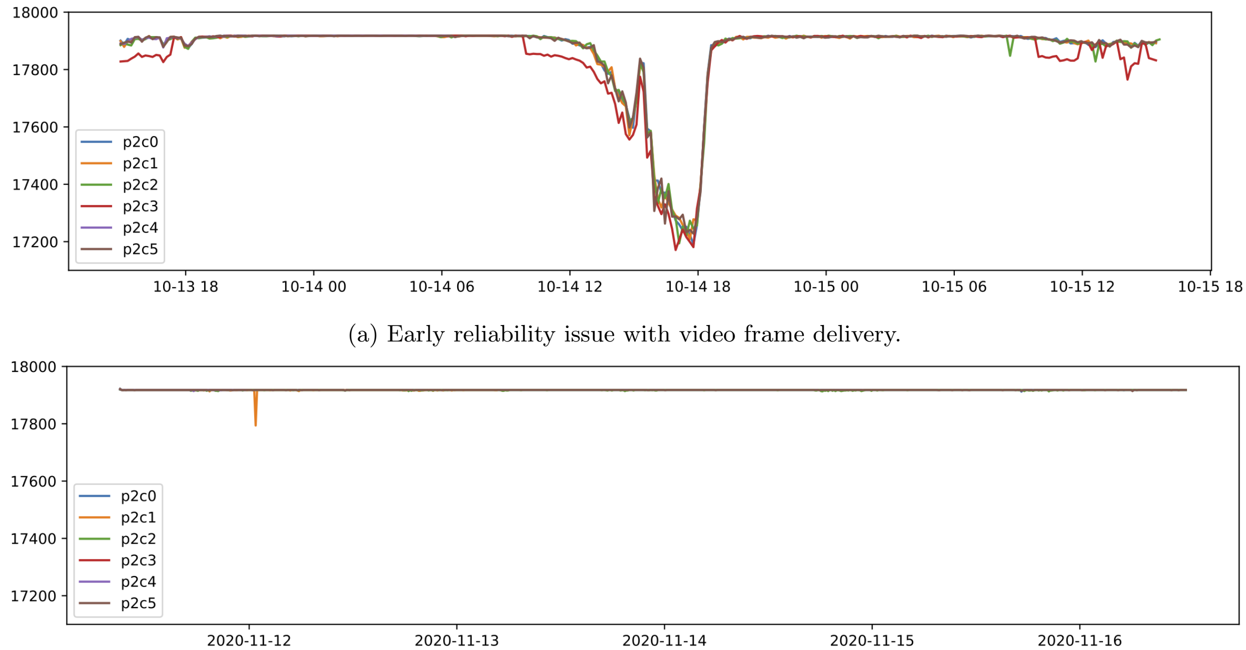
- Camera lowering device. The camera lowering device is a critical component of all traffic monitoring cameras in Tennessee (Figure 3 right). It allows the camera cluster to be safely lowered to the ground for routine cleaning and maintenance using a winch at the base of the pole. The validation system confirmed that the new-generation lowering device is also able to transmit data from six 4K resolution video cameras through the lowering device and down the pole where it is tied into the existing TDOT fiber network.

- Cameras and camera mounting bracket. The system uses a custom, 6-camera mount (Figure 3 middle) attached to a lowering device. Camera pan/tile/zoom capabilities allow remote alignment to achieve the necessary 180-degree overlapping field of view across cameras on each pole and between camera poles. Deploying multiple cameras to each pole extends coverage of the testbed by reducing the number of poles needed. The weather tight camera mount holds a network switch responsible for making data streams transmittable through the lowering device.

- Hub building access. The landing point for video data from the camera network is the TDOT network hub building. At this point the fiber optic cables are connected to a network switch that connects the computational and data servers responsible for buffering video data, computing vehicle trajectories, and storing resultant data.

- Video ingestion. Camera streams are mapped to individual servers tasked with handling the raw network stream and producing decoded video frames for processing. This ingestion required a custom data pipeline to be written in GStreamer, which the team completed in consultation with experts at Nvidia and RidgeRun. The resulting pipeline can dynamically route and buffer video streams, archive video snapshots of interesting segments, and monitor the integrity of incoming video. Each camera clock is set by a centralized network time server. Synchronizing at camera capture time rather than server receive time allows precise synchronization across cameras. The pipeline serves as the interface point at which computer vision tracking algorithms take decoded video frames as input for processing.

- Trajectory generation. The core of trajectory processing is a custom multi-object tracking algorithm called localization-based tracking (LBT) [11, 12]. The algorithm is based on existing open-source components – a deep neural network image detector [14, 18] and the *Kalman Intersection Over Union* (K-IOU) tracker [3, 4] – along with enhancements we have made for increasing speed and accuracy. The primary improvement in LBT over existing K-IOU is that it exploits the motion model of the



(a) Early reliability issue with video frame delivery.

(b) Frame delivery issue fixed with hardware change.

Figure 4: Video frames delivered per 10-minute interval, tracked over time for uptime statistics.

Kalman filter to replace computationally expensive detection steps with a cheaper vehicle localizer. The Kalman filter makes a prediction of the vehicle location in the next frame based on its most recent position and the vehicle's individual motion model. The vehicle localizer detects the position of the vehicle within a small region extracted from the full image that is centered around the Kalman filter predicted location. In this manner, a smaller portion of each image is ultimately processed compared to running detection on the entire image. Particularly in sparse or free-flow traffic, most of the image space will not contain vehicles so LBT can be very efficient. The results enable faster tracking without sacrificing accuracy: at least a 250% speedup over tracking by detection using K-IOU, compared on a single offline camera video stream using an Nvidia RTX6000 GPU [12]. We retrained the object detector on 10,000 vehicles to improve performance given the non-standard overhead field of view. Synchronized overlapping cameras enable trajectory stitching in 3D coordinates across the instrument.

- Uptime. We have been tracking frame delivery statistics from each camera to the servers hosted in the hub building. Initially the system delivered 95% of frames from cameras. This frame loss is shown for six of the cameras in Figure 4a; the number of frames delivered across ten-minute intervals is tracked for each camera over 48 hours. Cameras exhibited a simultaneous and dramatic decrease in number of frames delivered – degrading down to a 4% loss rate in this particular case. It was discovered that an upgraded ethernet surge arrester was needed for this application and the upgrade resulted in 99.95% of all frames received; the frame delivery tracking is shown after the upgrade in Figure 4b. Frame counts now exhibit very little variability, save for a small momentary drop experienced by one of the cameras.

5 Full system build-out

Design and construction of the full-length testbed will primarily replicate the successful strategy of the validation system. Modifications to accommodate the larger scale will focus mostly on the cyber infrastructure. The detailed timeline for full system design, construction, and commissioning phases is given in Table 1; completion of construction is scheduled for Q3 2022, with all functions of the fully-commissioned testbed

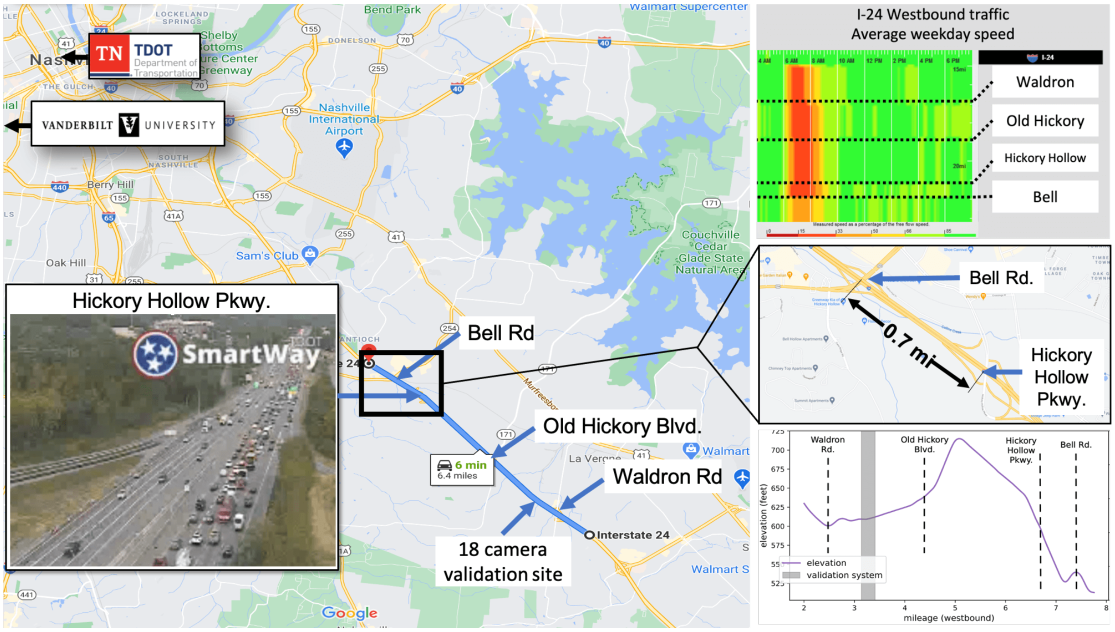


Figure 5: Overview of testbed location in Nashville, TN.

scheduled to be online in Q2 2023. We detail the major considerations for the full system in the subsequent sections.

Location

The physical assets of the testbed (e.g., poles, fiber, cameras) are located on I-24 between the interchanges of Bell Rd. (approximate westernmost extent), to Waldron Rd. (easternmost extent); see Figure 5. The stretch includes a major recurring bottleneck, approximately 13% truck traffic, and more than 150,000 vehicles a day that pass through the roadway. This will effectively extend the testbed in the direction of Nashville from the site of the validation system. Placement of camera poles in the testbed area will continue the strategy of minimizing occlusion by using the same 110 ft tall poles, placing them directly adjacent to the roadway shoulder, and spacing poles 500-600 ft apart.

Cameras, poles, and physical infrastructure

Cameras, poles, network switches, lowering devices, etc., will follow the same design as the 18-camera validation system, including only minor changes that were informed during the construction and testing process. For example a wider field of view camera may result in removal of one camera per pole.

Computational infrastructure and networking

The video data streams from the camera network require dedicated hardware and software to ingest, process, and store the large volumes of data. Computational servers are built around graphics processing units (GPUs), which are efficient processors of neural network computations underlying trajectory generation algorithms. Each compute server hosts eight GPUs and the number of required servers is based on tracking algorithm performance on the validation system. This performance will dictate the ultimate size of the computational array for the full testbed.

Processed vehicle trajectory data resulting from the camera network will be made available to the research community by bundling and hosting in a data repository. Trajectory data will be segmented temporally, with recent data available in small segments and older data available as compressed bulk downloads. A data hosting server will automate this rolling process as new data is constantly generated, and also host a dashboard informing users of the data and system status.

Table 1: Full testbed design, construction, and commissioning timeline.

	Cyber infrastructure	**Physical infrastructure**	**Project management**
Design Phase			
Q3 2021	Finalize software and hardware architecture.	Locate 1.5 mi. instrument site. ROW plans.	Form executive board for instrument dev. and ops.
Q4 2021	Develop server specifications and place order.	Develop and submit construction plans.	Executive board reviews plans with stakeholders.
Q1 2022	Server hardware, OS, and network configuration.	Construction field review; bid documents and letting.	Develop business and long term funding plans.
Construction Phase			
Q2 2022	Finalize trajectory extraction software package.	Begin construction (major component sourcing).	Write data dissemination and privacy policies.
Q3 2022	Software integration and unit testing.	Construction continues.	Write experimental plan and safety procedures.
Commissioning Phase			
Q4 2022	Full system testing of new construction.	Construction completion, inspection, integration.	Develop infrastructure maintenance schedule.
Q1 2023	Burn-in testing. Preparation of first dataset.	Burn-in testing, reporting, constr. contract close-out.	Review results of tests for contract release.
Q2 2023	Implement automated data hosting and dissemination.		Review validation results of vehicle trajectories.

6 Conclusions

The I-24 MOTION open-road testbed will add new capabilities to transportation experimental and research facilities in the United States. It will provide the opportunities for testing traffic management and automated vehicle technologies in real traffic, with high resolution vehicle data collection capabilities. The continuous view of the testbed's pole-mounted 4K resolution cameras provides the ability to study the traffic stream at the individual vehicle level, broadly across the 6-mile extents. The data produced from this sensing system will enable new research opportunities that rely on large amounts of high-fidelity vehicle trajectory data.

The Tennessee Department of Transportation, during the validation phase of the testbed, constructed a three-pole system that demonstrated the concept and design of the system in operation. This 1600-foot system will be extended to the full six miles during 2021-2022. Technical and logistical challenges encountered during the validation phase are remedied in the design of the full system. Once fully operational in 2023, the testbed will automatically and continually collect data from 300 cameras, process the video into vehicle trajectories, and share this data to the transportation community.

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