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Project 502: Digital Twin for Driving as Planning Support Tool

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JULY 2025 RESEARCH REPORT

Grant Program: US DOT BIL, Safety21, 2023 - 2028 (4811)

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Technical Report Documentation Page

<table>
<tr><td>1. Report No.</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Digital Twin for Driving as Planning Support Tool</td><td>5. Report Date
July 31st, 2025</td></tr>
<tr><td>6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Erick Guerra
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<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
University of Pennsylvania
Jitsik</td><td>10. Work Unit No.</td></tr>
<tr><td>11. Contract or Grant No.
Federal Grant # 69A3552344811 / 69A3552348316</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address</td><td>13. Type of Report and Period Covered
Final Report (July 1, 2024 – June 30, 2025)</td></tr>
<tr><td>14. Sponsoring Agency Code
USDOT</td></tr>
<tr><td colspan="3">15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.</td></tr>
</table>

16. Abstract

This research project aims at assessing the potential of Virtual Reality for driver training.

17. Key Words	**18. Distribution Statement**
Digital Twin, Driving Simulation	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
		33	

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Contents

1. Project Overview

The objective of this project is to develop an actionable model of the Philadelphia Roosevelt Boulevard that can be used to assess roadways changes in the context of the Route for Change program developed by the City of Philadelphia. This report documents the progress of the project in different phases, from the initial set-up of a digitized scene to the final optimized simulation environment. The larger goal is to utilize high-fidelity simulation techniques to enhance traffic safety and urban mobility. The project utilizes Road Runner 2023, the CARLA open source simulator environment, and Unreal Engine 5 to generate realistic environments and provide accurate road conditions. The simulation environment is based on the Philadelphia Roosevelt Blvd., a critical road network chosen for its complex intersections and high-traffic density. This report details the development process, including tool selection, scene creation, and progressive enhancements to the simulation environment.

2. The Route for Change Initiative

The Route for Change Program is a transformative initiative focused on improving the safety, accessibility, and overall conditions of Roosevelt Boulevard. Initiated by the City of Philadelphia in cooperation with PennDOT and SEPTA, and supported by a USDOT TIGER VI planning grant, the program targets Roosevelt Boulevard, a critical 14-mile corridor connecting North Philadelphia to the broader region. Due to its confusing geometry and high speeds, Roosevelt Boulevard has become one of Philadelphia's most dangerous roads, with over 2,800 crashes recorded between 2013 and 2017. In response to the challenges and opportunities posed by Roosevelt Boulevard's complex geometry and high crash rates, our project uses digital twin technology to simulate and assess the corridor. This project supports the Route for Change Program's goal of transforming the Boulevard into a safe, accessible, and connected multimodal corridor that unites neighborhoods.

2.1 Background

Originally designed as a picturesque rural roadway, Roosevelt Boulevard has evolved into a vital urban artery supporting diverse neighborhoods and significant commercial and industrial activities. The program area extends 12.3 miles within Philadelphia (from N. Broad Street to the Bucks County line) and an additional 1.7 miles into Bucks County, ending at Neshaminy Mall.

The corridor includes:

- 56 signalized intersections
- 94 unsignalized intersections with 129 access points
- 252 non-intersection access points

Unique geometric characteristics cause the Boulevard to act as a boundary or barrier between neighborhoods on either side, including:

- Changing center and side median widths
- Diagonal streets that create long, skewed intersections with the Boulevard
- Crossovers between inner (express) and outer (local) lanes
- Prominent roadway curves between Whitaker Avenue and Godfrey Avenue, known as the “S-Curve”
- Grade-separated intersection

The sheer width and complex design make the Boulevard a major barrier between neighborhoods, with features like changing medians, diagonal streets, crossovers, prominent curves (especially the “S-Curve”), and grade-separated intersections.

2.2 Safety Challenges

Despite past safety efforts, Roosevelt Boulevard remains one of the most dangerous corridors in Philadelphia:

- Between 2013 and 2017, there were 2,846 reportable crashes (46 crashes per mile per year)
- 62 fatal crashes, averaging 12 deaths per year

Key crash analysis findings include:

- Excessive speeding is the most common and severe contributing factor
- Risky driving behaviors (DUIs, aggressive driving, fatigued driving) have particularly severe consequences here
- Pedestrian crossings are extremely dangerous due to long distances and poor crossing facilities
- Red-light running remains an issue, although reduced at camera-enforced intersections
- Fixed-object crashes, especially in the S-Curve, are likely to cause serious injury or death

2.3 Vision and Goals:

The long-term vision for Roosevelt Boulevard focuses on creating a **safe, accessible, and reliable** corridor that unites neighborhoods and offers diverse, connected transportation choices.

Main themes:

• **Safety**: Improve transportation safety for all modes of travel along the Boulevard by reducing the number of traffic fatalities to zero

• **Accessibility**: Better connect the modes of travel using the Boulevard so it is easier to reach more destinations and activities

• **Reliability**: Provide dependable transportation options along the Boulevard

2.4 Program Priorities

Based on crash data and community feedback from five rounds of public forums, the program's top priorities are:

- Increase safety
- Reduce travel time
- Reduce wait time
- Reduce confusion
- Manage access

2.5 Recommended 2025 Corridorwide Improvements

Road for Change Report	Timeline	Specific Planned Work	Desired Outcomes	How Digital Twin or Related Tools Could Be Used	Benefits of Using Digital Twin
Direct Bus (Phase A & B) and BRT	Phase A launched 2017 Phase B by ~2025 Full BRT by 2040	- Phase A: Launched Boulevard Direct (reducing stops from 88 to 9). - Phase B: Extend Direct Bus further across corridor, connect Frankford TC and Wissahickon TC. - 2040: Dedicated BRT lanes in both alternatives.	• Shorter bus travel times • More reliable service • Increased ridership • Smoother transfers to local routes	• Build a virtual model of bus operations along the corridor • Simulate how buses move through signals, stops, and congestion • Test different stop spacing, station locations, and lane designs • Model how ridership shifts if service frequencies change	• Optimize BRT design without costly trial-and-error • Identify best placement for stations and lanes • Prove time savings to secure funding • Improve reliability predictions for operations planning
Local Bus Stop Improvements	By 2025	- Upgrade 62 local bus stops with shelters, benches, lighting, and	• Improve rider comfort and safety • Increase ridership	• Use pedestrian flow simulation to analyze crowding and sidewalk width needs • Evaluate how shelters and new bus stop designs affect	• Avoid creating new pedestrian bottlenecks • Ensure compliance with ADA and safe sightlines

		ADA-compliant boarding areas	through better waiting environme nts	visibility, pedestrian circulation, and safety • Test scenarios where stops are moved or consolidated	• Invest in stops that will deliver the biggest benefits
Business Access and Transit (BAT) Lanes	By 2025	• Implement BAT lanes along parts of the Boulevard • Allow buses priority travel during peak times • Permit parking, loading/delivery in off-peak periods	• Faster bus speeds during peak • Maintain business access and deliveries • Reduce delay for buses in mixed traffic	• Create a virtual traffic model that shows how BAT lanes affect travel times for buses, cars, and trucks • Test time-of-day restrictions (e.g. off-peak parking) and their impacts • Measure impacts on delivery truck routing, parking, and loading times	• Ensure BAT lanes don't create unexpected congestion • Balance business needs with transit reliability • Avoid unnecessary costs from incorrect lane configurations
Pedestrian & Bicycle Safety Improveme nts	By 2025	• Repaint crosswalks • Realign curb ramps for shorter crossings • Build curb extensions to shorten crossing distances • Close sidewalk gaps • Extend protected bike lanes to the Boulevard	• Safer crossings for pedestrian s • Increased walking and biking • Fewer crashes involving pedestrian s and bikes	• Simulate pedestrian wait times and crossing movements at specific intersections • Model driver yielding behavior at new curb extensions or bike crossings • Analyze potential crash conflict points between cars, bikes, and pedestrians under new layouts	• Prioritize safety projects with highest impact • Refine designs to avoid new conflicts • Provide visuals to gain public support for changes
Intersectio n Redesigns	By 2025	• Redesign ~48 intersections • Changes include new signal timing, realigned crosswalks, geometric changes (e.g. lane reconfigurations, new left-turn lanes), and improved signage • Specific high-crash locations targeted (e.g.	• Lower crash rates • Better traffic flow • Safer crossings for pedestrian s and cyclists	• Virtually build each proposed new intersection geometry (e.g. new lane alignments, roundabouts) • Simulate vehicle queues, pedestrian crossings, and turn delays • Test different signal timing plans and traffic phasing for peak and off-peak hours	• Reduce risk of creating new congestion problems • Fine-tune designs before construction • Justify project costs by demonstrating time savings and safety benefits

		Summerdale/Adams S-curve)			
Crossover Improvements	By 2025	• Improve or extend 9 of the 34 crossover lanes • Improve signage and geometry to reduce confusion • Accommodate new BAT lanes where relevant	• Reduce driver confusion moving between express and local lanes • Lower crash risk • Improve traffic flow	• Simulate vehicle weaving patterns and driver lane changes at each specific crossover • Test how proposed changes affect queues, gap acceptance, and merging speeds • Model impacts of new signage or lane markings	• Avoid new bottlenecks from poorly designed crossovers • Reduce driver errors and crashes • Save costs by testing changes virtually instead of rebuilding multiple times

Key Typologies (Existing and Recommendation Corridor Typology): pp119-126

2.6 2025 Programmatic Actions

The program identifies strategies to improve safety for all with:

- Automated Speed Enforcement (ASE) Program
- Vision Zero Educational Program
- Signage Inventory & Evaluation
- Lighting Assessment
- Transportation Demand Management (TDM) strategies

2.7 Guiding Principles for 2040

- Prioritize zero traffic fatalities (Vision Zero)
- Reconnect divided neighborhoods
- Build on 2025 improvements
- Create consistent treatments for predictability
- Maintain separation between express and local lanes

2.8 2040 Alternatives

- Alternative 1: Partially Capped Expressway
- Alternative 2: Neighborhood Boulevard

3. Tools Used for Digital Twin Development

The following tools and technologies were utilized in the Jitsik project:

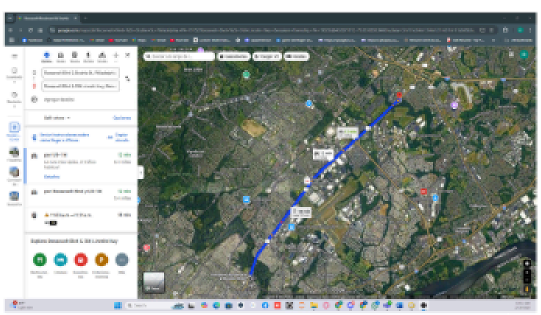
- CARLA Simulator - Used for autonomous vehicle and traffic simulation.
- Python - For scripting and data analysis.
- Unreal Engine 5.5 - For rendering and simulation environments.
- Git/GitHub - Version control and project management.
- Road Runner 2023a - Used to generate and refine project scenes.

4. Initial Phase

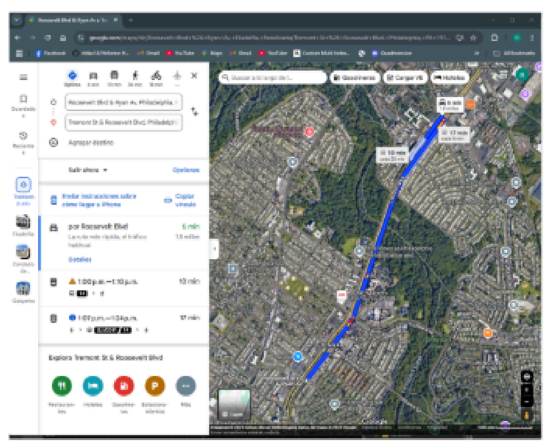
4.1 The Digital Twin

The foundation of our work requires a high-quality 3D model for the digital twin, ensuring accurate spatial representation. Our primary concern is the precision of the mesh geometry rather than the realism of textures, as both Unity and Unreal Engine can achieve realistic visuals even with artificial textures.

To create this 3D model, we primarily use Road Runner, which processes aerial imagery and Open-StreetMap (OSM) data to generate an estimated street structure. We then manually refine this model to enhance accuracy and alignment with real-world conditions.



(a) Roosevelt BLVD



(b) Road Map of Roosevelt Blvd

Figure 1: Initial development phase showcasing early scene setup.

4.2 Geographic scope

The initial phase (a) represents the geographic scope of the project. Thus far 2.9 miles of the Roosevelt Blvd. were modeled. Figure (b) represents Phase 2 of the development. Both Phase 1 and Phase 2 remain in active development, with ongoing improvements in road accuracy, intersections, and scene optimizations. This section outlines the advantages and limitations encountered during the development of the simulation environment.

5. Work in Progress

The following images illustrate the progressive development of the simulation environment. Each step represents an improvement in the accuracy of the map, the detail of the roads, and the enhancements of the scene. The development focused on improving terrain elevation, lane markings, intersections, and AI-based vehicle movement.

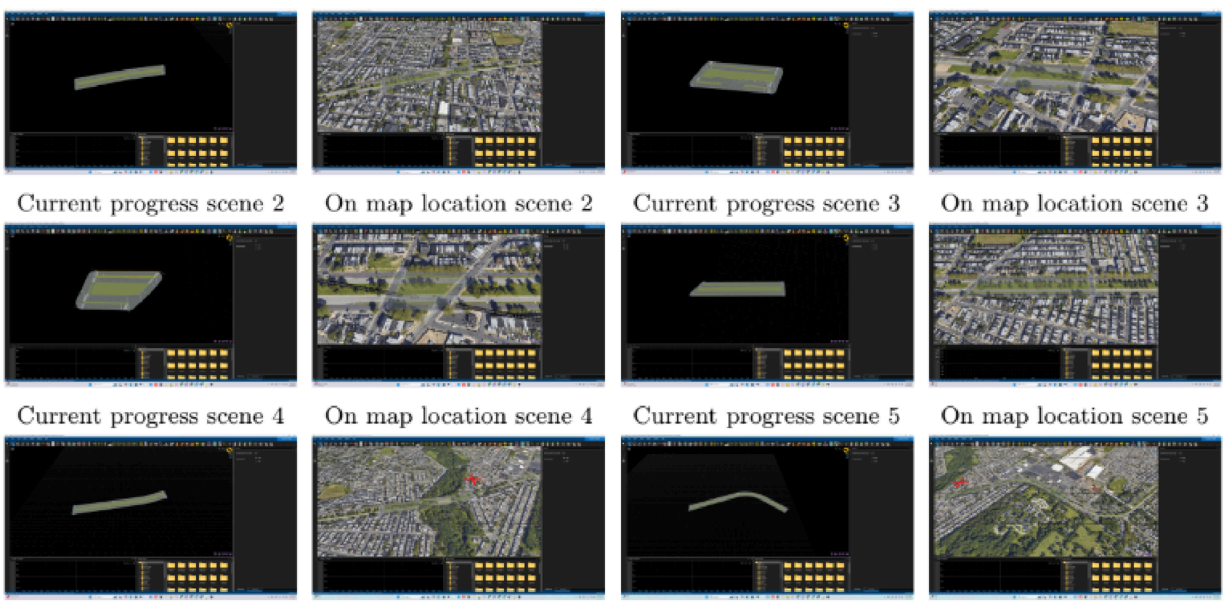


Figure 2: Step-by-step development of the simulation environment.

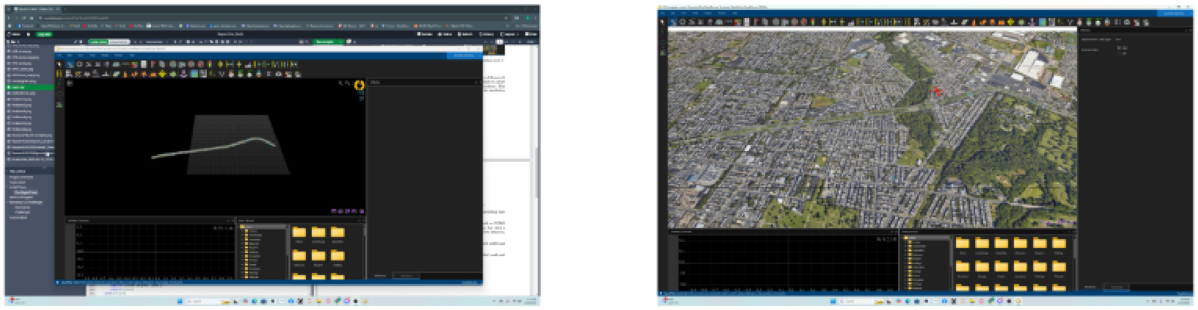


Figure 3: Current progress on the map.

6. Results & Challenges

6.1 Results

The development of the Roosevelt Blvd. simulation has resulted in several benefits, including:

- High Realism: The simulation accurately replicates real-world road conditions, including lane markings, intersections, and traffic flow patterns.
- AI Integration: The environment is compatible with AI-driven traffic models, such as SUMO (Simulation of Urban Mobility) for traffic flow analysis and CARLA (Learning to Act with a Car) for autonomous vehicle testing. These models enable realistic simulations of driver behaviour, pedestrian interactions, and traffic congestion scenarios.

We are also working on including an AI-assisted design agent, which would create alternate street designs.

- Scalability: The system is designed for future expansion, allowing integration with additional datasets, new road sections, or enhanced AI-based decision-making tools
- Efficient Workflow: The use of Road Runner 2023 simplified the creation of detailed roads and intersections.

6.2 Challenges

Despite the progress, some limitations were encountered during development:

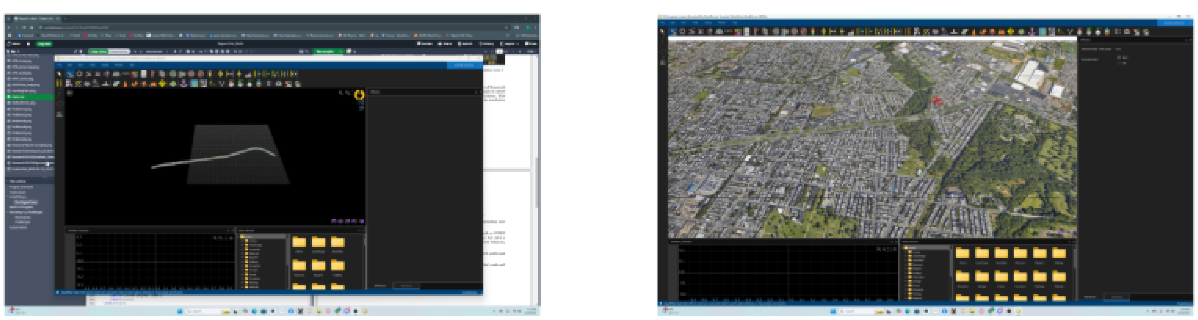


Figure 4: Challenges faced during development: rendering artifacts and performance issues.

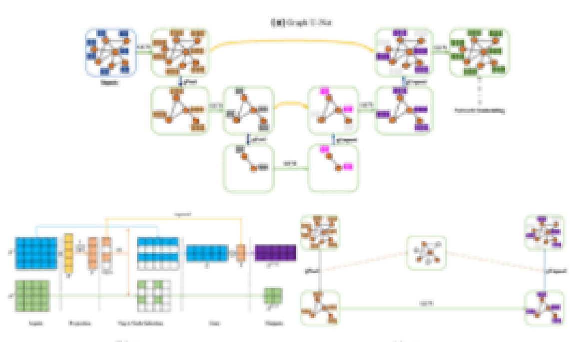
- High Computational Requirements: The simulation requires significant processing power, with up to 10 GB of VRAM on a 1660-ti to run a sim with up to 50 vehicles, in real-time.
- Rendering Challenges: Some elements of the scene caused visual inconsistencies.
- Time-Intensive Development: The creation and fine-tuning of the map took longer than expected. The fine-tuning of the map and lane fixes can take up to 4-5 hours for just a mile of the road.

We currently have a simulation working for a part of the scene, integrated with the SUMO traffic model in CARLA

6.3 Future Work

Now that we can create some sample scenes using our method, we need to optimize the digital twin further. We need to generate more accurate streets without the need for human labour to restore the missing connection of lanes, and nodes, especially the intersection, tunnels, and bridges. We are planning to implement learning from existing street designs to generate alternative designs. We currently have two possible approaches to handle this. We can either use existing designs, create random designs, and have a reinforcement method to learn from the output score in simulation, or we can collect data in the simulation on plenty of street designs, to understand optimal designing through Graph Neural Networks. Now both of these approaches have their challenges to be implemented.

(a) Road Runner Scenario Generator



(b) U-Net Graph Neural Network

The first challenge in either of the approaches is having better automation of creating the structure and a good way of representing the data, which can be used to regenerate the 3D street design. Simulating multiple iterations for reinforcement learning might be slower and very

computationally expensive. While using any generative network, we need to have a diverse enough dataset of 3D designs, which are realistic, and follow the usual design constraint.
In addition, the design also needs to follow the local design guidelines and actively check for constraints. One of the other challenges comes with the integration of the system. As we rely on various systems, integration can become a bottleneck in optimizations.
We are currently planning to simulate Roadrunner with a scenario generator, using Matlab and Simulink, instead of using a high-computation simulator like Carla. The other question that arises with this approach is how real the traffic is, as humans do not always adhere to rules. Therefore, we aim to implement a traffic generator which would take into account human error and factors like rash driving, and generate traffic in a less orderly fashion, but more realistic, by visualizing traffic using the camera and having a probability distribution on these factors.

7. Publications

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8. Collaborators and Research Students

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- Anthony Hyacinth

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Addendum TRR paper

The following paper was peer reviewed for the Transportation Research Record and is pending for publication

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Digital Twin of the Philadelphia's Roosevelt Boulevard: a microsimulation based on real life traffic

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Word Count: 5176 words
Submitted 05/31/2025

Keywords: Digital Twin; Driving Simulator; Scene Construction; Traffic Flow Model

ABSTRACT
The use of digital mapping with precise GPS coordinates has allowed intelligent navigation, which is now ubiquitous in vehicles. The flat 2D imagery provided by Google Maps was recently enhanced by the introduction of dynamic 3D representations of the Earth. Unity3D [1] and Unreal Games Engines [2] now offer Application Programming Interfaces that can be leveraged for geospatial applications. This technology, which offers visually compelling results for flight simulation and drone applications, opens new opportunities for driving simulation. This paper presents an innovative approach for developing a drivable Digital Twin of Philadelphia's Roosevelt Boulevard to enhance urban planning and traffic management using advanced simulation technologies. We introduce a complete pipeline that integrates geospatial imagery with data from Google Maps and OpenStreetMap (OSM) [3] through tools like CityEngine [4] and Matlab RoadRunner [5], enabling the creation of highly detailed, editable 3D urban scenes. This methodology facilitates rapid modifications to urban landscapes, exemplified by the integration of a bus lane into existing road infrastructure, demonstrating significant advancements over traditional methods. The core of our approach is a dynamic traffic flow model developed within the Unity driving simulator, utilizing probabilistic distributions and real-world data from the Next Generation Simulation dataset (NGSIM) [6] dataset to mirror actual traffic conditions accurately. This model supports the simulation of realistic, varied, and dynamic traffic patterns, crucial for testing and evaluating urban traffic scenarios and infrastructure changes. The implementation showcases the potential of digital twins for transforming urban planning and traffic systems by providing a reliable platform for scenario testing and decision-making.

Keywords: Digital Twin; Driving Simulator; Scene Construction; Traffic Flow Model

1. INTRODUCTION
The integration of geospatial imagery into modern applications has significantly advanced, along with the driving application in digital twins for intelligent transportation systems. However, there are still challenges presented by the current state of technology, such as 3D model scarcity, time-consuming processes and limitations of non-editable 2D surface representations.

We anticipate that the development of robust Digital Twins of complete neighborhoods can have a solid impact on many fields. First and foremost, Digital Twins with realistic traffic flow simulators can allow researchers to assess the safety of various road designs. They can iterate on the placement of bus or bicycle lanes, roundabouts, traffic lights and measure the impact on traffic safety and congestion. Our case study, the Philadelphia Roosevelt Boulevard is being developed in symbiosis with the "Route for Change" program, launched by the City of Philadelphia [7]. This artery, which is the frequent site of fatal crashes, is the focus of a comprehensive, multi-phase US 1 Improvement Program. Public hearings were conducted in late Fall 2023 with additional hearings planned. At stake are the reduction from 12 lanes to 8 ("Alternative A") or 6 ("Alternative B") and the proposed introduction of a Roosevelt Boulevard Subway. In its final state, our Digital Twin design will include the different options with associated safety and congestion metrics. While a realistic representation of the traffic flow design is paramount to assess these metrics, aesthetics remain an important aspect. The participation of residents to public hearings can be facilitated by the presentation of visually compelling scenarios [8, 9, 10]. Another application of Digital Twins, can be driving education itself. The decreasing cost of Virtual Headsets can translate into driving simulators that can be fully immersive and allow students to drive in real life neighborhoods.

This paper addresses the challenges by introducing a complete pipeline for developing a drivable Digital Twin for Philadelphia's Roosevelt Boulevard as a test case. Tile maps from Google Maps and OpenStreetMap (OSM) data are integrated with CityEngine and RoadRunner, to allow the construction of a vivid, editable scene for driving simulators. This pipeline includes data integration, static scene construction, alternative roadway layout demonstration and traffic dynamics evaluation.

For the dynamic traffic evaluation, we introduce a traffic flow model which combines driving regulations and probabilistic distributions which are integrated into the Unity driving simulator. By leveraging the Next Generation Simulation (NGSIM) dataset, we extract specific vehicle movement parameters and use them to develop a Gaussian distribution-based traffic model. This traffic model demonstrates the feasibility of our simulation, providing further information that can be used to improve the efficiency and safety of real dynamic traffic conditions.

2. METHODS

Our goal with the development of a Digital Twin is to create an environment that is as realistic as possible, so it can be used by traffic engineers to assess design alternatives for public transit improvements. Quoting George E. P. Box, a British statistician, “All models are wrong but some are useful”. As we build our simulation, we acknowledge the many factors which come in the way of a realistic simulation: any Digital Twin will always be a simplification of the real geographic neighborhood, Human Behavior is much more complex that any oversimplified and deterministic model, the physical aspects of cars themselves need to be included, weather and road conditions contribute to the complexity of the traffic flow, pedestrians and bicycles also need to be included… While we recognize the complexity of the challenge, we believe the constant improvement of simulation tools, data collection tools, and visualization techniques will help provide much needed tools to traffic engineers. As a consequence, many researchers are joining in the development of the Digital Twin ecosystem [11, 12, 13].

The methodology developed below proposes an efficient pipeline for creating precise and vivid drivable scenes shown in Figure 1 and a traffic flow model that reflects different dynamic traffic conditions. In the first stage of the methodology, high-resolution tile maps of the target neighborhood are acquired through Google Maps’ ping services. These maps serve as a foundational dataset, which is then processed using a custom Python script designed to enhance resolution and clarify structural details, resulting in a comprehensive construction map. Subsequently, the process extracts detailed building outlines from OpenStreetMap (OSM), a collaborative project to create a free editable map of the world[3]. This data is crucial for accurately defining the architectural boundaries and features of each structure. Using the extracted outlines, 3D models of the buildings are reconstructed with precision in CityEngine[4], a specialized software for urban environmental modeling, which offers realistic and scalable cityscape generation. The final phase of the workflow integrates the individually modeled buildings with the road infrastructure. This integration is achieved through a meticulous manual calibration process, ensuring that the spatial alignment and scale of roads and buildings harmonize seamlessly into a coherent and accurate 3D urban scene.

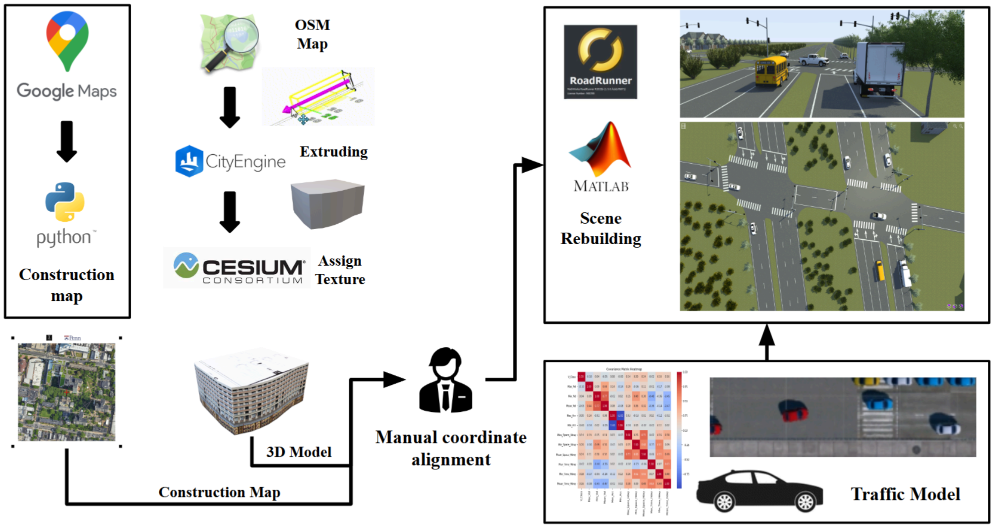

Figure 1: Pipeline for Developing Digital Twin.

2.1. Scene Construction

Our project leverages a synthesis of open-source data, sophisticated modeling techniques, and robust software platforms to construct intricate and lifelike scenarios for driving simulations. For the first step, we acquire original tile maps from Google Maps. A tile map is defined as a collection of prerendered, fixed-size images that depict map data across various zoom levels. A dedicated Python project was developed to automate the downloading of these tile maps, facilitating their transformation into high resolution construction maps through advanced image processing techniques and parameter computation. OpenStreetMap (OSM) is a collaborative initiative that provides an open-access, editable map of the globe. By harnessing data from OSM, we extract detailed building contours and associated terrain information, including elevation profiles. Our mapping accuracy is further augmented by integrating a texture database, which permits the random assignment of textures to each building model, thereby enhancing the visual richness and detail of the map representation. The resultant map visualization and various enhancements are depicted in Figure 2.

Figure 2: Examples of 3D Building Models Generation (Hospital of University of Pennsylvania)

For the second step, the refined blueprints are transformed into three-dimensional building models using the Cesium platform. During this phase, careful manual alignment of coordinates is performed to ensure spatial accuracy. In order to create a dynamic and realistic urban environment for driving simulations, we utilize Roadrunner, a versatile simulation tool developed by Matlab[5]. This tool enables the crafting of vibrant, customized scenes tailored specifically for the requirements of driving simulations. Both the 3D building models and the high-resolution construction maps are imported into Roadrunner, where they are integrated to form comprehensive urban landscapes. Notably, this workflow allows for the efficient reconstruction of complex urban intersections, which can be completed in approximately 40 minutes. This rapid modeling capability significantly enhances the realism and detail of our simulations, thereby contributing to effective and life-like simulation of the driving experience.

Figure 3: Scene Building: Scene Created in RoadRunner(left), Google Earth(right)

Once the scene has been completed in Roadrunner, it is exported to Unity for the creation of immersive scenarios. A detailed analysis of real-world traffic data underpins the development of a traffic flow model that accurately replicates diverse traffic conditions, including rush hour congestion and other time-dependent variations. By employing rule-based vehicles, we establish a dynamic traffic model that offers a realistic simulation of real-world dynamics. This methodical approach ensures the generation of authentic and realistic scenarios within Unity, facilitating extensive testing and analysis. Our project exemplifies the seamless integration of various technologies and methodologies to enhance the efficiency of developing immersive driving simulations. Utilizing Python for image processing and data analysis, combined with the use of OpenStreetMap data and a texture database, we effectively create high-resolution construction maps and detailed 3D models. Roadrunner and Unity serve as advanced platforms for scene construction and scenario development, respectively, enabling the simulation of dynamic traffic environments with exceptional accuracy and fidelity.

2.1.1 Traffic light management

Typically traffic signals have timing control plans that follow standards developed by the National Electrical Manufacturers Association (NEMA) [14]. For our Unity3D implementation, the research team used a built-in Unity asset "Simple Traffic System" which has an integrated Traffic Light manager. Of note NEMA logic for management of control signals can be obtained by integrating SUMO [15, 16]. The signal timing parameters—including phase durations, cycle times, and offsets—can be easily modified through Unity's user interface or via scripting. Each intersection can be configured individually to reflect real-world or experimental signal plans.

2.2. Traffic Flow Model

The development of digital twins for intelligent transportation systems is gaining significant attention, primarily due to the challenge of creating simulations that effectively mirror realistic, varied, and human-like traffic patterns [17]. Such simulations offer a dynamic and innovative method for exploring traffic dynamics, revisiting traffic safety, city planning and urban design interventions. A central objective within this context is to design seamless and coherent interactions between the autonomous vehicle (ego car) and other vehicles in its vicinity, while accurately replicating the complex behaviors characteristic of human drivers. This endeavor encompasses several layers of complexity, including the detailed interaction between road configurations and vehicle dynamics, and the nuanced understanding of driver

preferences and societal interactions [18].
Existing open-source traffic simulation platforms such as SUMO, PTV Vissim [19] and CARLA [20] have been instrumental in creating traffic flows. While these models provide a reliable option to simulate traffic on various driving environments, they are not based on the ground truth that can be observed on a specific artery. The work presented offers to replicate the true nuances of human driving by developing a stochastic traffic flow model based on road observations. For this first phase of the development, we leverage the NGSIM, a public database made available to researchers by the US Department of Transportation, to calibrate the proposed stochastic model. In a second phase of the study, we plan to use real life traffic measured on the Philadelphia Roosevelt Boulevard through the use of deployed speed cameras [21, 22]. For this project, 10 speed cameras were deployed starting June 2020 along a corridor that spans 15 miles. The data gathered from these cameras will enable the research team to fine tune the traffic flow parameters using the real Roosevelt Boulevard traffic flow.
In this paper, we introduce a novel approach for generating traffic flow, which leverages driving regulations and probabilistic distributions, effectively implemented within the Unity driving simulator. Initially, we extract vehicular movement characteristics and inter-vehicle interaction data from the NGSIM dataset. Following a thorough data cleansing process, we identify and extract pivotal features pertinent to the traffic flow model, subsequently constructing a Gaussian distribution. In addition, we propose a set of fundamental principles for governing vehicle movement. The efficacy of the developed model is corroborated through validation exercises conducted on the Unity driving simulation platform, with empirical findings demonstrating that our method is capable of achieving a parametric and human-like representation of traffic flow.

2.2.1 Data Preparation, Feature Extraction, and Modeling
The NGSIM dataset is a highly valuable resource in the field of traffic engineering and transportation research. It provides detailed vehicle trajectory data that captures the dynamic nature of traffic flow on selected road segments. The dataset encompasses high-resolution data on vehicle trajectories over specific time intervals, including detailed information such as the position, speed, and acceleration of individual vehicles, as well as lane changes and interactions between vehicles. This data was collected using video cameras mounted on elevated platforms, which monitored sections of highways and arterial roads at various locations within the United States.

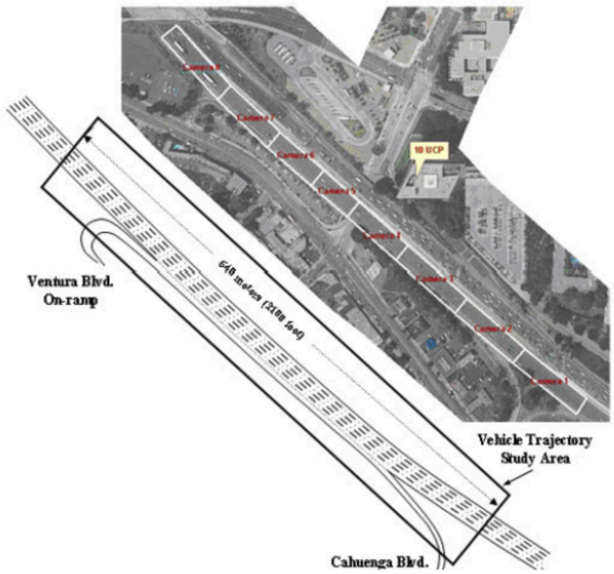

Figure 4a: Bird's eye view of the US101 Highway;

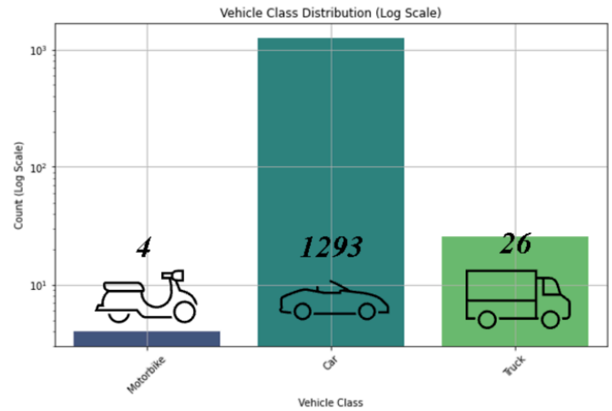

Figure 4b: Data from US101 Highway (Collected during the time period of 8:20-8:35AM for a total of 1,323 complete vehicle tracks, of which, 1293 were car tracks, 26 were truck tracks, 4 were motorcycle tracks)

For our research project, as it is shown in Figure 4, data acquisition was carried out on the U.S. Highway 101 (a north–south highway that traverses the states of California, Oregon, and Washington on the West Coast of the United States.), with a focus on the time interval between 8:20 and 8:35 AM. This process yielded a comprehensive dataset that comprised 1,323 distinct vehicle trajectories, segmented into 1,293 car trajectories, 26 truck trajectories, and 4 motorcycle trajectories. Given the disproportionately small number of non-car trajectories, our analysis is exclusively concentrated on car trajectories, as the limited data on trucks and motorcycles do not suffice for a robust categorization within the scope of our study. This selective focus enables a more detailed and accurate exploration of car driving patterns, essential for the objectives of this research.

Rich of this empirical data, we proceed to design a stochastic model for car behavior. First, we determine which variables have a significant impact on the modeling of traffic flow by analyzing correlation coefficients. The correlation coefficient, represented by r, quantifies the degree and direction of a linear relationship between two variables. The formula for the Pearson correlation coefficient is shown as:

$$r = \frac{\sum(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum(x_i - \overline{x})^2 \sum(y_i - \overline{y})^2}}$$

where x_i and y_i are the individual sample points indexed with i.

The heatmap illustrated in **Figure 5** represents a covariance matrix that represents the extent of co-variation among pairs of variables related to vehicle dynamics, as derived from data collected on the US101 freeway.[6] The color spectrum within the heatmap, where red hues signify positive correlations and blue hues denote negative correlations, visually encodes the strength of these relationships. Values approaching 1 or -1 indicate strong positive or negative correlations, respectively, while values near 0 suggest a minimal linear relationship between the variables. One can infer from the analysis of the covariance matrix that there is a significant direct correlation between the average velocity (Mean_Velocity) of vehicles and their maximum velocity (Max_Velocity). Additionally, a substantial inverse correlation is noted between the minimum time headway (Min_Time_Hdwy) and the maximum velocity (Max_Vel). This relationship suggests that vehicles operating at higher speeds generally maintain greater time headways. Furthermore, the data reveals a pronounced negative association between the mean time headway (Mean_Time_Hdwy) and the mean velocity (Mean_Velocity), underscoring the dynamic interplay between speed and spacing on the freeway.

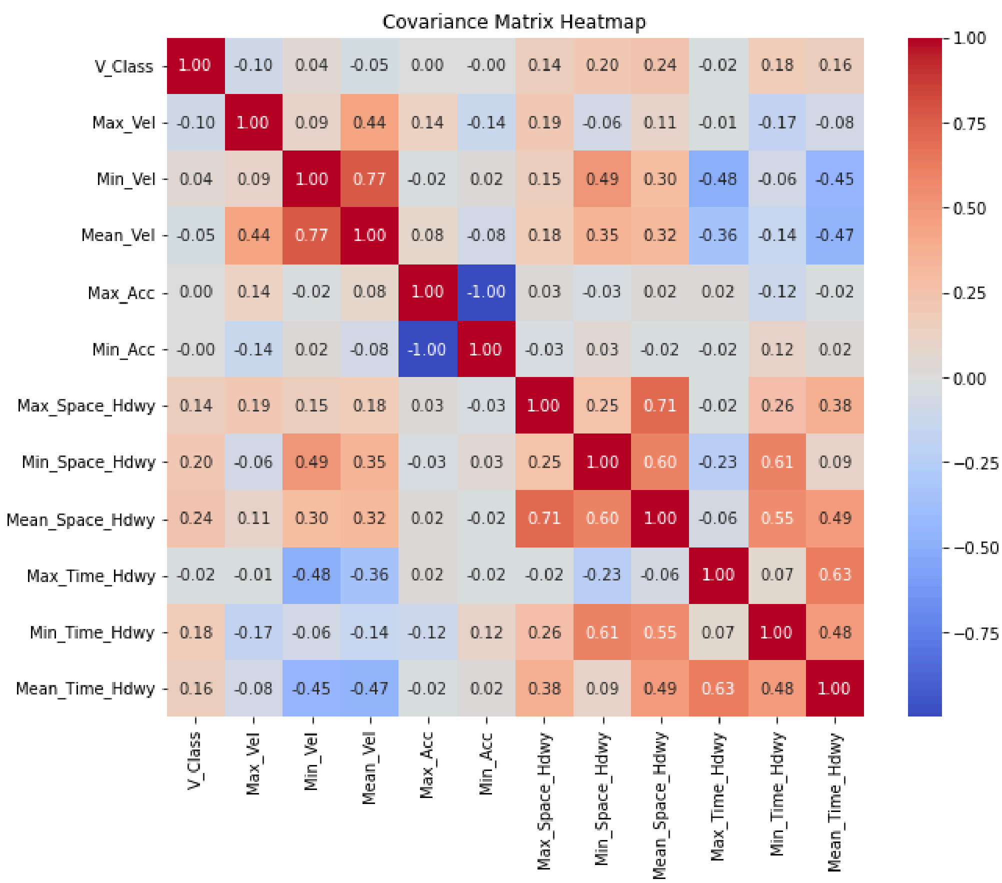

Figure 5: Covariance Matrix Heatmap Illustrating the Interrelationships Among Vehicle Dynamic Parameters on US101 Freeway During Morning Peak Hours

Figure 6 provides a comprehensive analysis of vehicle velocity distributions. The mean vehicular speeds are graphically represented through a green curve, which closely approximates a Gaussian distribution, centered around 25 miles per hour. This central tendency suggests that the average velocity observed across vehicles predominantly stabilizes at this value. Such a distribution implies a typical flow condition under normal traffic states. In contrast, the minimum velocities, depicted in red, exhibit a distribution that is markedly skewed towards lower velocities. The density curve peaks near zero, indicating a frequent occurrence of very low speeds, which might be reflective of congestive traffic conditions or idling vehicles. On the other hand, the maximum velocity distribution, illustrated in blue, appears to follow a Gaussian shape but with a peak around 45 miles per hour. This distribution suggests that higher velocities are not uncommon but are bounded, likely due to traffic regulations or road conditions that limit maximum speed.

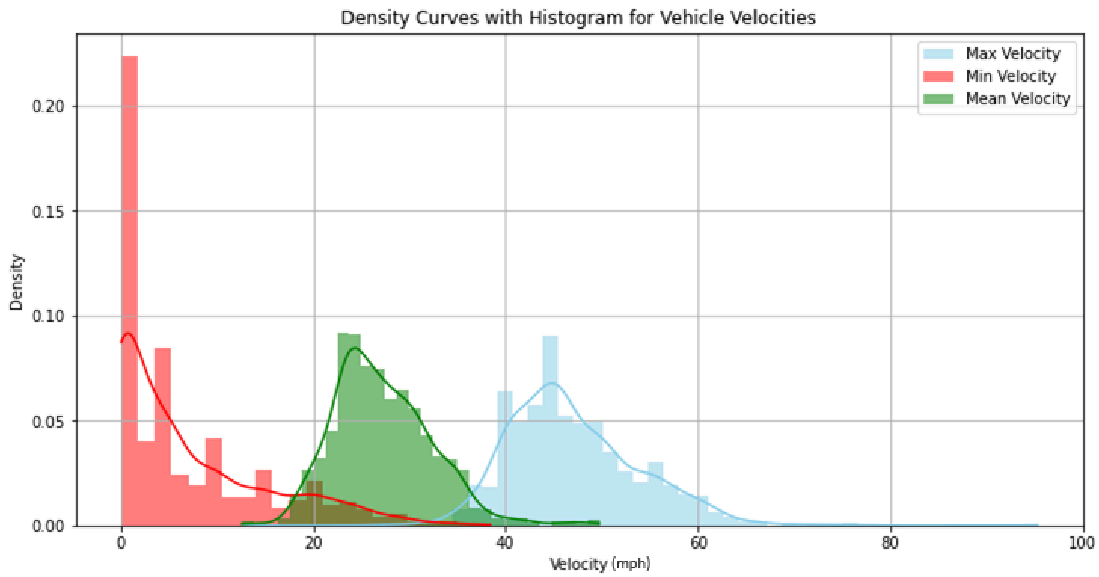

Figure 6: Comparative Density Distribution of Maximum, Minimum, and Mean Vehicle Velocities on a Freeway

Figure 7 depicts the density and frequency distributions of minimum and mean time headways in freeway traffic, with the x-axis specifying the time headway in seconds and the y-axis denoting the density. Time headway is a critical concept in traffic engineering, defined as the time interval between two consecutive vehicles as they pass a fixed point on a roadway. Mathematically, it can be expressed as:

$$TH = \frac{T_{n+1} - T_n}{1}$$

where

- TH is the time headway,
- T_{n+1} is the timestamp when the following vehicle passes the reference point
- T_n is the timestamp when the leading vehicle passes the same point.

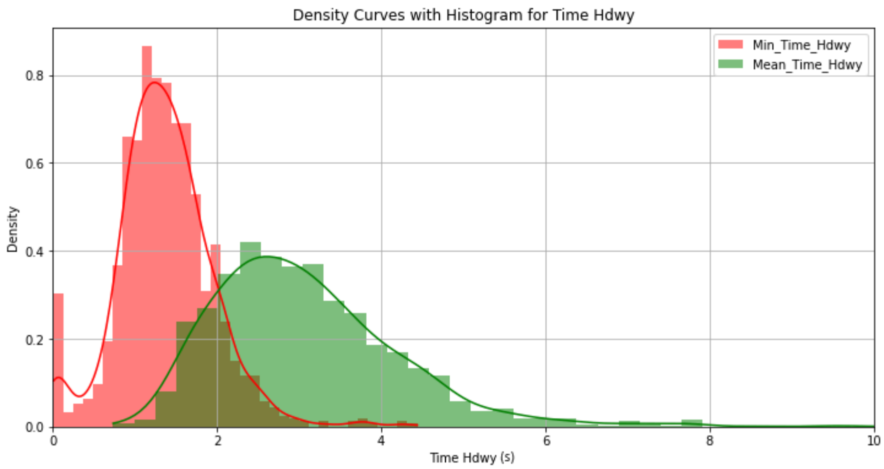

Figure 7: Distribution Analysis of Minimum and Mean Time Headways on Freeway Traffic Conditions

This metric is essential for assessing traffic flow and density, and is particularly useful for determining roadway capacity, designing signal timings, and evaluating the performance of transportation systems. A shorter time headway implies higher traffic density and possibly congested conditions, while a longer time headway indicates lower density, which may correspond to free-flowing traffic. Understanding the distribution of time headways across a network can help traffic engineers and planners optimize traffic movement and enhance road safety [19].

The analysis of the time headway distributions[23] within vehicular traffic reveals distinctive patterns. The mean time headway distribution (depicted in green) exhibits a Gaussian-like profile with an apex at around 2.5 seconds. This infers that, on an average scale, the temporal distance between vehicles is typically around 2.5 seconds, with the likelihood diminishing for larger headway intervals. In contrast, the minimum time headway data (represented in red) predominantly congregates at the lower end of the spectrum, indicating a preponderance of instances where vehicles follow each other at minimal temporal gaps. This characteristic is symptomatic of dense traffic where brief headways are common, perhaps indicative of congested driving conditions or aggressive driving behavior. From the above analysis, we find that traffic flow dynamics can be modeled through a bi-variate Gaussian distribution framework, which incorporates a quartet of pivotal variables: Maximum Velocity, Mean Velocity, Minimum Time, and Mean Time Headway.

$$f(\mathbf{\Sigma}, \mu, \quad) = \frac{1}{(2\pi)^2 \, |\, \mathbf{\Sigma} \,|^{1/2}} \exp\left(-\frac{1}{2}(\quad - \mu)^T \quad {}^{-1}(\quad - \mu) \right)$$

$$\Sigma = \begin{bmatrix} 47.368302 & 15.706657 & -0.682055 & -0.643502 \\ 15.706657 & 26.809399 & -0.429600 & -2.839082 \\ -0.682055 & -0.429600 & 0.340115 & 0.331012 \\ -0.643502 & -2.839082 & 0.331012 & 1.378618 \end{bmatrix}$$

$$\mu = \begin{bmatrix} 47.001988 \\ 27.229243 \\ 1.374084 \\ 3.092426 \end{bmatrix}$$

where:

- **x** is a 4-dimensional column vector representing the variable of interest.
- μ is a 4-dimensional column vector representing the mean of the distribution.
- Σ is a 4×4 covariance matrix that characterizes the spread and the correlation of the variables in the distribution.
- $|\Sigma|$ is the determinant of the covariance matrix Σ.

This statistical approach enables the encapsulation of both the extremities and the central tendencies of vehicular movements and temporal spacing on thoroughfares.

2.2.2 Basic Traffic Rules

In modeling vehicular behavior within a simulated traffic environment, five fundamental principles are postulated:

a) Vehicle attributes are determined through a stochastic process that involves random sampling from a Gaussian distribution, providing a foundational basis for individual vehicle characteristics.

b) The algorithm governing each vehicle stipulates that it should operate at the highest possible velocity, in adherence to prevailing traffic conditions and within the constraints of safety regulations.

c) Continuous environmental scanning is mandated for each vehicle during every frame of simulation. Should the presence of an obstacle or the signal of a red traffic light be detected, the vehicle is required to decelerate.

d) In instances where the velocity of a preceding vehicle is lower than that of the following vehicle, the latter is programmed to maintain its course for a predefined number of frames, subsequent to which it will execute a lane change to facilitate overtaking.

e) Upon the occurrence of a collision, the implicated vehicle is programmed to be virtually eliminated from the simulation after the lapse of a specified number of frames, thus simulating the aftermath of an accident.

These rules aim to replicate realistic traffic flow and vehicle interactions, enhancing the authenticity of the traffic simulation.

3. ANALYSIS AND RESULTS

3.1. Traffic Flow Simulation on Unity Driving Simulator Platform

In the context of our research, we applied our software to validate its effectiveness in real-world scenarios by undertaking a quick streetscape modeling project on Roosevelt Boulevard, PA, as detailed in Figure 8 (a). This specific application involved the integration of a bus lane into the existing infrastructure of Roosevelt Boulevard. Traditionally, such an integration would require extensive time commitments and resources due to the complexities associated with modifying urban roadways. However, the utilization of our innovative software significantly expedited this process. The proposed addition of a bus lane, illustrated in Figure 8 (b), was executed to demonstrate the software's capability in swiftly adapting roadway plans to include additional transportation modalities. This feature of the software is particularly critical in urban planning and civil engineering, where rapid prototyping of traffic scenarios and infrastructural changes is essential for effective decision-making and planning.

Our software's ability to rapidly model and integrate a bus lane into the existing roadway system of Roosevelt Boulevard showcases its potential as a transformative tool in urban transportation planning. It facilitates a more dynamic and responsive approach to urban design, where modifications can be implemented and assessed in real-time, significantly reducing the turnaround time traditionally associated with such projects. This capability not only enhances the efficiency of urban planning processes but also contributes to more sustainable and adaptable urban environments.

(a) Without Bus lane **(b) With Bus lane**

Figure 8: A quick streetscape modeling of Roosevelt Blvd; (b) a hypothetical scenario of adding a bus lane

3.2. Traffic Flow Algorithm Tuning

For our research project, we employed a Unity-based simulation environment for the rigorous evaluation of our traffic flow generation algorithm. The Unity 3D game engine offers solid rendering capabilities, comprehensive physics modeling, and proficiency in real-time 3D simulations. This platform was deliberately chosen for its high fidelity in mimicking real-world traffic scenarios, thereby providing a robust framework for our experiments.

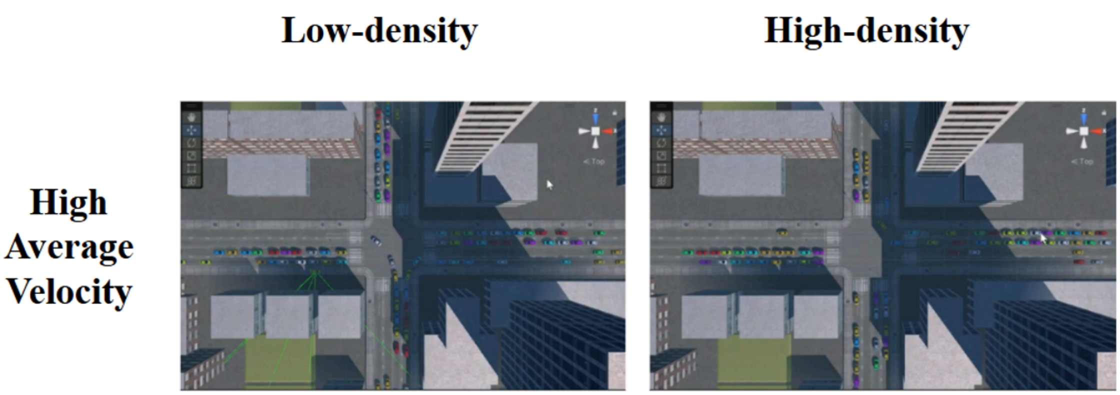

Figure 9: Comparative Visualization of Traffic Flow Density and Average Velocity in a Unity-Based Simulation

Figure 9 serves as a visual representation of our experimental setup. Within this framework, we systematically altered the parameters pertaining to vehicular speeds and traffic flow densities. These modifications allowed us to assess the adaptability and resilience of the traffic flow generation algorithm across a spectrum of traffic conditions.

The results of these tests, graphically depicted in Figure 9, provide a visual illustration of the algorithm's performance. They highlight the algorithm's capability to generate realistic and dynamically varied traffic patterns. The outcomes not only corroborate the algorithm's operational effectiveness but also highlight its precision in simulating an array of traffic conditions with notable accuracy. The ensuing figure succinctly encapsulates these findings, affirming the algorithm's proficiency in replicating diverse traffic scenarios within the simulated environment, thereby underscoring its potential utility in real-world applications.

4. DISCUSSION

This paper describes the development and application of a novel pipeline for constructing a drivable Digital Twin (DT) for Philadelphia's Roosevelt Boulevard. Utilizing advanced geospatial imagery and a combination of urban planning tools, including CityEngine and RoadRunner, integrated with tile maps from Google Maps and data from OpenStreetMap, we have successfully demonstrated a methodology that accelerates the modification of urban landscapes in digital environments. This is particularly evident from the rapid integration of a bus lane into the existing roadway system, a task that traditionally involves considerable time and resource commitments.

Our approach has significant implications for urban planning and traffic management, especially in addressing the challenges associated with urban traffic flow and safety. Roosevelt Boulevard, known for its hazardous traffic conditions, served as an ideal case study for applying our DT workflow. The ability to quickly iterate and simulate various traffic scenarios can lead to better-informed decisions in urban development and infrastructural modifications, potentially reducing traffic fatalities and improving road safety. Moreover, the use of Unity for simulating traffic dynamics provided a robust platform for testing and validating our traffic models against realistic traffic conditions. This facilitated not only the visualization of traffic patterns but also the assessment of potential interventions in a controlled virtual environment. The simulation results highlighted the effectiveness of the traffic flow model in replicating diverse traffic conditions, thereby offering a promising tool for traffic engineers and planners. The implications of our study extend beyond traffic management. The methodology employed can serve as a blueprint for other cities aiming to enhance their transportation systems or to test infrastructure changes before implementation. Additionally, the flexibility and scalability of the DT approach mean that it can be adapted to various urban and traffic conditions, making it a versatile tool in the broader field of urban planning.

The computational aspects are an important part of the simulation. All objects in the simulation are represented by polygons and the number and complexity of these polygons can limit the performance of the simulation. The resolution of the Digital Twin and numbers of actors such as pedestrians, bicycles and vehicles can quickly add to the complexity. This can result in lower frame rates. To ensure a seamless experience, it is crucial that the simulation maintains a consistent frame rate above 60 frames per second (FPS).This can be accomplished by using a Level of Detail (LOD) technique [24]. In this framework, the detail and complexity of objects are decreased as the distance between the object and viewer increases.

A growing body of work documents the interest in Digital Twins of cities for urban work [25] but also for traffic research [25, 26]. Our work aims at facilitating the design of arteries to optimize traffic flow and ultimately, safety [27, 28, 29].

Despite the advancements demonstrated in this study, there are limitations that must be acknowledged. One significant limitation is the reliance on available geospatial and traffic flow data, which may not always be updated or comprehensive enough to capture the complex dynamics of a real world environment. Additionally, the computational demand of simulating detailed traffic scenarios at high fidelity remains a challenge, particularly when scaling up to larger urban areas. Moreover, while the Unity platform provides robust capabilities for traffic simulation, the current traffic models still rely on approximations and may not fully capture the unpredictability of human driving behaviors. Further refinement of the traffic models is required to enhance their predictive accuracy and realism. Future research will focus on several key areas to address these limitations:

(1) Data Integration: We plan to incorporate real-time data feeds into our simulations to enhance the responsiveness and accuracy of our traffic models. This includes live traffic updates, weather conditions, and other dynamic factors affecting traffic flow.

(2) Model Complexity: Efforts will be made to develop more sophisticated traffic models that better

mimic human driving behaviors and interactions. This involves the integration of machine learning techniques to predict and simulate more complex traffic scenarios.
(3) Multi-Modal Transportation: Future studies will include the modeling of multi-modal transportation systems within the DT to reflect the increasing diversity in urban mobility solutions, such as public transit, cycling, and pedestrian pathways.

"A second limitation derives from the different road networks used for traffic modeling and road modeling. While our traffic flow is calibrated for the NGSIM dataset which is based on US Highway 101, our 3D model represents the Roosevelt Boulevard in Philadelphia. We anticipate reconciling this gap in a second phase of the project, as we will be re-calibrating our traffic flow model after an analysis of the data stream from 10 speed cameras that were recently installed on the Philadelphia Roosevelt Boulevard [21]."

5. CONCLUSION

In conclusion, the development of a drivable Digital Twin using our proposed pipeline represents a significant advancement in the field of urban planning and traffic simulation. By enabling rapid and accurate modeling of urban traffic scenarios, our approach aids in the efficient planning and safe management of urban roadways. As we move forward, the integration of more dynamic data sources and advanced modeling techniques will further enhance the utility and accuracy of digital twins, paving the way for their broader adoption in urban development and traffic management initiatives.

ACKNOWLEDGEMENTS

This work was funded, in part, by a grant from Safety21, University Transportation Center at Carnegie Mellon University, through the University of Pennsylvania which provided support through the US Department of Transportation (USDOT). The Department specifically disclaims responsibility for any analyses, interpretations or conclusions. The content is solely the responsibility of the authors and does not necessarily represent the official views of the US DOT.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Helen Loeb, Xiaoxia Dong, Rahul Mangharam, Erick Guerra; data collection: Rajnish Gupta, Ramon Diaz; analysis and interpretation of results: Rajnish Gupta, Ramon Diaz; draft manuscript preparation: Helen Loeb. All authors reviewed the results and approved the final version of the manuscript.

DECLARATION OF CONFLICT OF INTERESTS

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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