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The Concept of a Digital Twin in the Arctic Environment

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Abstract

A Digital Twin is a virtual environment that simulates, predicts, and optimizes the performance of its physical counterpart. Digital Twin models hold great potential in wireless networking testing and development. This paper aims to envision our concept of simulating the operation of different sensors in vehicle test-track conditions. Vehicle parameters are embedded into the edge computing entity, which uses them to generate a test configuration for the Digital Twin. This configuration is then applied in simulated sensor-output prediction, ultimately producing event data for the vehicle entity. The sensor suite—comprising radar, cameras, GPS and LiDAR—is modeled to provide the multi-modal input required for generating simulated perception data in the Digital Twin. To ensure realistic perception behavior, the physical vehicle is represented within a digital environment that reproduces the actual test track. This allows LiDAR occlusions to be attributed to genuine environmental structures (e.g., trees, buildings, other vehicles) rather than simulation artifacts. Within the Digital Twin, the objective is to evaluate how sensor signals—such as radar waves and LiDAR light pulses—propagate through the environment and how real-world obstacles may weaken or distort them. Historical datasets are used to calibrate and validate the Digital Twin, ensuring that the simulated sensor behavior aligns with real-world observations; the data collected during previous test runs can be used for visualization and analysis. Weather conditions are modeled to evaluate how rain, fog and snow impact sensor performance within the Digital Twin environment, to learn about the effects and predict sensor operation in different weather conditions. In this article, we examine the Digital Twin of our test track as a development environment for designing, deploying and testing ITS-enhanced road-weather services and warnings. These services integrate real-world road-weather observations, forecast data, roadside sensors and on-board vehicle measurements to support safe driving and optimize vehicle trajectories for both passenger and autonomous vehicles. This research is expected to benefit stakeholders involved in automotive testing, simulation and road-weather service development.

Keywords: Digital Twin; LiDAR; 5G; GPS; V2X; IMU

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1. Introduction

Digital Twins have gained significant attention for their potential in designing, evaluating and testing wireless networks, particularly in addressing the complexities inherent in real-world system development and validation [1].

Standardization bodies, such as 3GPP and ITU-T, have begun exploring the role of Digital Twins in future network architectures [2].

The 5G New Radio (5G NR) standard was finalized by 3GPP in its Release 17 cycle, and attention has since shifted toward defining the vision for 6G. These developments are

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increasingly connected to Digital Twin research, as future networks are expected to rely on virtualized representations of physical systems. Early 6G research anticipates support for more demanding applications—including advanced autonomous-vehicle operations and AI-driven control—through higher reliability, lower latency and integrated sensing–communication capabilities. These expected features strengthen the relevance of Digital Twins, which provide controlled virtual environments for evaluating such requirements. Prior studies indicate that Digital Twins can support the development and evaluation of wireless-network and autonomous-vehicle applications by enabling controlled, repeatable experimentation that is difficult to achieve in physical environments.

Digital Twin-enabled development environments can be used to train and test AI algorithms for UAVs and other autonomous vehicles, provided that the virtual environment offers sufficient fidelity in sensor modeling, mobility patterns and wireless-network behavior.

In the context of autonomous-vehicle networks, AI techniques are increasingly used for tasks such as trajectory optimization and network-resource adaptation. Our work focuses on enabling these AI-driven functions to be evaluated within a Digital Twin of the test track. In our implementation, the Physical-to-Virtual (P2V) connection is established by replicating the Sod5G test track—including terrain, infrastructure and sensor configurations—inside the simulation environment. The corresponding Virtual-to-Physical (V2P) connection enables algorithms tested in the Digital Twin to be deployed back onto the real test track for validation [3]. Within autonomous-vehicle networks, high-fidelity Physical-to-Virtual replication is necessary because vehicle-control algorithms and network-layer functions are highly sensitive to spatial accuracy, sensor occlusions and link-quality variations that must be preserved in the Digital Twin. However, this requirement poses a significant challenge, as AVNs involve tightly coupled processes—sensor fusion, vehicle dynamics and high-frequency wireless-channel variations—that are difficult to reproduce with sufficient temporal and spatial resolution in real time [4].

For AVN research, a Digital Twin is expected to capture the interactions between autonomous-vehicle software and radio-network components, allowing these elements to be examined in a controlled virtual environment before testing on the physical track.

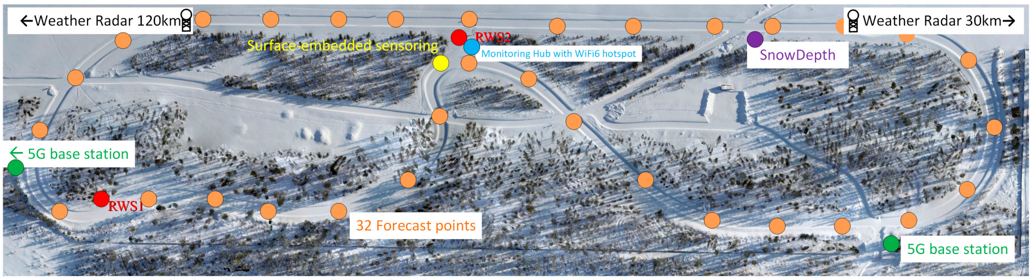
In many AVN studies, a Digital Twin is complemented by a physical testbed to validate key interactions under real conditions, although the extent of physical integration depends on the research objectives.

To illustrate how Digital Twins and physical testbeds can be combined in practice, prior work such as the AERPAW platform provides a relevant example [5,6]. Related work has also examined test systems for automotive sensor interfaces in electronic control units (ECUs) [7]. While these efforts focus on vehicle-centric sensors, our work differs by targeting road-weather sensors installed both on vehicles and at fixed roadside stations, enabling weather-condition evaluation within the Digital Twin. In our envisioned setup, simulated road-weather data generated within the Digital Twin is transmitted to the real vehicle system, where it is processed using each vehicle's operational software.

Volvo has applied Digital Twin concepts to autonomous-driving development by creating high-fidelity virtual replicas of trucks and test environments, enabling closed-loop Software-in-the-Loop and Hardware-in-the-Loop testing for vehicle-behavior validation [8]. For Volvo, a Digital Twin means high-fidelity virtual replicas of trucks and environments, allowing for virtual driver development in autonomous driving and fast, scalable testing, helping to build safe autonomous transport solutions. The key element in Volvo's testing process is closed-loop Software-in-the-Loop (SIL) simulation, running the virtual driver software inside a simulation containing Digital Twins of both the site and truck. The autonomous driving system reacts to simulated environments and decides when to steer, brake, or accelerate. In parallel Hardware-in-the-Loop (HIL) testing, physical components like electronic control units (ECUs) and computing hardware are connected to the simulator alongside the virtual driver. Our Digital Twin development aligns with Volvo's approach in emphasizing high-fidelity virtual environments and closed-loop testing, although our work focuses specifically on weather-related systems rather than vehicle-centric development.

The work in [9] demonstrates the feasibility of developing a Digital Twin for wind-power applications using the Unreal Engine. This serves as a relevant reference point for our study, although our focus is on a more complex combination of fixed and mobile infrastructure. In our work, we also adopt the Unreal Engine due to its high-fidelity rendering, flexible sensor-simulation support and compatibility with real-time physics. Unlike the scenario in [9], our Digital Twin models a more heterogeneous environment that includes fixed infrastructure, mobile vehicles, roadside weather sensors and communication nodes.

Focusing on our contribution, our own Digital Twin entity is also a combination of physical entity and virtual simulation systems. The Sod5G test track in Sodankylä, Northern Finland, is used as a testing and development environment for intelligent traffic, autonomous vehicles, and road-weather services [10]. The test track is supplemented with a multitude of communication systems, e.g., vehicle-to-vehicle (V2V) radios for ITS-G5 and C-V2X, a WiFi6 hotspot, and 5G test networks. A test-track sky view with instrumentation highlighted is presented in Figure 1. Although Sodankylä typically experiences a long winter season, specific weather conditions cannot be guaranteed at any given time. The Digital Twin therefore enables controlled replication of snow, ice, fog and other harsh conditions independent of the actual weather during testing.



Location: Sodankylä, Lapland, Finland, 67°23'26.2"N 26°37'03.9"E
Statistics: Main route of 1.7 km, 300m asphalt, 1400m gravel. Additional gravel routes of 800m
Weather instruments: 2 road weather stations, surface-embedded weather sensoring, Snow-depth sensor, monitoring hub with edge computing
Fixed communication instrumentation: 2 5G base stations, ITS-G5 tranceiver in RWS2, WiFi6, C-V2X and Starlink tranceiver in monitoring hub

Figure 1. Sod5G test track and its instrumentation.

Alongside the communication systems, we have two well-equipped road-weather stations and variety of roadside and on-board weather equipment for both continuous and campaign-like weather measurements. Within this study, the Digital Twin is used primarily to examine how weather conditions influence both sensor performance and vehicle behavior, complementing physical measurements collected on the test track. These simulations allow us to study how weather conditions influence both sensor outputs and vehicle responses. The Digital Twin can be used to test how certain sensors and devices react to, for example, rain, fog or snow cover. The vehicle's behavior can be examined in different conditions, such as on slippery roads or in poor visibility. The simulation environment also enables the modeling of special situations, such as disturbances caused by several vehicles.

Our objective is to develop a realistic and versatile virtual test platform that supports sensor development, vehicle testing and the study of weather impacts on traffic operations.

The Digital Twin thus serves as an important tool in both research and product development.

The rest of the article is composed as follows. We first introduce the Digital Twin entity of the Sodankylä test track, with the monitoring hub of the track and environmental simulation approach. The following sections present different simulation scenarios in the

Digital Twin entity. The application potential of the Digital Twin is estimated next, followed by the evaluation of the platform for the different environmental evaluation purposes. Finally, the future work aspects are estimated.

In this article, we study a Digital Twin of our test track that serves as a development environment for ITS-enhanced road-weather services. We first compare the use of simulation, Digital Twin and physical testbed environments for their suitability in developing and testing ITS and road-weather services. We discuss representative use cases to illustrate how these environments differ in supporting ITS and road-weather applications. Finally, we provide the concept idea of our test track and embedded Digital Twin, where the Digital Twin is used to develop and test AI-aided road-weather and safety solutions for both autonomous unmanned aerial vehicles (UAVs) and the rest of the traffic actors. The research questions addressed in this work are:

- Can AI use a Digital Twin to learn autonomous driving within a test track in all weather conditions?
- Can AI models trained in the Digital Twin use real or simulated weather-monitoring data to learn how to operate under harsher conditions than those observed in the physical measurements?

We evaluate the proposed Digital Twin using measurements collected from the Sod5G physical testbed. The rest of the article is structured as follows. Section 2 presents the Digital Twin entity, including the monitoring hub and environmental simulation components. Section 3 introduces simulation scenarios, followed by AI integration and autonomous decision-making in Section 4. Section 5 provides discussion, and Section 6 concludes with future work considerations.

2. Materials and Methods

2.1. Digital Twin Entity

The Digital Twin of the Sod5G test track replicates real vehicles and roadside instrumentation within a virtual simulation environment, enabling their behavior and interactions to be mirrored in real time. The operation of the Digital Twin relies on communication interfaces between the vehicle and the command center, combined with a georeferenced map model of the test track that provides the spatial framework for simulation. The command center collects data from test-track vehicles, as well as from local weather-monitoring instruments, including the on-site weather radar systems. GPS and IMU data from the vehicle are transmitted to a Python-based data-processing module at the command center, which serves as the software interface for handling incoming measurements. This module computes the vehicle's 2D position (X, Y) within the digital map and uses IMU-derived orientation angles to determine its heading; vertical components are available if required but are simplified in the current implementation. The overall data-flow process is illustrated in Figure 2.

This data is imported into the Unreal Engine 5 simulation environment, which provides high-fidelity 3D rendering and real-time physics capabilities suitable for Digital Twin applications.

The Python-based interface transmits both vehicle data (GPS and IMU) and weather observations from the RWS1 and RWS2 stations to the Unreal Engine environment. The instrumentation and data contents of these stations are described in [11] of the Sod5G test track to the Unreal Engine environment. These inputs allow the Digital Twin to recreate weather-dependent environmental conditions within the simulation. The system can render a range of atmospheric conditions that influence sensor performance and vehicle perception. Figure 3 illustrates the visual simulation entity of the Digital Twin with road-weather station RWS2 data presented. The sky view of the test track is presented on the right side of the image, allowing for the presentation of the location of test-track objects. The interface allows researchers to access real-time road-weather measurements and other test-track data directly within the simulation.

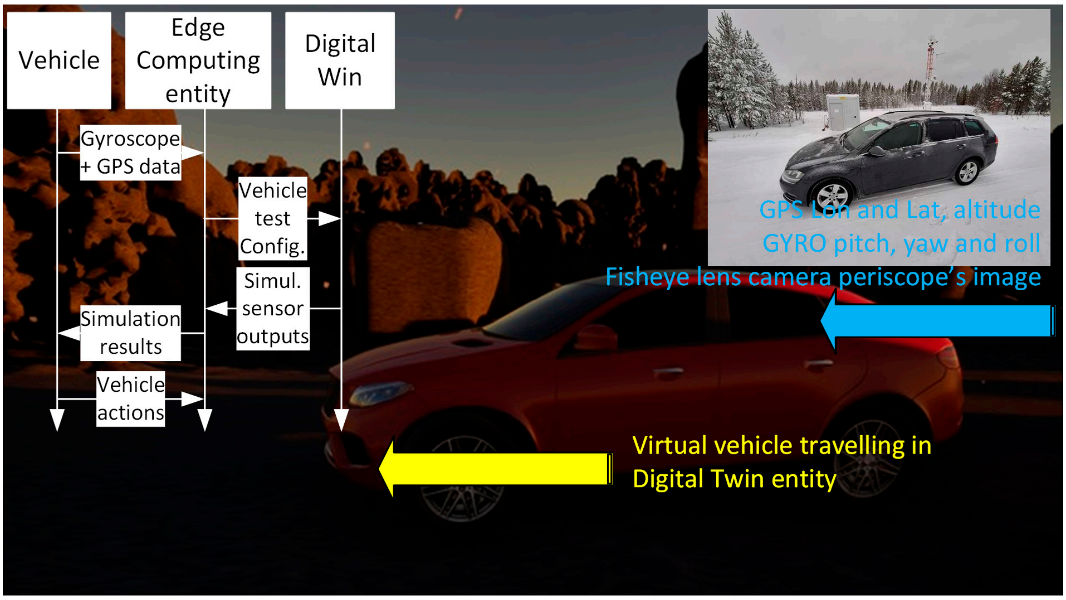
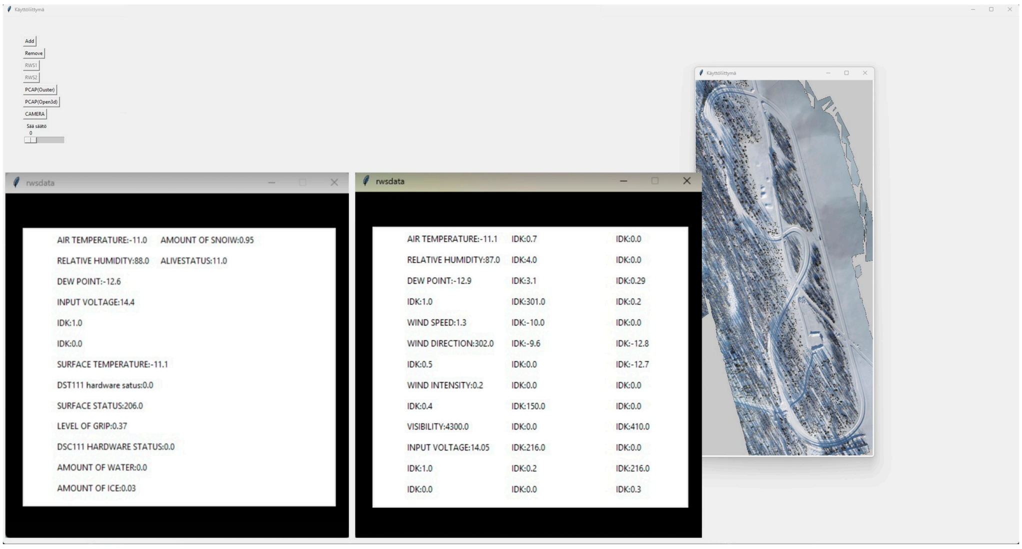


Figure 2. Digital Twin entity model.



```
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RELATIVE HUMIDITY:88.0     ALIVESTATUS:11.0
DEW POINT:-12.6
INPUT VOLTAGE:14.4
IDK:1.0
IDK:0.0
SURFACE TEMPERATURE:-11.1
DST111 hardware satus:0.0
SURFACE STATUS:206.0
LEVEL OF GRIP:0.37
DSC111 HARDWARE STATUS:0.0
AMOUNT OF WATER:0.0
AMOUNT OF ICE:0.03
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```
AIR TEMPERATURE:-11.1      IDK:0.7         IDK:0.0
RELATIVE HUMIDITY:87.0     IDK:4.0         IDK:0.0
DEW POINT:-12.9            IDK:3.1         IDK:0.29
IDK:1.0                    IDK:301.0       IDK:0.2
WIND SPEED:1.3             IDK:-10.0       IDK:0.0
WIND DIRECTION:302.0       IDK:-9.6        IDK:-12.8
IDK:0.5                    IDK:0.0         IDK:-12.7
WIND INTENSITY:0.2         IDK:0.0         IDK:0.0
IDK:0.4                    IDK:150.0       IDK:0.0
VISIBILITY:4300.0          IDK:0.0         IDK:410.0
INPUT VOLTAGE:14.05        IDK:216.0       IDK:0.0
IDK:1.0                    IDK:0.2         IDK:216.0
IDK:0.0                    IDK:0.0         IDK:0.3
```

Figure 3. Digital Twin graphical user interface.

2.2. Monitoring Hub and Edge Processing Capabilities

The Sod5G test track is equipped with a centralized monitoring hub, also referred to as the command center, which provides real-time oversight of all Digital Twin operations and physical testbed activities. The monitoring hub performs time-synchronized collection, preprocessing and visualization of data from vehicles, roadside sensors and weather stations, ensuring that all data streams are aligned for real-time Digital Twin updates (Figure 4). In addition to centralized control, the system employs on-site edge computing hardware equipped with GPU-accelerated processing, enabling real-time execution of data-intensive tasks. This architecture supports low-latency data processing and local AI inference by reducing the need to transfer sensor streams to external servers. As a result, edge processing tasks related to ITS operations can be executed directly at the interface between vehicle-to-everything (V2X) communication and roadside infrastructure.

The combination of centralized monitoring and distributed edge processing ensures both scalability and responsiveness in complex testing scenarios. Figure 5 provides an overview of the monitoring hub's visualization setup, highlighting the data streams available for real-time analysis. The main screen behind shows the virtual counterpart of the vehicle traveling in the 3D-modeled test track entity, with the position shown in the parallel sky view image. The small screen in the front is used for presenting the desired parameters for the measurement scenario, in this case the road-weather station data.

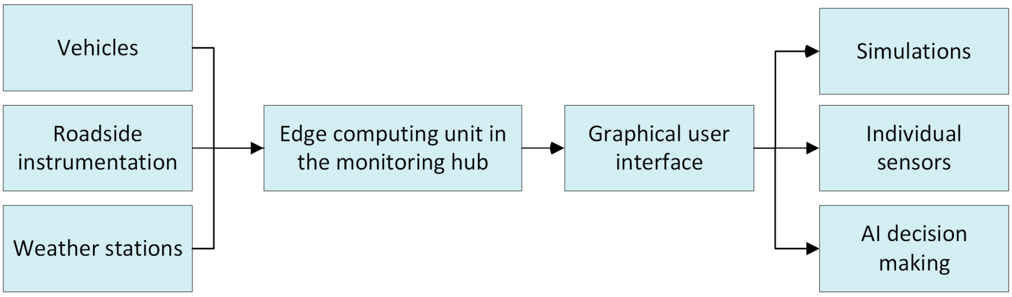

Figure 4. The responsibilities of the edge computing unit in the monitoring hub.

Figure 5. Monitoring hub screens and their contents.

2.3. Environmental Simulation and Sensor Response

The Digital Twin also enables controlled manipulation of weather conditions within the simulation environment. This functionality allows us to examine how different sensors—such as LiDAR, cameras and GPS—respond to varying atmospheric conditions. This would also make it possible to assess the reliability and accuracy of the sensors in varying weather conditions, which is particularly important in the development and testing of autonomous vehicles. At the current stage, the Digital Twin incorporates measured weather data from the road-weather stations, but active manipulation of these parameters is not yet supported. Comprehensive measurements describing sensor performance under diverse weather conditions are not yet available, and obtaining such datasets is part of the future work. The Digital Twin uses a georeferenced map based on the EPSG:3386 projection, which aligns with Finland's national coordinate system and ensures consistency between physical measurements and the virtual environment.

Unreal Engine 5 was selected due to its ability to render large, high-resolution 3D environments efficiently, particularly through its Nanite virtualized-geometry system. Nanite enables the processing and rendering of highly detailed 3D models without any loss of performance. The Digital Twin environment was constructed using LiDAR point-cloud (Version X5) data combined with 360° visual imagery from an Insta360 X5 camera (Arashi Vision Inc., Shenzhen, China). The point cloud was preprocessed to remove noise and align overlapping scans, after which the data was fused into a textured 3D mesh. While this approach provides high spatial accuracy, the level of detail varies locally depending on LiDAR sampling density and camera exposure conditions. Rendering and manipulating such a large, detailed mesh is computationally demanding, and Nanite significantly improves performance by handling high-polygon geometry more efficiently than conventional rendering pipelines. An example image from the Digital Twin environment is shown in Figure 6.

Figure 6. Environment of the Digital Twin.

Nanite's virtualized-geometry approach optimizes rendering by dynamically adjusting the level of detail, which supports real-time simulation even with large, complex models. This is especially important when simulating the operation of sensors in a complex environment where details affect perceptions and signal flow.

To ensure realistic weather simulations, the Digital Twin is continuously calibrated using measurements from the two road-weather stations installed along the Sod5G test track. These stations provide high-resolution atmospheric and surface observations, which are used to align simulated conditions with real-world phenomena. These measurements are used to calibrate the Digital Twin's weather models by adjusting parameters such as visibility range, precipitation intensity and surface conditions to match the distributions observed in the physical data. Alignment between virtual scenarios and physical observations is achieved by comparing simulated outputs with real measurement profiles and iteratively adjusting simulation parameters until the deviation falls within acceptable error limits.

3. Potential Sod5G Digital Twin Simulation Scenarios

The Sod5G Digital Twin entity allows for multitude of simulation scenarios employing different numbers of vehicles, on-board instrumentation, weather conditions and even physical infrastructures. To demonstrate the flexibility of the Digital Twin, we present five representative simulation scenarios that illustrate its use in different operational and environmental conditions.

3.1. Foggy Morning at the Test Track

The Digital Twin visualizes dense fog conditions based on low-visibility measurements from the RWS stations. In the Unreal Engine environment, visibility-related parameters from the RWS stations are transferred through the Python (v. 3.11.7, Python Software Foundation, Amsterdam, the Netherlands) interface and mapped to the fog-rendering settings in the simulation, either by using the measured visibility value directly or by triggering preset fog levels. The simulation could test how LiDAR and cameras react to reduced visibility—the scenario is used to evaluate obstacle-detection latency and the performance of the vehicle's automated steering under reduced-visibility conditions. Figure 7 shows the fog-simulation scenario within the Digital Twin environment. A vehicle approaches the road-weather station location with limited visibility. The performance of LiDAR and camera sensors under various weather conditions is being investigated in parallel research efforts [12], which complement the scenario presented here.

Figure 7. Foggy morning illustration (objects on the right caused by small plants beside the track, red color on the left caused by spatial coordinate system conversion inaccuracy).

3.2. Meeting Several Vehicles at an Intersection

In this simulation, a vehicle detects three other vehicles approaching an intersection at the same time. This scenario enables examination of how the simulated sensors perceive surrounding vehicles and how vehicle-to-vehicle communication behaves under multi-vehicle conditions using the 5G connection model available in the Digital Twin. The scenario allows for controlled analysis of communication effects such as increased channel load, message collisions and potential delays arising from multiple vehicles transmitting simultaneously. Safety performance is evaluated using metrics such as minimum inter-vehicle distance, time-to-collision and the number of vehicles occupying the intersection simultaneously.

The scenario can be seen in Figure 8. Figure 8 illustrates the relative vehicle positions used in the intersection scenario.

Figure 8. Illustration of several vehicles at an intersection.

3.3. Slippery Road and Sudden Braking

The scenario uses measured or predefined weather-related parameters—such as snowfall rate or road-surface slipperiness—to generate low-friction conditions within the Digital Twin. The simulation introduces a sudden obstacle, requiring the vehicle to perform an emergency stop under low-friction conditions. The simulation could examine how the vehicle's sensors and control systems react to the situation, and how well the vehicle can stop safely. Real friction measurements from the road-weather station or onboard friction sensors can be applied so that the simulated braking event corresponds to the conditions measured on a specific day. Braking distances for different approach speeds are computed using the friction values measured by the road-weather station or onboard sensors, allowing for the stopping performance to be evaluated under realistic low-friction conditions. Scenario is viewed in Figure 9.

Figure 9. Illustration of slippery road and sudden braking.

3.4. GPS Signal Interference in a Forest Area

The Sod5G test track area consists of open areas and forested areas, with some parts of the forested areas having a high density of trees. The vehicle drives through dense trees, which weakens the GPS signal. The Digital Twin simulates GPS degradation and temporary signal loss by reducing satellite visibility and introducing controlled noise into the position estimates. This scenario, viewed in Figure 10, evaluates the vehicle's ability to maintain navigation continuity by relying on redundant sensing sources—primarily IMU and LiDAR—when GPS accuracy deteriorates. In this scenario, the GPS signal is partially blocked by the forest canopy, leading to satellite occlusion and reduced signal strength. Although signal degradation is forest-induced in this scenario, similar positioning errors may arise from other known factors such as atmospheric effects, multipath propagation or temporary satellite-geometry limitations.

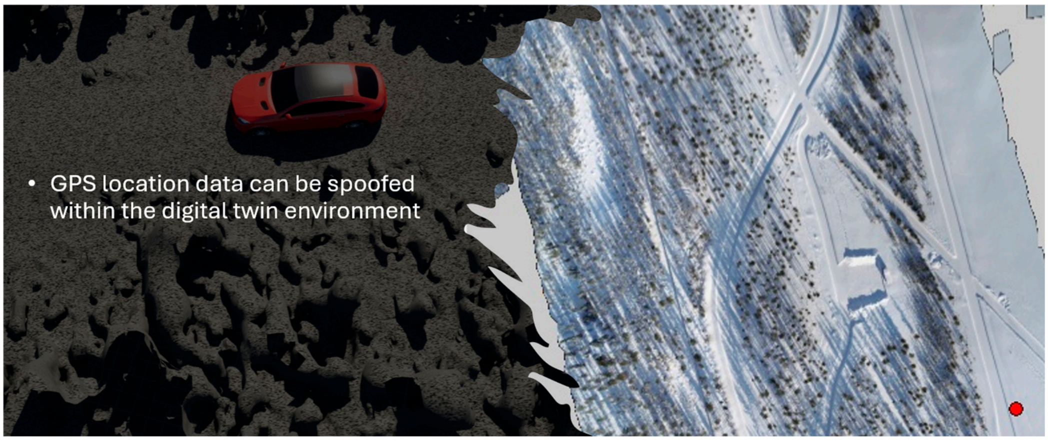

Figure 10. Illustration of GPS signal interference.

3.5. *Rapid Change in Weather Conditions*

This test simulates a situation in which the weather changes quickly—from sunny to rainy and windy, or from light snowing conditions to heavy snowing. The Digital Twin adjusts the visual and environmental parameters dynamically based on the incoming weather data, allowing the simulation to reflect changing conditions with minimal delay. The scenario enables analysis of weather-induced degradation in camera imagery and LiDAR point-cloud quality by comparing sensor outputs under different simulated atmospheric conditions. This scenario is illustrated in Figure 11, where snowing density starts to increase, affecting visibility. The performance of LiDAR and camera sensors under varying visibility and precipitation levels is being investigated in a parallel study [8].

Figure 11. Illustration of a rapid change in weather conditions.

3.6. *New Potential Application of Digital Twin*

A planned extension of the Digital Twin is to evaluate weather-aware routing methods. In this scenario, the routing method selects routes based on dynamic weather and road-surface conditions rather than distance alone.

The Digital Twin makes it possible to visualize how the vehicle makes decisions in changing conditions—for example, choosing the safest and most efficient route in a situation where the weather and road conditions vary.

The routing model incorporates factors such as road-surface friction, wind conditions affecting vehicle stability and visibility reductions due to fog or snowfall. These variables influence route selection by modifying the estimated travel time, risk levels and operational constraints. particularly for vehicles with large side-surface areas or lower mass, which are more sensitive to lateral wind forces. The Digital Twin could simulate these conditions in an Unreal Engine environment, and the algorithm's operation could be monitored visually. The visualization enables clear inspection of how environmental factors influence routing outcomes within the simulation. At the same time, it provides valuable information for improving traffic safety, developing autonomous vehicles and designing intelligent transport systems, for example. This scenario is well-suited for illustrating the interaction between weather conditions, sensor data and route-planning logic and can be visualized and interacted with in real time within the Digital Twin environment.

4. AI Integration and Autonomous Decision-Making

In addition to physical modeling and weather simulation, the Digital Twin provides a controlled environment for developing and evaluating AI algorithms related to perception, decision-making and trajectory planning in autonomous vehicles. The virtual environment supports safe and repeatable experimentation by providing detailed 3D geometry, calibrated weather representations and synchronized sensor-simulation outputs, all of which are essential for evaluating AI behavior under varying operational conditions.

Table 1 summarizes the AI application areas currently supported by the Digital Twin, grouped according to perception, localization, control and decision-making functionalities relevant to autonomous-vehicle operation. The Digital Twin supports offline algorithm development—such as reinforcement-learning-based policy training using simulated sensor streams—and facilitates real-time inference evaluation through its low-latency data interface to the physical testbed. This enables controlled testing of perception and decision-making models under varying environmental and traffic conditions.

Table 1. Key AI applications supported by the Digital Twin.

Application	Overview
Trajectory planning	AI models can be trained to optimize vehicle paths based on road geometry, weather, and traffic conditions
Sensor fusion	Combining data from LiDAR, cameras, GPS, and IMU to improve perception accuracy and robustness
Obstacle detection and avoidance	Testing how AI systems respond to dynamic hazards such as pedestrians, other vehicles, or sudden weather changes
Adaptive behavior under uncertainty	Evaluating how AI adapts to degraded sensor input, such as during fog or snow, using redundancy and predictive modeling
Communication-aware decision-making	Integrating V2X communication data to enhance cooperative driving and situational awareness

5. Discussion

A key advantage of our Digital Twin implementation lies in its ability to create a highly realistic virtual environment that closely mirrors the physical test track. This realism is crucial for developing and testing autonomous driving systems, particularly those relying on on-board perception sensors such as cameras and LiDAR. By simulating detailed 3D environments—including road textures, vegetation, buildings, and dynamic objects like other vehicles, the Digital Twin enables accurate emulation of how these sensors perceive the world. For instance, camera sensors can be tested under varying lighting and weather conditions, while LiDAR systems can be evaluated for point-cloud accuracy in complex geometries. These simulations allow developers to assess sensor performance, validate object detection algorithms, and refine autonomous navigation strategies without the risks and costs associated with real-world testing. The integration of Unreal Engine 5 with Nanite technology further enhances this capability by rendering high-fidelity scenes in real time, making the Digital Twin an effective testbed for perception-driven autonomy.

To support the development of robust autonomous driving systems, the Digital Twin environment can simulate how environmental factors degrade sensor performance and cause sensor obfuscation in adverse conditions. These simulations are essential for testing perception algorithms under realistic and challenging conditions. Table 2 lists the effects the Unreal Engine-based environment can model. By incorporating these effects, the Digital Twin becomes a powerful tool for evaluating sensor fusion, redundancy mechanisms, and fail-safe behaviors in autonomous vehicles.

Table 2. Effects that are possible to model within the Unreal Engine-based environment.

Phenomenon	Effect
Snowfall accumulation	On camera lenses or LiDAR domes, leading to partial or total visual occlusion
Rain droplets	Causing light scattering and distortion in camera images, reducing object detection accuracy
Fog and mist	Reducing visibility range and contrast in both camera and LiDAR data
Wet road surfaces	Introducing glare or reflections that confuse vision-based systems
Snow-covered terrain	Altering LiDAR reflectivity and reducing ground segmentation accuracy

6. Conclusions and Future Work

This work presents the concept of a Digital Twin entity co-existing with an intelligent-traffic, physical, road-weather services winter test track. The physical test track contains a multitude of communication systems and a variety of fixed and on-board road-weather measurement systems. Digital Twin entity contains the same track and instruments, with the possibility to change weather conditions and instrument parameters. In this paper we have envisioned the potential concept scenarios that can be created with the existing instrumentation. We have conducted the evaluation measurements of test-track communication systems and we do have measurement accuracy information from our meteorological devices, but we have not yet brought this data to the Digital Twin entity.

In future research we will focus on developing the simulation scenarios, especially focusing on the scenarios presented in Section 3, as well as taking measurements with our physical instruments in different weather and environmental conditions, in order to create the responses envisioned in Section 3.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

3GPP	3rd Generation Partnership Project
5G NR	Fifth generation (Cellular) network, New Radio
6G	Sixth generation (Cellular) network
AERPAW	Aerial Experimentation and Research Platform for Advanced Wireless
AI	Artificial Intelligence
AV	Autonomous Vehicle
AVN	Autonomous Vehicle Network
GPS	Electronic Control Units
ECU	Global Positioning System
HIL	Hardware-in-the-Loop
IMU	Inertial Measurement Unit
ITS	Intelligent Transportation Systems
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
LiDAR	Light Detection and Ranging
P2V	Physical-to-Virtual
RWS	Road-Weather Station
SIL	Software-in-the-Loop
UAV	Unmanned Aerial Vehicle
UGV	Uncrewed Ground Vehicle
V2P	Virtual-to-Physical
V2X	Vehicle-to-Everything communication
V2V	Vehicle-to-Vehicle communication

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