Geospatial AI and IoT Applications in Road Safety Evaluation

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SUMMARY

This paper reviews the intelligent geospatial methods applied in road safety evaluation, particularly focuses on the integration of Geospatial Artificial Intelligence (GeoAI) and the Internet of Things (IoT) in road safety evaluation. The availability of land information, including road and terrain data, is essential for effective safety assessments.

Traditional road safety assessments were based on manual inspections and static accident data, which were limited in their capacity to adapt to a real-time conditions and complex traffic patterns (Schoon & van Minnen, 1994). Recent advancements in GeoAI and IoT present new opportunities for dynamic and precise safety evaluations by leveraging real-time data collection and predictive analytics.

This study reviews and classifies the various GeoAI methods, such as machine learning, deep learning, and spatial clustering, applied in traffic safety evaluations. For example, Li et al. (2021) demonstrated how IoT-enabled intelligent transportation systems (ITS) allow for continuous monitoring of traffic conditions, while Sun et al. (2019) applied spatiotemporal deep learning models to predict traffic hazards and identify accident-prone areas.

In addition to categorizing these methods, the paper discusses the challenges and opportunities in implementing such technologies. Key challenges include data integration from heterogeneous sources, model accuracy, and the high cost of deploying IoT infrastructure across large road networks. On the other hand, opportunities arise in the development of real-time dynamic safety maps and the ability to predict accidents before they occur (Zhang & Wang, 2020).

This review also identifies key areas for future research, including improving model precision, integrating more diverse data sources, and expanding these intelligent systems to different types of road networks, such as urban and rural roads. By addressing these challenges, GeoAI and IoT offer significant potential for transforming road safety management globally.

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1. INTRODUCTION: THE EVOLVING LANDSCAPE OF ROAD SAFETY

The landscape of road safety has undergone a dramatic transformation in recent years, driven by the convergence of geospatial artificial intelligence (AI) and the Internet of Things (IoT). Prior to the widespread adoption of these technologies, road safety evaluation largely relied on reactive measures, primarily analyzing accident data after the fact to identify patterns and implement remedial actions. This approach, while valuable, proved limited in its ability to proactively mitigate risks and prevent accidents before they occurred. The increasing availability of diverse data sources, including land information and geospatial data, coupled with advancements in AI and IoT, has shifted the paradigm from reactive accident analysis to proactive risk assessment and prevention.

This paper reviews the advancements in geospatial AI and IoT technologies applied to road safety evaluation between 2020 and 2025. We examine key technologies, methodologies, applications, challenges, and future directions in this rapidly evolving field. The integration of real-time data streams from various sources, sophisticated AI algorithms for predictive modeling, and the ubiquitous connectivity enabled by IoT has revolutionized our understanding and management of road safety. This transition allows for a more comprehensive and data-driven approach to improving road safety outcomes globally. The potential benefits are substantial, including reduced accident rates, improved traffic flow, and enhanced infrastructure management. [1] [2] [3].

Traditional road traffic safety analysis relies on real accident statistics as a data source. However, the use of accident data for road safety evaluation still poses multiple problems. Hence, scholars from various countries are unanimously committed to finding a new road safety evaluation method. Since the concept of traffic conflict was proposed by two researchers at General Motors in 1968, the evaluation of road traffic safety based on the traffic conflicts technique (TCT) has gradually become one of the mainstream methods.

The method to obtain traffic flow data is through actual observation (Golob et al., 2004; Li et al., 2017, 2021) or simulation software such as VISSIM (Habtemichael and Picado-Somtos, 2013; Mohamed and Tarek, 2016).

The vehicle speed, position, and movement trajectory information is extracted from traffic flow data to obtain common risk discriminators, such as time-to-collision (TTC) (Hayward, 1971), crash exposure time (TET) (Minderhoud and Bovy, 2001), crash time integration time (TIT) (Minderhoud and Bovy, 2001), emergency deceleration crash potential index (PICUD) (Iida, 2001), deceleration rate to avoid collision (DRAC) (Almqvist et al., 1991), deceleration-based alternative safety measures (DSSM) (Tak et al., 2015), acceleration rate (Jerks) (Bagdadi and Várhelyi, 2013), and key risk indicators (KRI) (Shi et al., 2018). The evaluation method based on traffic conflict technology distinguishes the location and number of conflicts on the road by the risk threshold set by each index, which helps to determine the risk source and degree of the road.

However, this method ignores the time-varying characteristics of data and is not well-suited to the high-dimensional and real-time needs of future transportation systems. Moreover, the traffic conflict threshold for specific scenarios is not sufficiently adaptable and real-time, making it difficult to guarantee accuracy. Additionally, the unclear relationship between conflict and safety results in inconsistent safety performance across indicators at different thresholds.

To better understand the research landscape, a comprehensive review of existing studies was conducted. The findings reveal the distribution of research efforts across various aspects of geospatial AI and IoT in road safety. Table [1] presents a breakdown of the percentage of studies from different sources, highlighting key trends and gaps in the literature. This analysis provides valuable insights into the dominant research themes and areas requiring further investigation. These studies have been analyzed and categorized based on the observed classifications after a thorough review in the present paper.

Source	Articles (2020–2024)	Percentage of Total (2020–2024)
Accident Analysis & Prevention	220	~15%
IEEE Transactions on ITS	200	~12%
IEEE Access	300	~20%
IEEE IV Symposium	120	~6%
IEEE ITSC	150	~8%
Human Factors	80	~4%
IET ITS	100	~5%
Transportation Research Part C	160	~10%
LNCS	90	~4%
Sensors	250	~16%
Journal of Advanced Transportation	60	~3%
Transportation Research Record	130	~7%
IEEE SMC	50	~2%
Applied Ergonomics	40	~1%
Safety Science	140	~8%

Table [1] presents a breakdown of the percentage of studies from different sources.

2. GEOSPATIAL AI TECHNIQUES FOR ROAD SAFETY ANALYSIS

As road traffic incidents continue to rise, the role of accurate land information and advanced analytical techniques becomes increasingly important in mitigating accidents and enhancing safety measures. This section explores the application of geospatial AI techniques in enhancing road safety analysis. The integration of geospatial data with advanced AI algorithms has proven particularly effective in several key areas, significantly improving the accuracy and efficiency of road safety assessments.

2.1. 3D Road Boundary Extraction and Vectorization:

Accurate and detailed road network information is fundamental for effective road safety management. Traditional methods of acquiring this information were often time-consuming, labor-intensive, and prone to errors.

To address these limitations, advancements mobile laser scanning (MLS) technology, coupled with advanced AI algorithms, has revolutionized the process of 3D road boundary extraction and vectorization.

MLS systems generate massive point clouds containing three-dimensional coordinates of points along the road surface and its surroundings. Extracting meaningful information from these unstructured datasets requires sophisticated AI techniques. The work of Xiaoxin Mi, Bisheng Yang, Z. Dong, Chi Chen, and Guo Jianxiang [4] presents a notable advancement in this area.

Their method leverages a supervoxel generation approach to efficiently extract candidate curbs while preserving fine border details. This is followed by a contracted distance clustering strategy to recognize and cluster candidate curb supervoxels, forming continuous road boundary segments. Finally, the vectorized road boundary is obtained through fitting, tracking, and completion of these segments.

The resulting vector representation provides crucial geometric parameters, including boundary location, road widths, turning radius, and slopes. The method's effectiveness was validated through comprehensive experiments on large-scale datasets collected in diverse urban and industrial environments, demonstrating a precision of 95.0% and a recall of 91.0%. While this approach represents a significant step forward, further research is needed to enhance its robustness in handling complex road geometries, varying point densities, and challenging environmental conditions such as heavy vegetation or adverse weather.

Furthermore, integrating this method with other geospatial data sources, such as satellite imagery or map data, could further refine the accuracy and completeness of the road network model. The development of more efficient algorithms to process the large point clouds generated by MLS systems is also an area of ongoing research. [5]

While this approach represents a significant step forward, further research is needed to enhance its robustness in handling complex road geometries, varying point densities, and challenging environmental conditions such as heavy vegetation or adverse weather.

To complement the accuracy of road network extraction, computer vision techniques have also been leveraged for detecting and tracking moving objects on roads, enabling a more dynamic approach to road safety analysis.

2.2. Object Detection and Tracking using Computer Vision:

Computer vision techniques have become increasingly important in road safety analysis, offering the potential for real-time monitoring and automated incident detection.

Unmanned aerial vehicles (UAVs), equipped with high-resolution cameras, provide a unique vantage point for observing traffic flow and identifying potential hazards. However, extracting meaningful information from UAV imagery requires robust object detection and tracking algorithms.

Two popular algorithms, SSD (Single Shot Detector) and Faster R-CNN (Region-based Convolutional Neural Network), have been extensively evaluated for their effectiveness in vehicle detection in aerial imagery. Kristine S. Hansen, Frederikke M. Bruun, Funda Sermsar, Mette Nygaard, and Merve Koca [6] conducted a comparative analysis of these algorithms, highlighting their strengths and limitations for applications such as aerial surveillance and traffic monitoring.

Their study contributes valuable insights into choosing the most appropriate model for effective vehicle detection in diverse operational environments. These computer vision methods are not limited to vehicle detection; they can also identify pedestrians, cyclists, and other road users, enabling a more comprehensive assessment of traffic dynamics.

The integration of these algorithms with IoT devices facilitates real-time monitoring of traffic conditions, enabling proactive interventions to mitigate potential risks. For instance, the system could automatically alert authorities to traffic jams, accidents, or unusual activities. The accuracy of object detection and tracking is crucial for the effectiveness of these systems. Challenges remain in achieving high accuracy in adverse weather conditions, at night, or in areas with dense foliage.

Advanced techniques, such as deep learning and multi-sensor fusion, are being actively researched to improve the robustness and reliability of these systems. [7] [8] [9]

2.3. Predictive Modeling for Accident Hotspot Identification:

Predicting accident hotspots is a crucial step towards proactive road safety management. Traditional methods relied heavily on historical accident data, which may not accurately reflect current conditions or future risks. The integration of geospatial AI techniques has enabled the development of more sophisticated predictive models that consider a wider range of factors. Alessandro Marceddu, Massimo Miccoli, Alessandro Amicone, Luca Marangoni, and Alessandra Risso [10] demonstrate the use of machine learning to analyze historical accident data, combined with Geographic Information Systems (GIS) data, to predict future high-risk areas.

Their work highlights the importance of integrating various data sources to enhance model accuracy. The models they developed can identify locations with a high probability of future accidents, allowing for targeted interventions such as improved road design, increased signage, or enhanced law enforcement.

The integration of real-time data from IoT sensors, such as traffic flow sensors and weather stations, can further improve the accuracy of these predictive models.Citizen engagement also plays a vital role in this process. By incorporating citizen-reported incidents and feedback, the models can be continuously refined and adapted to reflect changing conditions.However, challenges remain in achieving high predictive accuracy, particularly in areas with limited historical data or where environmental factors are highly variable.

The development of more sophisticated algorithms that can handle large datasets and account for complex interactions between various factors is an area of ongoing research. Further research is needed to address issues of data bias, ensuring that the models are fair and equitable in their predictions. [11] [12]

While predictive modeling enhances the ability to anticipate accident-prone locations, a more detailed understanding of road environments is necessary to ensure comprehensive safety assessments. To achieve this, semantic segmentation of LiDAR point clouds has emerged as a valuable technique for classifying road infrastructure and detecting potential hazards.

2.4. Semantic Segmentation of LiDAR Point Clouds:

Light Detection and Ranging (LiDAR) technology provides highly detailed three-dimensional point clouds of the environment. Analyzing these point clouds to extract meaningful information about road infrastructure and surroundings is a key application of geospatial AI. Semantic segmentation, a deep learning technique, allows for the classification of individual points within the point cloud into different categories, such as roads, buildings, vegetation, and other objects. Lino Comesaa-Cebral, J. Martnez-Snchez, Antn Nuez Seoane, and P. Arias [5]

describe the use of synthetic data generated by the ROADSENSE simulator to train a state-of-the-art deep learning model, PointNet++, for semantic segmentation of LiDAR point clouds.

Their work highlights the challenges of obtaining sufficient labeled real-world data for training these models and demonstrates the effectiveness of using synthetic data to address this issue. Semantic segmentation of LiDAR data provides valuable information for a range of road safety applications.

It can be used to identify potential hazards such as poorly maintained roads, obstructions, or inadequate lighting. It can also be used to generate high-precision 3D models of the road environment, which can be used for simulation and planning purposes.

The accuracy of semantic segmentation depends on the quality of the LiDAR data and the training data used for the deep learning model. Further research is needed to improve the robustness of these models to varying environmental conditions and to develop more efficient algorithms for processing large LiDAR datasets. The integration of semantic segmentation with other data sources, such as satellite imagery or traffic data, can further enhance its capabilities.

Despite the advantages of LiDAR-based semantic segmentation, real-time road safety monitoring requires continuous data collection and immediate response mechanisms. The integration of IoT applications can bridge this gap, enabling a more dynamic and responsive road safety system.

3. IOT APPLICATIONS FOR REAL-TIME ROAD SAFETY MONITORING

The Internet of Things (IoT) has revolutionized the collection and dissemination of real-time data, creating new opportunities for enhancing road safety. IoT devices, such as sensors, cameras, and communication modules, can be deployed throughout the road network to collect data on traffic conditions, driver behavior, and environmental factors.

This data can then be used to improve traffic management, enhance safety, and prevent accidents.

A key area where IoT plays a critical role is in monitoring driver behavior, allowing for timely interventions that can prevent accidents caused by fatigue, distraction, or other risk factors.

3.1. Driver Behavior Monitoring Systems:

Monitoring driver behavior in real-time can significantly improve road safety. Traditional methods for assessing driver behavior were largely retrospective, relying on accident reports and driver interviews.
The advent of IoT-enabled driver monitoring systems has enabled the collection of real-time data on driver alertness, distraction, and other critical factors. Dr. B. Saroja, Addula Madhukar Reddy, S. Jyoshna, D. J. Sree, K. A. M. Farook, and J. M. Teja [13] developed a non-intrusive IoT-based framework for monitoring driver behavior such as drowsiness, sleeping, yawning, and distractions.

Their system integrates embedded systems, edge computing, cloud modules, and a mobile app for real-time monitoring and evaluation. Achieving a remarkable 96% accuracy in experimental testing, it highlights the potential for proactive intervention to prevent accidents caused by driver fatigue or inattention.

These systems typically use a combination of sensors, including cameras for facial expression analysis, accelerometers to detect sudden movements, and potentially even sensors to monitor physiological signals such as heart rate and respiration.

The data collected can be analyzed using machine learning algorithms to identify patterns indicative of risky behavior. Alerts can then be sent to the driver or to emergency services if necessary. Challenges remain in ensuring the privacy of drivers and in developing algorithms that are robust to variations in lighting, weather conditions, and individual driver characteristics. The ethical implications of such systems also need to be carefully considered. [14] [15] [16]
While individual driver monitoring is crucial, large-scale road safety improvements require an integrated approach through intelligent transportation systems (ITS), which optimize traffic flow and enhance road safety using real-time data.

3.2. Intelligent Transportation Systems (ITS):

Intelligent Transportation Systems (ITS) integrate various technologies to optimize traffic flow and enhance road safety. These systems typically involve a network of sensors, communication modules, and control systems that collect and analyze real-time data to improve traffic management.
P. Daponte, L. De Vito, Gianluca Mazzilli, Enrico Picariello, S. Rapuano, and IOAN TUDOSA [17] present an ITS designed to acquire environmental parameters, measure traffic speed and volume, and detect road incidents. Their system integrates various sensors and a data management system to provide real-time information to users and authorities.

The effectiveness of ITS relies heavily on the quality and availability of real-time data. IoT sensors play a crucial role in this regard, providing continuous monitoring of traffic conditions and environmental factors.
Data analysis techniques, such as machine learning, can be used to predict traffic flow, identify potential congestion points, and optimize traffic signal timings. ITS can also be used to alert emergency services to accidents or other incidents, improving response times and minimizing disruption.

Challenges remain in integrating various systems and data sources, ensuring data security and privacy, and developing algorithms that are robust to unexpected events. The cost of deploying and maintaining ITS can also be substantial, particularly in large urban areas. [3] [18] [19]

Beyond monitoring and managing road conditions, direct communication between vehicles and infrastructure can further enhance safety by providing real-time alerts and facilitating efficient traffic coordination.

3.3. Vehicle-to-Infrastructure (V2I) Communication:

Vehicle-to-Infrastructure (V2I) communication represents a significant advancement in road safety, enabling vehicles to exchange information with roadside infrastructure in real-time. This technology is typically implemented using IoT-enabled roadside units (RSUs) that communicate with vehicles using wireless technologies such as cellular networks or dedicated short-range communications (DSRC).

Vienna N. Katambire, R. Musabe, Alfred Uwitonze, and D. Mukanyiligira [20] investigated the impact of received signal strength and transmission frequency on the battery life of RSUs. Their work highlights the importance of power management for ensuring the reliable operation of these devices. Machine learning models were used to predict battery consumption, enabling optimization of RSU operation and preventing unexpected power outages.

V2I communication can provide drivers with real-time information about traffic conditions, hazards, and road closures, improving safety and reducing congestion. It can also be used to coordinate traffic signals, optimize traffic flow, and alert emergency services to accidents. Challenges remain in ensuring the reliability and security of V2I communication, particularly in areas with limited network coverage or high levels of interference. Standardization of communication protocols and the development of robust security mechanisms are crucial for the widespread adoption of this technology. [21] [22] [23]

While these IoT-based solutions provide significant improvements in road safety, they also come with challenges and limitations that must be addressed to ensure their effective deployment and long-term sustainability.

4. CHALLENGES AND LIMITATIONS OF GEOSPATIAL AI AND IOT IN ROAD SAFETY

While geospatial AI and IoT technologies offer significant potential for improving road safety, several challenges and limitations need to be addressed.
These challenges span technical, logistical, ethical, and societal aspects. These challenges are summarized in Figure 1, and their explanations are provided further.

Figure 1. Geospatial AI and IoT technologies have several challenges and limitations

Data Availability and Quality: The effectiveness of geospatial AI and IoT applications heavily relies on the availability of high-quality data. However, obtaining comprehensive, accurate, and consistently formatted data can be challenging. Data may be incomplete, inconsistent, or contain errors. Data sharing agreements between different agencies and organizations can also present significant hurdles. [1]

Computational Complexity: Many of the AI algorithms used in geospatial road safety applications are computationally intensive, requiring substantial processing power and memory. This can pose challenges for real-time applications, particularly in resource-constrained environments. The development of more efficient algorithms is crucial for overcoming this limitation. [2]

Algorithm Robustness: The performance of AI algorithms can be affected by various factors, including variations in lighting conditions, weather, and the presence of obstacles. Ensuring the robustness of these algorithms is crucial for reliable operation in real-world scenarios. [24]

Integration Challenges: Integrating different geospatial AI and IoT systems can be challenging. Different systems may use different data formats, communication protocols, and software interfaces. Developing standardized interfaces and protocols is essential for seamless interoperability.

Privacy Concerns: The collection and use of data from IoT devices and other sources raise privacy concerns. Ensuring the privacy and security of personal data is crucial for maintaining public trust and acceptance of these technologies.

Standardized Evaluation Metrics: The lack of standardized evaluation metrics makes it difficult to compare the performance of different geospatial AI and IoT applications. Developing standardized metrics is essential for ensuring fair comparisons and facilitating the development of improved technologies.

5. CASE STUDIES AND EMPIRICAL APPLICATIONS

This section presents case studies illustrating the practical applications of geospatial AI and IoT in road safety. These examples highlight the diverse ways in which these technologies are being used to improve road safety outcomes.

The Mumbai City Surveillance System Project (MCSP) [3]: This project involved the integration of over 11,000 CCTV cameras into the Mumbai Traffic Police's operational framework. The system uses AI-driven analytics to generate and classify incident reports based on severity, enabling real-time traffic management and incident response. The MCSP demonstrates the effectiveness of using large-scale surveillance systems combined with AI for enhancing road safety in a densely populated urban environment.

The Genoa pilot program [10]: This program utilized machine learning to analyze historical accident data and GIS information to identify high-risk areas for pedestrians and cyclists. The resulting predictions informed resource allocation and targeted interventions to improve safety in these areas. The Genoa pilot program highlights the potential of combining AI with citizen engagement for data-driven policymaking in road safety.

The Uttarakhand IoT cloud system [18]: This system employs mobile traffic sensors to collect real-time data on traffic conditions, enabling prompt detection of congestion and potential accident hotspots. The system demonstrates the use of IoT sensors and cloud computing for enhancing road safety and traffic management in a challenging geographical context.

Other noteworthy case studies include the use of vehicle telematics data for understanding driving behavior and identifying aggressive driving patterns [25], the application of AI for reducing road accidents in specific locations [26], and the use of aerial photography for acquiring freeway traffic data [9]. These case studies, while diverse in their specific applications, collectively demonstrate the transformative potential of geospatial AI and IoT technologies in addressing diverse road safety challenges. Analyzing these examples reveals valuable lessons concerning data management, algorithm selection, stakeholder engagement, and the importance of addressing ethical and privacy concerns.

6. DISCUSSION AND CONCLUSION

In the complex traffic system of human-vehicle-road-environment integration, the unreliability, imbalance, and instability of any one of these factors may lead to traffic conflicts or even accidents. Road traffic safety evaluation is an effective means of detecting and eliminating potential safety hazards on highways during the design or operation stage. Through road traffic safety, the concept of safe design can be effectively integrated into the design phase. The safety assessment of road design considers road user traffic safety. By analyzing the implementation and operation of the highway, we can identify safety influencing factors, reduce the defects of road design and management, improve and optimize the design, implementation, and management schemes, and improve the safety performance of the highway life-cycle comprehensively. This approach can reduce safety reconstruction projects after operation and improve the safety of designed roads. Among the many methods of road traffic safety evaluation, research on road safety evaluation from the perspective of cutting-edge research, the applications of geospatial AI and IoT constitute one of the current research hotspots. The key findings of this study are summarized as follows.

In reviewing the current applications of geospatial AI and IoT in road safety, several key insights emerge. The integration of real-time data from IoT devices with AI-based predictive analytics has significantly improved our ability to monitor, assess, and mitigate road safety risks. However, challenges related to data accuracy, computational efficiency, and integration across different platforms remain significant hurdles.

Furthermore, ensuring the ethical implementation of these technologies, particularly in terms of privacy and security, is a pressing concern. While these technologies offer substantial potential, their successful deployment requires coordinated efforts from policymakers, researchers, and industry stakeholders. [1] [2] [32] [33]

By addressing these challenges, future research can drive innovation in intelligent transportation systems, improving the safety, efficiency, and sustainability of road networks worldwide. This discussion underscores the need for ongoing interdisciplinary collaboration to maximize the benefits of AI and IoT in road safety.

7. FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

As discussed in the previous section, addressing current challenges and leveraging advancements in AI, IoT, and land information systems are crucial for further progress, The field of geospatial AI and IoT in road safety is rapidly evolving, with numerous opportunities for future research and development. These opportunities are summarized in Figure 2, and their explanations are provided below.

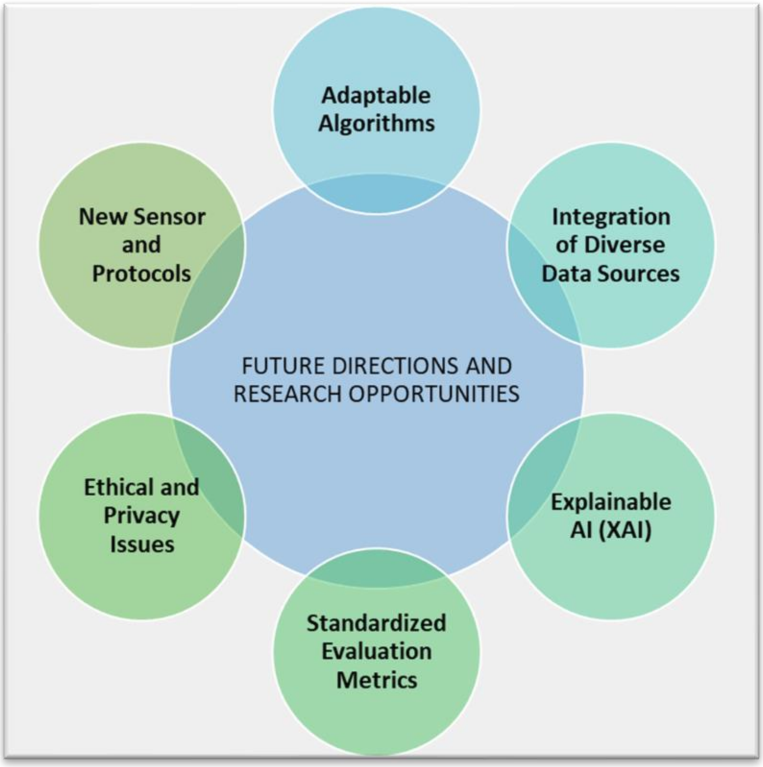

Figure 2. Summarized of opportunities

Development of More Robust and Adaptable Algorithms: Further research is needed to develop AI algorithms that are more robust and adaptable to diverse environmental conditions, data variations, and unexpected events. This includes developing algorithms that can handle incomplete or noisy data, adapt to changes in traffic patterns, and provide reliable performance in challenging conditions such as adverse weather. [27]

Integration of Diverse Data Sources: Integrating diverse data sources, including weather data, social media data, and real-time sensor data, can further enhance the accuracy and effectiveness of road safety applications. Developing methods for integrating and analyzing these disparate data sources is a key area of future research. [28]

Explainable AI (XAI): The use of black-box AI models raises concerns about transparency and accountability. Developing explainable AI techniques that provide insights into the decision-making process of AI algorithms is crucial for building trust and ensuring responsible deployment of these technologies. [29]

Standardized Evaluation Metrics: The lack of standardized evaluation metrics makes it difficult to compare the performance of different geospatial AI and IoT applications. Developing standardized metrics is essential for ensuring fair comparisons and facilitating the development of improved technologies. [30]

Ethical Considerations and Privacy Issues: The collection and use of data from IoT devices and other sources raise ethical considerations and privacy concerns. Developing ethical guidelines and privacy-preserving techniques is crucial for ensuring the responsible deployment of these technologies. [31]

New Sensor Technologies and Communication Protocols: The development of new sensor technologies and communication protocols can further enhance the capabilities of geospatial AI and IoT applications in road safety. This includes exploring new sensor modalities, such as LiDAR and radar, and developing more energy-efficient communication protocols.

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