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Project 581: StreetSavvi: Complete Street AI Companion for Digital Twin Driving

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1. Project Overview

The StreetSavvi project is an effort to bring the power of AI, Digital Twin technology, advanced simulation and visualization to provide stakeholders with a powerful tool for urban development.

In an ever-increasing Digital Age, the US DOT has put great effort into developing a large number of databases that encompass infrastructure, travel behavior and safety, and context as a way to answer the formidable challenge of moving people and goods in a safe and efficient way. Interestingly, commercial satellite and street imagery such as those produced by Google and other geospatial data providers emerge as an opportunity for an up-to-date inventory of transportation infrastructure. In addition, the acceleration of Artificial Intelligence through Machine Learning and its inference processes for data processing or the Large Language Models generative processes offer phenomenal opportunities to take a global approach to the field of transportation.

In this context, StreetSavvi, an advanced Digital Twin development platform, applies AI computer vision processes to geospatial data, namely satellite imagery, street imagery, and camera data, to develop photorealistic 3D models of neighborhoods and develop a scalable, efficient, and user-centric digital twin platform for urban transportation planning.

This project expands on the installation of speed cameras on the Roosevelt Blvd. Simulation and visualization tools allow the research team to partner with local stakeholders to assess the impact of various designs on multiple metrics such as traffic congestion, safety, cost… The StreetSavii framework provides a friendly AI based user interface for ideation to help with street design.

2. The AI paradigm shift for transportation

2.1 AI for infrastructure mapping

In 2014, the US DOT launched the Complete Streets AI initiative through its Small Business Innovation Research (SBIR) Program. The initiative aimed at developing decision-support tools for state, local, and tribal transportation agencies to help with siting, design, and deployment of Complete Streets. AI is a good fit here for a few specific, practical reasons tied to the nature of the problem: The data exists, but it's unstructured and enormous in volume**.** Cities already generate huge amounts of raw visual and sensor data — dashcam footage, satellite/aerial imagery, street-level video, IoT feeds. A human team manually reviewing footage to count pedestrians or catalog every sidewalk gap would take years and be prohibitively expensive. Computer vision and machine learning can process that volume automatically, turning raw video into structured data (sidewalk present/absent, bike lane type, pedestrian counts) at a fraction of the time and cost.

2.2 AI for vehicle navigation

Interestingly the databases generated for geographic infrastructure can play a prominent role in vehicle navigation by transforming static, map-based routing into a dynamic, context-aware system. Traditional GPS navigation relies on fixed road networks and basic distance/speed calculations, but AI-enhanced navigation ingests real-time data streams — traffic sensor feeds, historical congestion patterns, weather conditions, road incidents, and even crowdsourced driver behavior — to continuously recalculate optimal routes as conditions change. Computer vision further extends this capability at the vehicle level: cameras and sensors feed AI systems that detect lane markings, road signs, pedestrians, cyclists, and obstacles in real time, enabling advanced driver-assistance systems (ADAS) and, in more advanced implementations, autonomous or semi-autonomous navigation. The result is navigation systems that are not just about getting from point A to point B, but about doing so more safely and efficiently by anticipating road conditions, accounting for infrastructure quality (like the presence or absence of bike lanes or sidewalks), and adapting in real time — with the same caveat that model accuracy depends heavily on the quality and diversity of the underlying training and sensor data.

2.3 AI for driver education

Leveraging the AI infrastructure representation as well as automatic navigation can bring about powerful tools for education. While self-driving vehicles were announced for 2020, we are still a decade away from full deployment. In addition, it is largely anticipated that vehicle driven manually will coexist for years with self-driving vehicles making driving education an even more critical aspect of a safe deployment.

AI driven simulators can generate varied, realistic scenarios based on real-world traffic and incident data, rather than relying on fixed scripted routes. Computer vision can assess a student's performance in real time — tracking things like mirror checks, reaction time, and following distance — for objective feedback. Machine learning can also personalize training by identifying a student's specific weak points and adjusting future scenarios to target them, while incorporating more accurate infrastructure (bike lanes, crosswalks, mixed-use streets) so students practice on realistic, modern road conditions rather than idealized ones.

3. StreetSavvi - Digital Twin tool for urban development

3.1 Digital Twin framework

The foundation of our work requires a high-quality 3D model for the digital twin, ensuring accurate spatial representation. 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. Our methods, which were applied to the Roosevelt Blvd in Philadelphia, are thoroughly described in the TRR publication, (Loeb, H., Hernandez, J., Gupta, R., Diaz, R., Dong, X., Mangharam, R., & Guerra, E. (2026). Digital Twin of the Philadelphia's Roosevelt Boulevard: Microsimulation Based on Real-Life Traffic. *Transportation research record*, 03611981251398753.). The pipeline for Digital Twin creation can be summarized through the following diagram:
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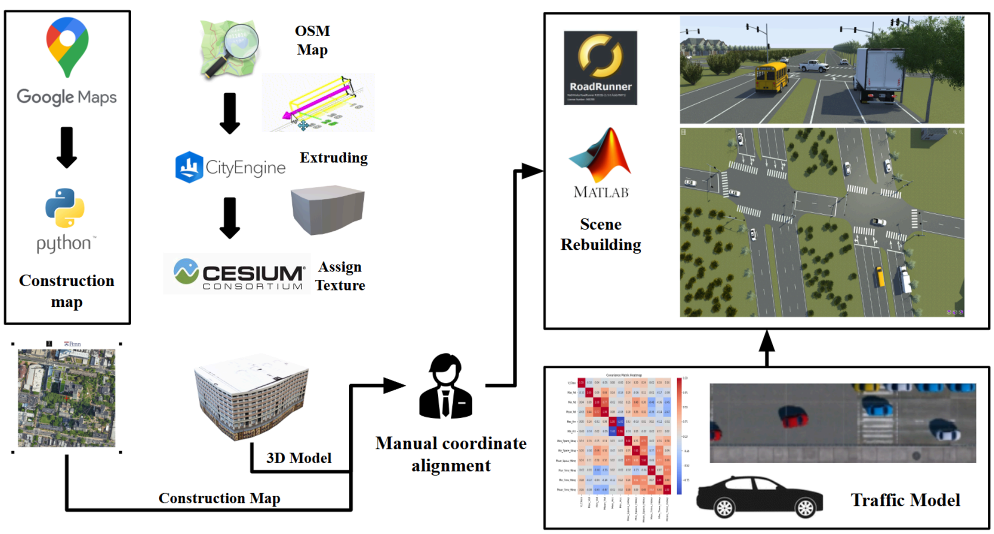


In the first stage of the methodology, high-resolution tile maps of the target neighborhood are acquired through Google Maps' ping services. These maps serve as a foundational dataset, which is then processed using a custom Python script designed to enhance resolution and clarify structural details, 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.

3.2 StreetSavvi application to the Philadelphia Roosevelt Blvd

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**

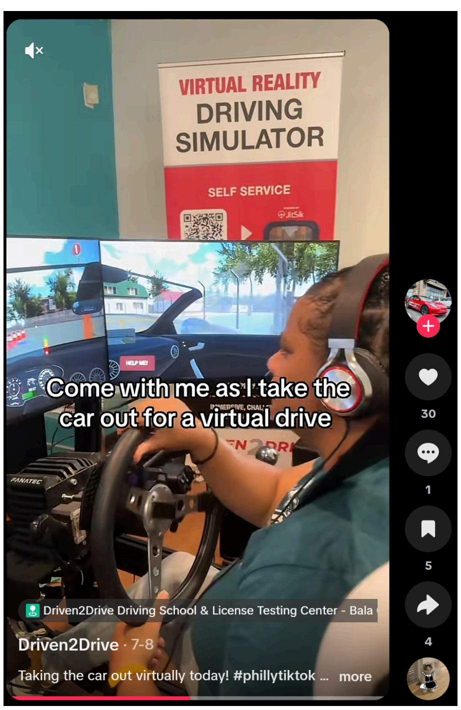
4. Digital Twin Driving

4.1 Immersive simulator for education

Driving simulation has increasingly been recognized as a promising tool for training in domains that involve complex, dynamic, and safety-critical tasks. However, despite its potential advantages, simulation has scarcely been adopted in educational settings. Earlier generations of driving simulators have faced limitations in realism, motion fidelity, and user immersion, which reduced confidence in their effectiveness as learning tools. Nevertheless, recent advances in computing power, graphics rendering, and Virtual and Mixed Reality interactivity have significantly improved the value of driving simulators. Our line of researched has permitted the development of two driving simulators: a full cab indoor Virtual Reality Driving Simulator and an In-Vehicle Virtual Reality Driving Simulator. These two simulators, the hardware choices involved and the development process were documented in the paper attached in addendum. (Loeb, H., Smagulova, A., Rosenberg, M., De La Pena, E., Sniegs, O., Virtual Reality Driving Simulator for Education - Form Factor, Cybersickness and Perception, Proceedings of DSC2026, 25th Driving Simulation Conference and Exhibition, Antibes, France, September 16-18 2026). This paper will be presented in Antibes in September 2026.

4.2 Deployment

With the support of Safety21 through its Year 3 of funding, much effort was dedicated to the deployment of our Mixed Reality Driving simulators. Thus far, our simulators have been deployed at 1) Community Independence Solutions of San Antonio, an Occupational Therapy Practice aimed toward assisting individuals of all ages and abilities to achieve safe & independent mobility via specialized evaluation, driver training, as well as providing driving alternatives. 2) The Bala Cynmyd location of Driven2Drive, a premier driving school and certified driving license center in the Philadelphia neighborhood, 3) the Automotive Technology Career Center of the Community College of Philadelphia.

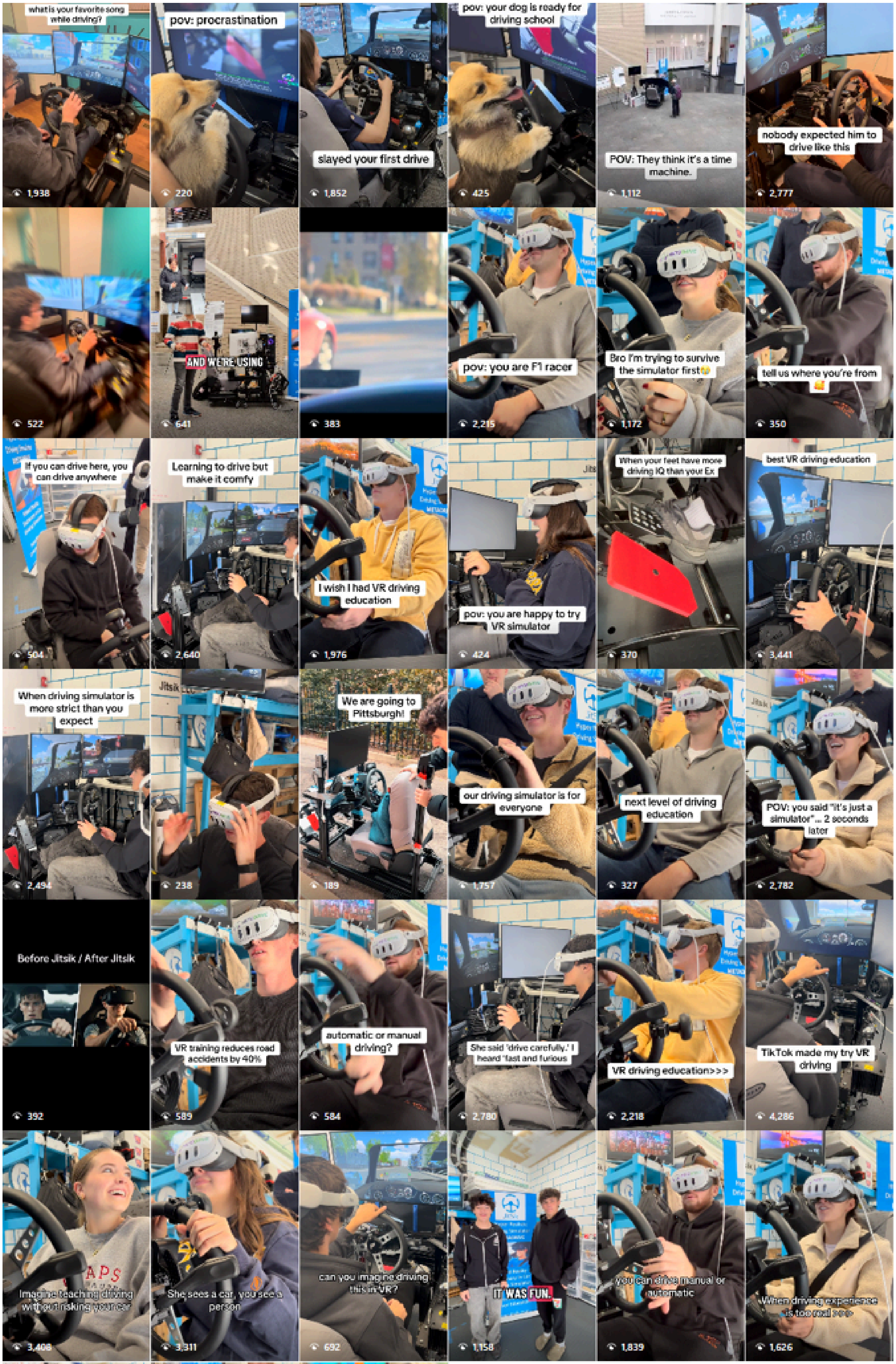


In addition, our simulators were exhibited at the 2025 ADED conference in Columbus Ohio (Association for Driver Rehabilitation Specialists).

4.3 Challenges

Our driving simulator has been leveraged by students from the The Anxiety and Agoraphobia Treatment Center at the Bala Cynwyd location of Driven2Drive, and has benefitted students with diagnosed driving anxiety. In addition, a social media campaign based on TikTok and Instagram has been developed to promote the simulator to novice students.

StreetSavvi: Complete Street AI Companion for Digital Twin Driving



While each post reached thousands of viewers, the need to be physically at the driving school venue has limited the impact of the technology. A proposed strategy for a larger deployment, could be the use of a personal vehicle for simulation. To that effect a kickstarter campaign was initiated to assess community needs and cost considerations.

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- Loeb, H., Hernandez, J., Gupta, R., Diaz, R., Dong, X., Mangharam, R., & Guerra, E. (2026). Digital Twin of the Philadelphia's Roosevelt Boulevard: Microsimulation Based on Real-Life Traffic. *Transportation research record*, 03611981251398753.
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- Oskars Sniegs, CEO MetoDrive
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Addendum TRR 2026 paper

Loeb, H., Hernandez, J., Gupta, R., Diaz, R., Dong, X., Mangharam, R., & Guerra, E. (2026). Digital Twin of the Philadelphia's Roosevelt Boulevard: Microsimulation Based on Real-Life Traffic. *Transportation research record*, 03611981251398753.

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

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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.

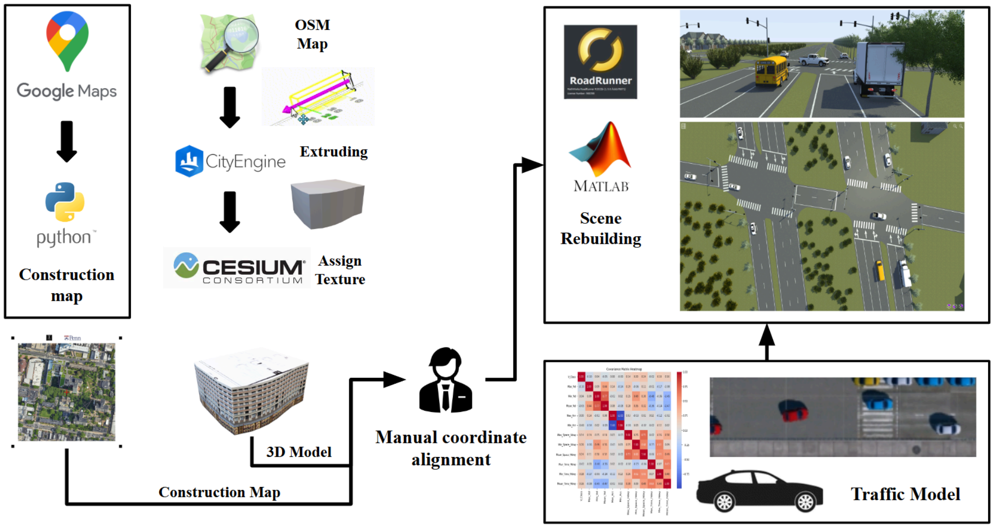

Figure 1: Pipeline for Developing Digital Twin.

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.

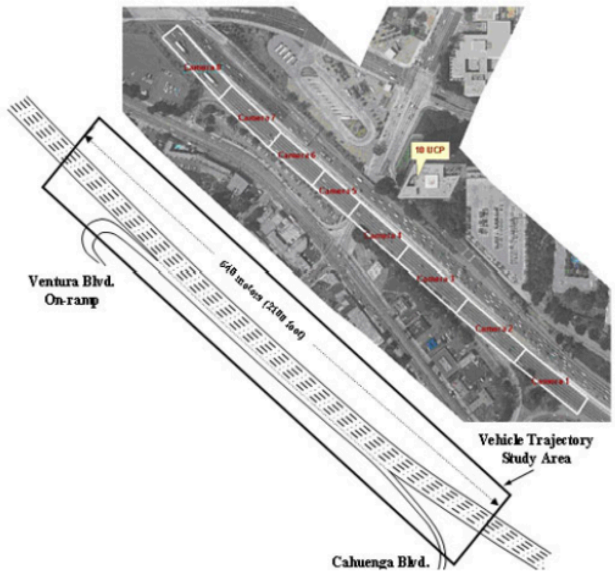

Figure 4a: Bird's eye view of the US101 Highway;

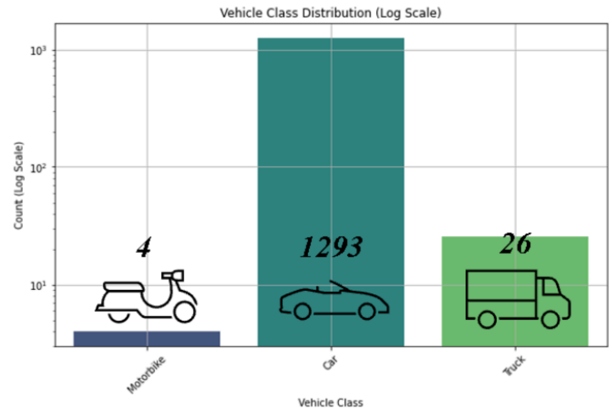

Figure 4b: Data from US101 Highway (Collected during the time period of 8:20-8:35AM for a total of 1,323 complete vehicle tracks, of which, 1293 were car tracks, 26 were truck tracks, 4 were motorcycle tracks)

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 *xi* and *yi* 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.

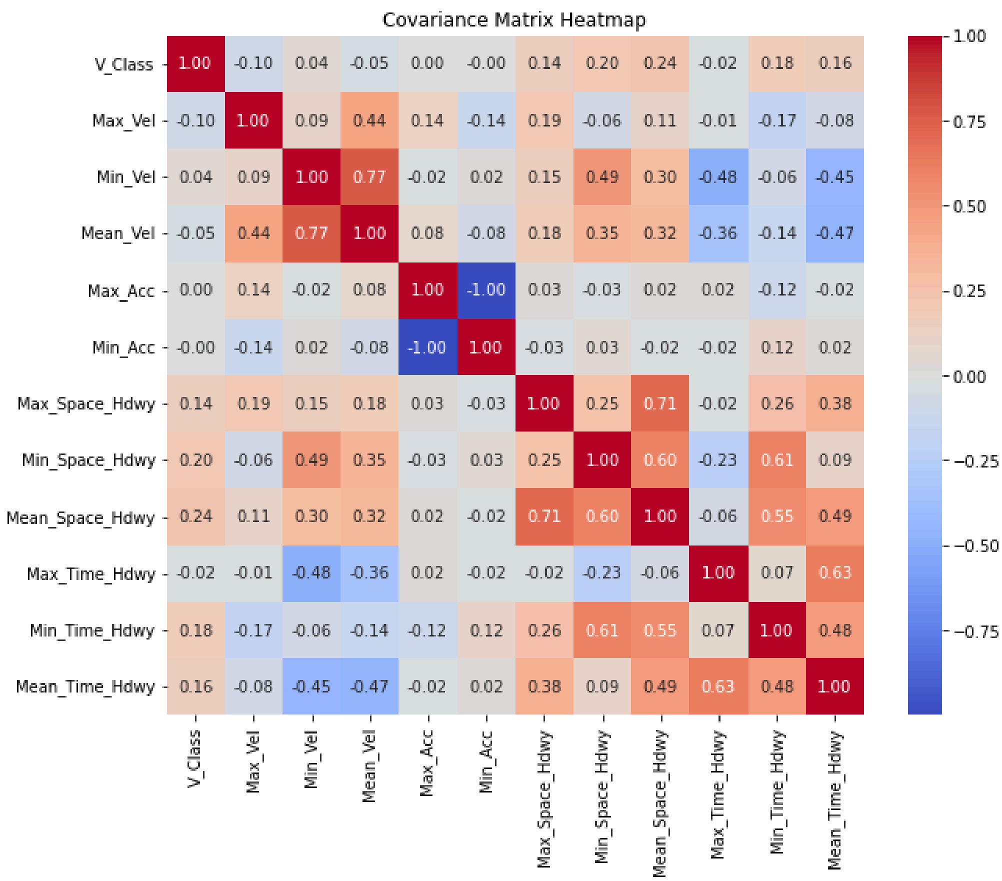

Figure 5: Covariance Matrix Heatmap Illustrating the Interrelationships Among Vehicle Dynamic Parameters on US101 Freeway During Morning Peak Hours

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.

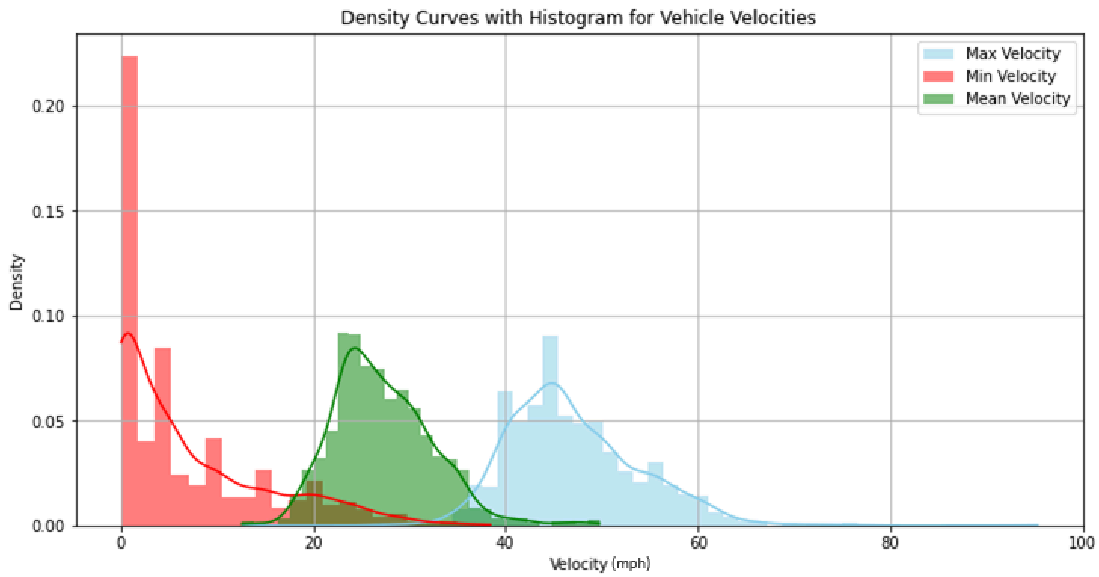

Figure 6: Comparative Density Distribution of Maximum, Minimum, and Mean Vehicle Velocities on a Freeway

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.

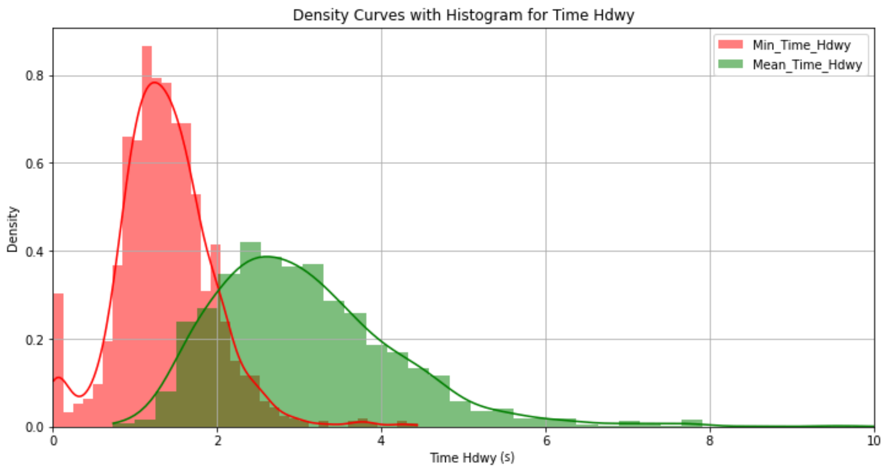

Figure 7: Distribution Analysis of Minimum and Mean Time Headways on Freeway Traffic Conditions

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:

- $\mathbf{x}$ 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.

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.

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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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Addendum DSC2026 paper

Loeb, H., Smagulova, A., Rosenberg, M., De La Pena, E., Sniegs, O., Virtual Reality Driving Simulator for Education - Form Factor, Cybersickness and Perception, Proceedings of DSC2026, 25th Driving Simulation Conference and Exhibition, Antibes, France, September 16-18 2026.

Virtual Reality Driving Simulator for Education - Form Factor, Cybersickness and Perception

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Abstract *– Driving simulation has increasingly been recognized as a promising tool for training in domains that involve complex, dynamic, and safety-critical tasks. However, despite its potential advantages, simulation has scarcely been adopted in educational settings. Earlier generations of driving simulators have faced limitations in realism, motion fidelity, and user immersion, which reduced confidence in their effectiveness as learning tools. Nevertheless, recent advances in computing power, graphics rendering, and Virtual and Mixed Reality interactivity have significantly improved the value of driving simulators. In this work, we compare the perceived value of two driving simulators: a full cab indoor Virtual Reality Driving Simulator and an In-Vehicle Virtual Reality Driving Simulator. A cohort of 418 study participants were exposed to challenging driving scenarios. The results showed that the cybersickness and withdrawal rate remained low (12%) and did not depend on the simulator form factor. In addition, among participants who rated the experience, the large majority (72%) considered it very positive (Awesome or Great). This paper described the technology developed and details the results of the Human Study.*

Keywords: *Driving Simulation, Virtual Reality, Mixed Reality, Driver's Education.*

Introduction

A brief history of driving simulation

Each technology breakthrough brings a wealth of development. This is true for driving education. Over the years, various technology breakthroughs have led to various driving simulators (see Table 1).

Table 1: Driving Simulator Generations

Era and Simulator Type	Technology	Key Outcome
Mechanical 1920-1950	Levers and pulleys	Procedural memory (shifting/steering). Muscle memory training
Film-Based 1960-1980	16 mm or LaserDisk	Hazard perception (watching, not doing).

CGI 1990-2010	3D Graphics/Monitors	Interactive decision-making.
VR/MR 2015- Present	Headsets & Haptics	Full sensory immersion; mandatory in some regions.

The early days: Drivotrainer

The very first driving simulator can be traced to analog computers. The **Drivotrainer**, developed in 1951 by Aetna, was completely analog and worked like a synchronized training system reacting to a movie projected to students on a screen (Los Angeles City School District, 1955). It showed real traffic situations and taught students the basics of operating a car in a safe, controlled environment. Widely used in American schools during the mid twentieth century, the Drivotrainer helped standardize driver education. Despite its obvious limitations, the Drivotrainer became a common teaching tool in U.S. high schools from the 1950s through the 1970s. It however became quickly obsolete as the new generation of computers appeared.

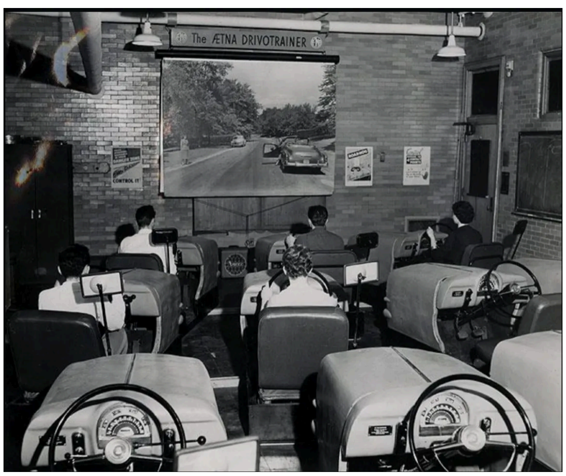

Figure 1: 1951 Aetna Drivotrainer

The advent of digital computers

Digital computers were a game changer in the field. Powerful processors could model vehicle dynamics, road conditions and traffic behaviours. High end graphic processors allowed for realistic, interactive environments for training, research, and entertainment. These systems, which have been widely adopted by auto manufacturers for research and development, became a useful tool in universities for Human Factors research. Still, the need for a 180 Field of View often meant the need for 3 monitors. While some high schools successfully used these systems, driving schools still see them as bulky and not realistic enough so that their use by driving students has so far been limited.

Perception of driving simulators by licensing agencies

Across the world

Driving simulators have seen a lot of development over time and so has their perception. As the level of realism increased and hardware costs decreased, simulators have increasingly become a valuable way to train and test driving students as they provide a safe, repeatable, objective environment for testing (Loeb, et al., 2024, Siyu Wu et al., 2025). Various countries have taken note and are adding simulator training and assessment to the licensing process. In Singapore, simulator training became mandatory in 2019 as a way to improve hazard perception. Students must complete 3 simulator modules before on road driving lessons. In India, new rules in 2024 allowed accredited schools to issue certificates instead of the traditional road test, showing how simulation can support licensing reform. France uses simulators in a hybrid way, both to reduce training costs and to help with license conversion from automatic to manual transmission. Since 2019, up to 10 hours of the required 20 for taking a driving test can be driven on a simulator. In the UK, simulators are used to train driving instructors, especially for managing stressful teaching situations. In Japan, simulators are used in a more standardized way, including training for traffic offenders and assessments for older drivers.

Table 2: Driving simulators across the world

Country	Year	Regulatory Milestone	Primary Use Case
Singapore	**2019**	**Mandatory:** The Traffic Police made it compulsory for all Class 2 and 3 learners to complete 3 simulator modules before the practical test.	Hazard perception for the top 10 accident causes (wet weather, cyclists).

India	**2024**	**Substitutive:** Ministry of Road Transport rules now allow certificates from accredited private schools to replace the RTO road test.	Modernizing licensing and reducing RTO congestion/ corruption.
France	**2019 / 2024**	**Hybrid:** In 2019, hours were increased; as of March 2024, up to 2 of the 7 hours for "automatic to manual" conversion can be on a simulator.	Lowering the cost of the license and streamlining transmission training.
UK	**2020 / 2022**	**Professional:** The AA and BSM launched VR-integrated instructor courses in 2020, cutting training time from 5 months to 3.	Training driving instructors on how to manage high-stress classroom environments.
Japan	**2010 / 2022**	**Standardized:** Honda began mass sales of safety simulators in 2010; in 2022, Japan led the creation of ISO 23019 for simulator standards.	Mandatory "Special Lessons" for traffic offenders and elderly driver assessments.

The State of Ohio Ready Set Drive Virtual Driving Assessment

In 2012, a research program developed at the Children Hospital of Philadelphia identified the most common crash scenarios through the National Motor Vehicle Crash Causation Survey, a nationally representative study of serious crashes conducted by the U.S. National Highway Traffic Safety Administration. The results indicated that the top five crash scenarios among teen drivers, accounting for 37.3% of their crashes, included: (1) going straight, other vehicle stopped, rear end; (2) stopped in traffic lane, turning left at intersection, turn into path of other vehicle; (3) negotiating curve, off right edge of road, right roadside departure; (4) going straight, off right edge of road, right roadside departure; and (5) stopped in lane, turning left at intersection, turn across path of other vehicle. (McDonald, et al., 2014).

In an effort to better assess driver performance at licensing time, the *Ohio - Ready Set Drive* program was introduced in 2019 to expose students to these challenges driving scenarios in simulation. All prospective new drivers in the State of Ohio, were asked to drive a Virtual Driving Assessment (VDA) prior to their in-car driving test. The analysis linked the VDA Performance Results, Licensing records and 1-year post-licensure crash records of 16,914 young drivers under the age of 25 (Walshe, et al., 2023). By using the outcome of time to first crash, a Cox proportional hazard model was used to estimate the risk of a crash during the follow-up period as a function of VDA Driving Class and Skill Cluster. The best performing *No Issues Driving Class* had a crash risk 10% lower than average (95% confidence interval [CI] 13% to 6%), whereas the *Major Issues with Dangerous Behavior Class* had a crash risk 11% higher than average (95% CI 1% to 22%). These results validated the value of the VDA as a screening tool for training and licensure. (Shapiro, 2023)

Product Solution

Immersion through Virtual and Mixed reality

Virtual Reality headsets came about in 2016 with the successful deployment of the Oculus Rift (Abrar, et al., 2016). Users discovered a new level of immersion for a reasonable cost. This technology has been acclaimed as a powerful education tool, which is a good fit for driver’s education as it can expose young drivers to challenging driving situations in a safe way. (Mangharam, et al., 2025). This paper highlights the MetoDrive Pro and MetoDrive Real, two driving simulators that are inherently based on Virtual and Mixed Reality for scenario rendering. With this technology, users can have a 360 FOV and can be fully immersed in driving. In addition, the use of Mixed Reality lets users see their hands and feet while they drive so they stay connected with the real world at all times.

Hardware platforms

MetoDrive Pro

The MetoDrive Pro was developed to offer participants a realistic experience of driving. The mechanical Treq frame offers robust support for all electronic components. A real car seat allows for comfort and realism. The racing Fanatec system was chosen for the steering wheels and pedals component. A Meta Quest 3 Virtual reality Headset was chosen for its wide commercial success. It offers an easy entry point into Mixed Reality. Since cybersickness can be problematic for some people, the research team chose to back the VR Meta Quest display with a set of 3 monitors. Participants can easily transition between The Virtual Reality and Monitors experience. Still, some scenarios such as parallel parking are best experiences through the use of the Virtual Reality Headset.

Figure 2: MetoDrive Pro

MetoDrive Real

With the goal of maximizing immersion and replicate the feel of a car, an alternative hardware setup was developed where a real vehicle was used to build an in-car driving simulator. In this setup, a Volkswagen Golf Mk4 was retrofitted into a Virtual Reality Driving simulator. For this setup, all mechanical components (steering column and pedals) were physically removed from the actual car and replaced with the Fanatec racing system. This system is attractive as it brings the feel and look of a real vehicle, which is crucial for novice users.

Figure 3: MetoDrive Real

Software

Driving scenarios

Both the MetoDrive Pro (Stanadone) and MetoDrive Real (In-Car) leverage the same software suite. Driving scenarios were developed with Unity 3D. These scenarios feature adverse traffic, through a multitude of environments: city, suburban and highway. Bicycle and pedestrian traffic are also scripted using Visual Studio C#.

A curriculum was developed where driver students can choose one of 14 driving levels. These levels include challenging scenarios that may include other cars, pedestrians, or weather challenges (see Table 3).

Table 3: Simulator driving challenge

Challenge Type	Scenario Description
Pedestrian	Pedestrian crossing on "Zebra"
Traffic	Truck obscuring pedestrian crossing
Pedestrian	Old and slow person crossing the street
Blind spot	Lane change with traffic
Weather	Icy road

Traffic	Hidden car exiting a garage
Traffic	Left lane merge on one way road
Pedestrian	Left turn with pedestrian crossing
Pedestrian	Children running on both sides of the street

Digital Twins of real cities

The MetoDrive software suite was built with a concern for authenticity. As a way to provide for realistic driving environments, the Unity 3D digital scenes were based on real geography. Scenarios in the MetoDrive Suite are based on a the City of Riga in Latvia, and the City of San Antonio, Texas, US. These two cities were converted into a Unity 3D model through the use of OpenStreetMap, Google Maps. 3D models of actual Street Signs were replicated, which results in a realistic Digital Twin environment of actual city streets and highways. (Wu, et al., 2024)

Methodology

Human Research

Research methodology and participants

For many companies, driving is a crucial component of their employees' responsibilities. Companies often maintain fleets of vehicles and are eager to improve the driving skills of their employees so as to avoid the heavy human and material costs of car crashes. Cybersickness has been largely documented as a negative side effect in driving simulation (Sniegs, et al., 2022). Our Research Team’s goal was to further research this effect for our VR driving simulators.

In May 2025, a Romanian energy company (name undisclosed) set out to raise awareness of the dangers of the road by exposing a large number of its employees to challenging scenarios on driving simulators.

For this experiment, 2 types of simulators were used. The first type was a standalone Driving Simulator (MetoDrive Pro) that can be used with a Virtual Reality Headset, but has an option for the use of 3 monitors. The second type of simulator was an in-car driving simulator (MetoDrive Real), for which the cockpit was retrofitted with Fanatec steering wheel and pedals. Data was collected from a pool of 418 employees who drive routinely for work.

This study, which exposed drivers to 5 challenging scenarios (busy intersection, hidden pedestrian, aggressive drivers, obstructed views, challenging lane switch) offered a robust way to assess the level of comfort of the participants with driving simulation and their possible cybersickness. After the experiment, participants were invited to rate their experience through a choice of 5 options:

1) Awesome, 2) Great, 3) Ok, 4) Bad, 5) Horrible.

In addition, the length in minutes of the experiment and the distance driven were recorded for each participant. A total of 241 participants drove the Standalone simulator vs a total of 177 for the In Car simulator.

Results and Discussion

Raw data for the experiment is presented in Table 4. Out of the initial pool of 418 participants, a total of 368 participants completed the experiment (88%) as 50 did not feel comfortable and had to withdraw.

Table 4: Driving simulators study raw data

Simulator Type	Users	Rating	Time (mn)	Avg Distance (m)
Standalone	101	Awesome	6	4934
In-Car	87	Awesome	8.1	4960
Standalone	59	Great	6.2	4904
In-Car	38	Great	6.2	4882
Standalone	27	Ok	6.1	4773
In-Car	18	Ok	6.4	4862
Standalone	2	Bad	6	5353
In-Car	0	Bad	x	0
Standalone	1	Horrible	7	5924
In-Car	1	Horrible	5	4716
Standalone	21	Missing Survey	6.9	3671
In-Car	13	Missing Survey	6.8	3462

Standalone	30	Unfinished	3,4	2377
In-Car	20	Unfiniched	3,6	2584

Simulation sickness

The pool of participants, who typically have no prior experience with Virtual Reality permits a good insight into the simulator sickness effect. Out of the 384 participants who completed the survey, 285 (74%) rated the experience as Awesome or Great. On the other side of the spectrum, a total of 54 participants did not complete the ride or rated the experience as bad or horrible, leading to a rate of 14% for a negative experience.

Simulator Form Factor

The In Car simulator provided an experience somewhat different from the Standalone experience. The car environment with its built in car seat and controls is instantly recognized by all participants. Still, the limitation to a Virtual Reality simulator with no monitors back up, could have made participants uncomfortable. Tabulating data, 241 participants used the Standalone simulator vs. 177 for the In Car simulator.

Using that same methodology to assess simulator perception, while comparing form factors led to the following results. Favorable impressions (Awesome or Great) for the Standalone simulator amount to 72% vs 76% for the In-Car Simulator. Unfavorable impressions (Bad or Horrible) amount to 15% for the Standalone Simulator vs 13% for the In Car simulator.

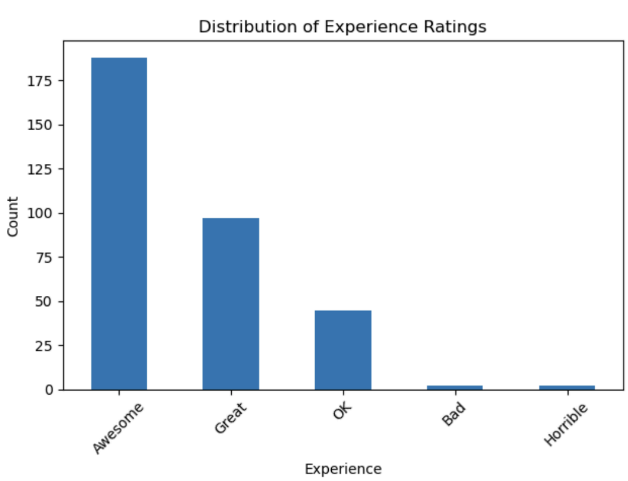

Figure 4: Distribution of Session Outcomes

When we compared the two simulator setups side by side, the difference was fairly small and we did not find any statistical difference in cybersickness, or overall impression. This result surprised us somewhat because the Standalone MetoDrive Pro and in-car Metodrive Real have distinctive features.

While we anticipated a strong interest by participants for the in-car simulator, we were somewhat worried the *VR only* feature would translate into a large cybersickness rate and a withdrawal from the study. This did not happen.

For participants who used the Standalone MetoDrive pro, we anticipated the use of that simulator in 3 monitors mode would possibly translate in a lower simulation sickness rate. Also participants might not rate the experience as positive since it is fully immersive when VR is not used. This did not happen.

Further studies with more granular variables will be needed. A future study will analyze how people react to the various scenarios and if Virtual Reality indeed makes a difference in people's driving reactions. The positive results are, however encouraging. We anticipate continued development in the field of Virtual reality for driving simulation.

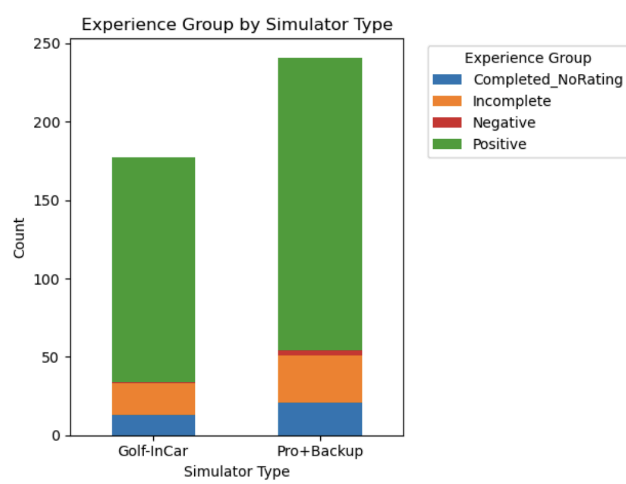

Figure 5: Outcome Distribution by Simulator Type

Conclusion

Driving simulation has come a long way since its early days. The combination of an immersive experience through Virtual Reality and the Digital Twins of real cities offers a true potential to make it a valuable tool in driving education. Our Human study of 418 participants showed that Virtual Reality was very well received, Withdrawal rate for cybersickness was just about 12% among a population of professional adults. A large majority of participants (72%) had a favorable impression of the simulation. Licensing agencies are slowly adopting the tool around the world. Still, much needs to be done to make the tool easily accessible to the larger population of driving students around the world.

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