

Digital Twin-Assisted 6G-V2X Intelligent Highway Safety System

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Abstract

What we put forth in this work is a Digital Twin-Assisted 6G-V2X Intelligent Highway Safety System, which aims to improve highway safety by combining Digital Twin technology with 6G and Vehicle-to-Everything (V2X) communication. In our proposed model, a virtual representation of the highway is created to monitor real-time road conditions, vehicle movements, traffic density, and possible accident situations. Information is collected from connected vehicles, roadside units, sensors, and other devices through the 6G-V2X network and is continuously used to update the Digital Twin.

What each part of the system mainly does is to monitor traffic behavior and identify possible risky conditions such as sudden braking, abnormal vehicle movement, high traffic density, and unsafe lane changes. The detected information is analyzed through the Digital Twin and communicated to near by vehicles and roadside infrastructure so that suitable warning and safety actions can be taken. The main idea of our proposed model is to identify and understand possible highway risks before they result in an accident, instead of only responding after an accident occurs. By combining Digital Twin technology, 6G-V2X communication, real-time traffic monitoring, and intelligent safety decision-making, the proposed system aims to provide faster information sharing, early risk

identification, and improved intelligent highway safety management.

Keywords: Digital Twin, 6G Communication, Vehicle-to-Everything (V2X), Intelligent Highway, Highway Safety, Intelligent Transportation System (ITS), Real-Time Traffic Monitoring, Accident Risk Detection, Vehicle Communication, Roadside Units, Predictive Safety, Smart Transportation.

1. Introduction

Nowadays, the rapid increase in highway traffic is creating more chances of road accidents and unsafe driving conditions. According to the World Health Organization (WHO), around 1.19 million people die every year due to road traffic crashes. Many accidents are related to sudden braking, high traffic density, unsafe lane changes, and abnormal vehicle movement. Because of this, there is a need for an intelligent system that can monitor highway conditions and identify possible risks earlier.

In our proposed model, Digital Twin technology is combined with 6G-V2X communication to improve highway safety. A virtual representation of the real highway is created, where vehicle movement, traffic conditions, and possible risk situations can be monitored. Information is collected from connected vehicles, sensors, and roadside units and is

continuously used to update the Digital Twin. The 6G-V2X network helps in exchanging safety information between vehicles and infrastructure with low communication delay. For example, when sudden braking or abnormal vehicle movement is detected, the information can be shared with nearby vehicles and roadside infrastructure. The Digital Twin can represent these changing conditions and help in identifying possible hazards.

2. Literature Review

In recent years, many researchers have worked on intelligent transportation, Digital Twin technology, V2X communication, and future 6G networks, because these technologies can support better traffic monitoring and road safety. The earlier works mainly focused on vehicle communication and traffic management, while the recent works are moving towards Digital Twin and 6G-based intelligent transportation systems.

Ali, Roccotelli, and Fanti (2022) studied Digital Twin technology for Intelligent Transportation Systems and discussed how a virtual representation of transportation systems can be used for monitoring and analysis. Their work mainly focused on the use of Digital Twins with IoT and 5G technologies, especially for electromobility and autonomous vehicles. This work shows that Digital Twin can be useful for representing real transportation conditions in a virtual environment.

He and Liu (2022) presented a study on 6G for Vehicle-to-Everything (V2X) communications, where the authors discussed the requirements of future connected and autonomous vehicles. They explained that future V2X systems need very fast, reliable, and low-latency

communication for exchanging large amounts of information. Their work also discussed different technologies and challenges related to 6G-based vehicular communication.

Noor-A-Rahim et al. (2022) discussed the enabling technologies, challenges, and opportunities for 6G-V2X communication. The authors explained that 6G can support intelligent transportation by providing hyper-fast, ultra-reliable, and low-latency information exchange. They also discussed the role of machine learning in future vehicular communication and networking.

Ficzere and Varga (2023) studied large-scale Cellular-V2X deployment based on 5G and also discussed the vision towards 6G. Their work examined challenges related to large-scale C-V2X deployment, standards, use cases, and future 6G development. This provides an important base for understanding how present 5G-based vehicle communication can move towards future 6G-V2X systems.

2.1 Research Gap and Contribution

2.1.1 Research Gap

From the existing studies, it can be observed that Digital Twin technology is mainly used for monitoring and representing transportation systems, while V2X and 6G technologies mainly focus on communication and fast data exchange between connected vehicles. However, there is still a need to bring these technologies together for continuous highway safety monitoring.

Most existing approaches focus on individual areas such as traffic monitoring, vehicle communication, or accident detection. The continuous connection between the actual highway and its Digital

Twin for identifying possible risks at an early stage is still not fully explored. Because of this, a combined system is needed that can monitor the highway condition, communicate safety information, and identify possible risks in real time.

2.1.2 Contributions

1. A Digital Twin of the highway environment is developed to represent the real-time traffic and road conditions.
2. 6G-V2X communication is used to exchange important safety information between vehicles, roadside units, and other connected infrastructure.
3. The system considers different safety conditions such as sudden braking, high traffic density, abnormal vehicle movement, and unsafe lane changes.
4. Data collected from vehicles, sensors, and roadside units is continuously used to update the Digital Twin so that the changing highway situation can be monitored.
5. The proposed system aims to identify possible risks at an early stage and provide faster safety information to connected vehicles, thereby supporting a more intelligent and responsive highway safety environment.

3 Materials and Methodology

3.1 Overall Research Framework

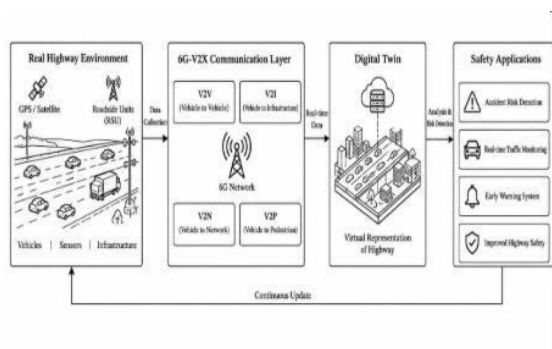


Figure1 Overall Research Framework

The proposed framework combines the **real** highway environment, 6G-V2X communication, Digital Twin, and safety applications. Real-time data is collected from vehicles, sensors, GPS, and roadside units. This data is transmitted through the 6G-V2X network and used to update the Digital Twin.

3.2 Dataset Description

The proposed system uses highway and vehicle-related data collected from connected vehicles, sensors, GPS, and roadside units. The main dataset features are:

Feature	Description	Unit/Type
Vehicle Speed	Current Vehicle Speed	Km/h
Vehicle Position	Vehicle Location	Latitude/Longitude
Traffic Density	Vehicles in a road section	Vehicles/km
Lane ID	Current lane of vehicle	Categorical
Acceleration	Change in Vehicle Speed	m/s ²
Sudden Braking	Indicates Sudden Braking	Binary
Lane Deviation	Movement away from the lane	m
Inter Vehicle	Distance from nearby Vehicle	m
Weather Condition	Current weather condition	Categorical
Communication Delay	Data Transmission Delay	ms
Risk Level	Safety condition	Low/Medium/High

Table 1 Dataset

These variables are processed and provided to the Digital Twin for representing the current highway condition. The main output is the risk level, which helps the system identify possible unsafe situations and generate early safety warnings.

District	Year	Accidents	Deaths	Injured
Tirupati	2023	1,029	518	1,207
Chittoor	2023	703	343	865

Table 2 Historical Accident Information

These records can be used as historical accident information for the proposed system. Along with real-time vehicle and traffic features, they can support the Digital Twin in understanding accident-prone conditions and identifying similar risk situations.

3.3 Data preprocessing

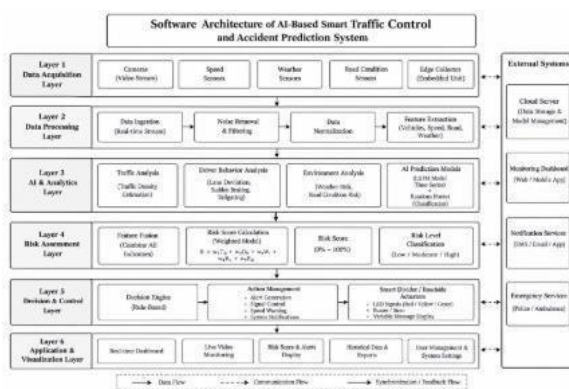


Figure 2 Data Preprocessing

3.3.1 Physical Highway and Data Collection Layer

The first layer represents the real highway environment. Data is collected from connected vehicles, GPS, sensors, roadside units (RSUs), and accident records. The main variables include vehicle speed, position, acceleration, traffic density, lane

deviation, braking condition, inter-vehicle distance, weather, and road condition.

Traffic density can be represented as:

$$D = \frac{N}{L}$$

where DD is traffic density, NN is the number of vehicles, and LL is the road length considered.

Vehicle acceleration is calculated as:

$$a = \frac{v_t - v_{t-1}}{\Delta t}$$

where v_t is the current speed, v_{t-1} is the previous speed, and Δt is the time difference.

3.3.2 Data Preprocessing Layer

The collected data may contain missing values, duplicate records, and different value ranges. Therefore, preprocessing is carried out before the data is used for further analysis. For numerical features, normalization can be performed using:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

where XX is the original value and X_{min} , X_{max} are the minimum and maximum values.

This makes the different features suitable for the risk analysis process.

3.3.3 6G-V2X Communication Layer

After preprocessing, the required information is transmitted through the 6G-V2X communication network. Communication can take place through V2V, V2I, V2N, and V2P links. The communication delay can be represented as:

$$T_{total} = T_{processing} + T_{transmission} + T_{propagation}$$

where the total delay depends on processing, transmission, and propagation time. The system aims to exchange important safety information with low

delay so that warnings can reach nearby connected vehicles quickly.

3.3.4 Digital Twin Layer

The Digital Twin creates a virtual representation of the real highway. The state of the Digital Twin can be represented as: $SDT(t) = F[S_{real}(t), D(t)]$ $S_{DT}(t) = F[S_{real}(t), D(t)]$

where $SDT(t)$ $S_{DT}(t)$ represents the Digital Twin state, $S_{real}(t)$ $S_{real}(t)$ represents the real highway state, and $D(t)$ $D(t)$ represents the collected data at time t . Whenever new highway data is received, the Digital Twin is updated:

$$SDT(t+1) = SDT(t) + \Delta S(t) \quad S_{DT}(t+1) = S_{DT}(t) + \Delta S(t)$$

where $\Delta S(t)$ $\Delta S(t)$ represents the change in the highway condition.

3.3.5 Risk Analysis Layer

The processed data is used to calculate the safety risk. In our proposed model, important factors such as speed, traffic density, braking, lane deviation, distance, and weather condition are considered. A simple weighted risk model is:

$$R = w_1S + w_2D + w_3B + w_4L + w_5C = w_1S + w_2D + w_3B + w_4L + w_5C$$

where:

- RR = overall risk score
- SS = speed-related risk
- DD = traffic/distance-related risk
- BB = braking risk
- LL = lane-deviation risk
- CC = road/weather condition risk
- $w_1, w_2, \dots, w_5$ $w_1, w_2, \dots, w_5$ = corresponding feature weights

The risk level can then be represented as: $Risk = \{Low, R < T_1 \text{ Medium}, T_1 \leq R < T_2 \text{ High}$

$$h, R \geq T_2 \text{ Risk} = \begin{cases} Low, & R < T_1 \\ Medium, & T_1 \leq R < T_2 \\ High, & R \geq T_2 \end{cases}$$

This allows the system to separate normal highway conditions from potentially dangerous conditions.

3.3.6 Safety Warning Layer

When the calculated risk becomes high, the system generates an appropriate warning and communicates it through the 6G-V2X network. For a simple collision-risk condition, the time-to-collision can be represented as:

$$TTC = \frac{d}{v_r}$$

where d is the distance between two vehicles and v_r is their relative speed. A smaller TTC indicates that the vehicles are approaching each other more quickly, so the system can consider generating an early warning.

3.3.7 Continuous Feedback and Digital Twin Update

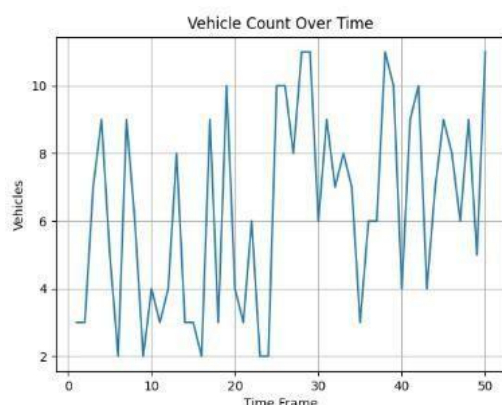
The final layer provides continuous feedback between the physical highway and the Digital Twin. New vehicle and road information is continuously collected and compared with the existing virtual model. The complete process can therefore be represented as:

Physical Highway $\rightarrow$ Data Collection $\rightarrow$ Preprocessing $\rightarrow$ 6G-V2X $\rightarrow$ Risk Analysis $\rightarrow$ Digital Twin $\rightarrow$ Safety Warning $\rightarrow$ Feedback Physical Highway $\rightarrow$ Data Collection $\rightarrow$ Preprocessing $\rightarrow$ 6G-V2X $\rightarrow$ Risk Analysis $\rightarrow$ Digital Twin $\rightarrow$ Safety Warning $\rightarrow$ Feedback

4. Results And Analysis

The obtained results are represented through traffic, risk, tracking, weather, and alert graphs. The main numerical observations are summarized below.

4.1 Traffic and Risk Results



Graph 1 Traffic and Risk

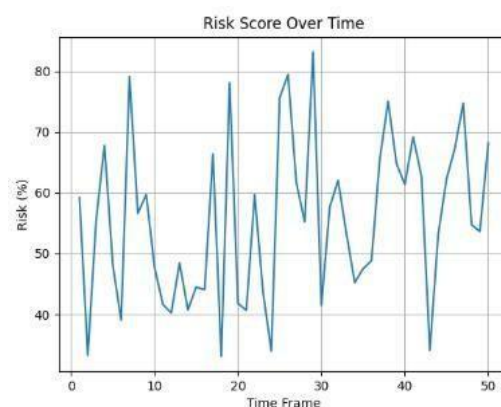
The vehicle count varies from approximately **2 to 11 vehicles** per time frame. The corresponding risk score varies from about **33% to 83%**.

Parameter	Observed Result
Minimum vehicle count	2
Maximum vehicle count	11
Minimum risk score	33%
Maximum risk score	83%
Main risk range	45–70%
Peak risk	~83%

Table 3 Vehicle Parameter

The results show that higher vehicle counts are generally associated with higher risk values. For example, when the vehicle count reaches **12–14 observations in the correlation dataset**, several risk values are above **70%**.

4.2 Risk Classification



Graph 2 Risk Classification

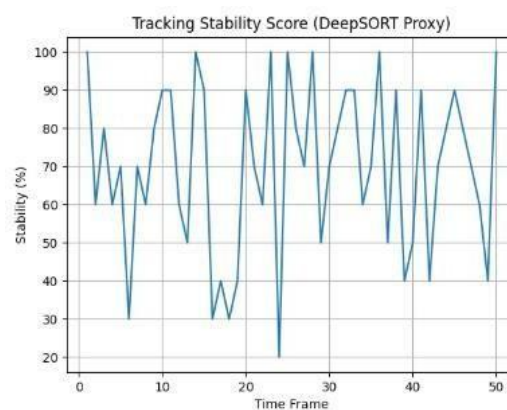
The final classification contains approximately 100 observations.

Risk Level	Number	Percentage
Low	6	6%
Moderate	55	55%
High	39	39%
Total	100	100%

Table 4 Risk Level

The largest portion is the **moderate-risk category (55%)**, followed by **high risk (39%)**. Only **6%** of the observations are classified as low risk.

4.3 Vehicle Tracking Results



Graph 3 Vehicle Tracking

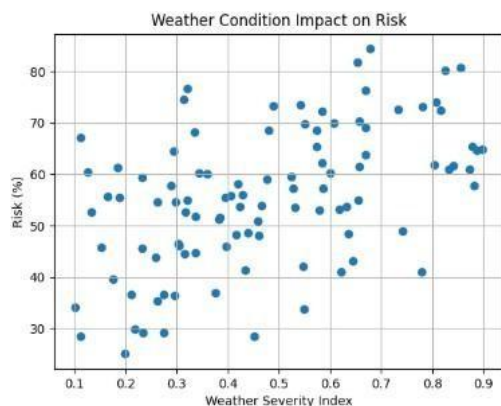
The tracking stability varies from approximately **20% to 100%**.

Tracking Parameter	Value
Minimum stability	~20%
Maximum stability	100%
Several stable frames	70–100%
Lowest observed region	20–40%

Table 5 Tracking Parameter

Most of the time frames show tracking stability above **50%**, while some frames show reduced stability.

4.4 Weather and Risk



Graph 4 Weather Condition

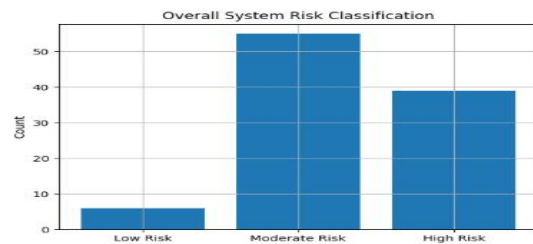
The weather severity index varies approximately from **0.1 to 0.9**, while the corresponding risk values range from around **25% to 85%**.

Parameter	Approx. Value
Minimum weather index	0.10
Maximum weather index	0.90
Minimum observed risk	~25%
Maximum observed risk	~85%

Table 6 weather condition

Higher weather-severity values contain several observations with risk values above **70%**, showing that weather condition can contribute to the overall safety risk.

4.5 Main Numerical Observation



Graph 5 Overall System

The overall results can be summarized as:

Vehicle Count: 2–11

Risk Score: 33–83%

Tracking Stability: 20–100%

Weather Index: 0.1–0.9

Low Risk: 6%

Moderate Risk: 55%

High Risk: 39%

These results indicate that the proposed system can monitor changing traffic conditions, calculate risk levels, track vehicles, and generate safety alerts based on the observed highway conditions.

4.6 Compact Numerical Summary

Parameters	Min	Max	Key Result
Vehicle Count	2	11	Variable Traffic flow
Risk Score	33%	83%	Peak risk~83%
Tracking Stability	20%	100%	Mostly above 50%
Weather Severity Index	0.10	0.90	Higher Values show higher risk cases
Low Risk	--	---	6%
Moderate Risk	--	---	55%
High Risk	--	---	39%
Total Observations	--	---	100

Table 7 Summary

Overall: The system recorded a maximum risk of approximately 83%, with 94% of observations classified as moderate or high risk. Traffic count, weather severity, and vehicle tracking were continuously monitored for risk assessment.

5. Discussion

From the obtained graphs, it can be seen that the traffic condition is changing continuously with time. The vehicle count is between 2 and 11, and the risk score changes from about 33% to 83%. When the number of vehicles increases, the risk value also generally increases. In the correlation graph, several cases with 12–14 vehicles have risk values above 70%, which shows that traffic density has a noticeable effect on the calculated risk.

The risk classification also gives a clear idea about the overall condition of the considered data. Out of 100 observations, 6 are low risk, 55 are moderate risk, and 39 are high risk. So, 94% of the observations come under moderate or high risk. This does not mean that 94% of real highway situations are dangerous; it only describes the distribution of the observations used in this analysis.

The vehicle tracking result varies from nearly 20% to 100%. In many time frames the tracking value is above 50%, while a few frames show lower stability. This is important because the risk calculation depends on information such as vehicle position and movement. If tracking becomes unstable, the accuracy of these parameters can also be affected.

Weather also shows some effect on the risk value. The weather severity index ranges

from 0.1 to 0.9, and the risk values in the observations range roughly from 25% to 85%. The points are not perfectly linear, which is reasonable because the final risk is also affected by traffic, vehicle movement, braking, and road conditions.

The alert graphs show that the system changes between 0 and 1 according to the detected condition. This means the alert is generated only at selected time frames instead of remaining active continuously. Overall, the results show that combining vehicle count, tracking information, weather condition, and risk calculation can provide a useful basis for identifying changing highway safety conditions.

6. Limitations

1. The system depends on continuous and accurate vehicle, sensor, GPS, and traffic data.
2. Complete 6G-V2X infrastructure is not yet widely available for real-time testing.
3. Sensor errors, missing data, and communication delay can affect the risk calculation.
4. The proposed model needs further testing on real highways under different traffic and weather conditions.
5. Continuous Digital Twin and risk processing requires sufficient computing resources.

7. Future Scope

1. The system can be tested using real-time highway and vehicle data.
2. AI and deep learning models can be added for earlier accident prediction.
3. The Digital Twin can include weather, road damage, pedestrians, and emergency vehicles.

4. Edge computing can be used to reduce processing and communication delay.
5. The system can be connected with ambulances, police, traffic signals, and smart highway infrastructure.
6. Future 6G-V2X deployment can support large-scale connected vehicle safety.

8. Conclusion

The proposed Digital Twin-Assisted 6G-V2X Intelligent Highway Safety System provides a way to monitor highway traffic and identify risky situations using connected vehicle and road information. The system considers factors such as vehicle speed, traffic density, sudden braking, lane deviation, inter-vehicle distance, and weather conditions for calculating the risk level.

From the obtained results, the risk values were between 33% and 83%. Among the 100 observations, 6% were low risk, 55% were moderate risk, and 39% were high risk. These results show that the system can identify different levels of traffic risk based on the changing highway conditions.

Overall, the proposed system brings together Digital Twin, 6G-V2X communication, traffic monitoring, and risk detection to observe highway conditions and provide safety warnings when risky situations are detected. The results show that this approach can be used for continuous highway safety monitoring.

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