Chapter 1

Introduction

1.1 Introduction

1.2 Autonomous Vehicle

An independent car is too called a self-driving car or driverless car or automated car. Anything the title but the point of the innovation is the same. Down the memory line, independent vehicle innovation tests begun in 1920 as it were and controlled by radio technology. Later on, trails started in 1950. From the past few a long time, upgrading robotization innovation day by day and utilizing all perspectives of utilizing in regular human life. The display situation of human creatures is dependent to computerization and mechanical autonomy innovation utilizing like agriculture, medical, transportation, vehicle and fabricating businesses, IT division, etc. For the final ten a long time, the vehicle industry came forward to inquiring about independent vehicle innovation (Waymo Google, Uber, Tesla, Renault, Toyota, Audi, Volvo, Mercedes-Benz, General Engines, Nissan, Bosch, and Continental's independent vehicle, etc.). Level-3 Independent cars came out in 2020. Everyday autonomous vehicle innovation analysts are understanding challenges. In the future, without human offer assistance, robots will manufacture autonomous cars utilizing IoT innovation based on client prerequisites and Favor these vehicles are exceptionally secure and comfortable in transportation frameworks like human traveling or cargo. Independent vehicles require information and upgrading persistently, so in this case, IoT and Artificial insights offer assistance to share the data gadget to the gadget. This audit paper tended to what the innovations and strategies are utilized in independent vehicles by writing surveys and the hole between them.

Trajectory of a vehicle

The direction of a vehicle is a multifaceted concept including its spatial facilitates, speed, speeding up, and indeed twitch, all fastidiously depicted as capacities of time (Reference 1). It typifies the complicated exchange between the vehicle's development and the transient measurement, giving a comprehensive understanding of its way through space over a assigned period. In the setting of independent vehicles, direction arranging develops as a foremost endeavor, looking for to chart the most ideal course for the vehicle's route from its show area to a foreordained goal (Reference 2).

This arranging handle unfurls in the midst of a complex web of contemplations, where different variables such as deterrents, winning activity conditions, and the inborn flow of the vehicle come into play. By unpredictably analyzing these components, direction arranging calculations endeavor to strike a sensitive adjust between effectiveness, security, and consolation, guaranteeing a consistent and strong travel for the independent vehicle.

Moreover, the centrality of vehicle direction modeling expands past the domain of independent driving, serving as a foundational foundation for the improvement of urban brilliantly administrations (Reference 3). Through fastidious examination and modeling of vehicle directions, analysts and professionals pick up important bits of knowledge into optimizing transportation frameworks, improving security measures, and invigorating the in general effectiveness of urban landscapes.

By leveraging progressed computational methods and real-world information, direction modeling encourages the recreation and forecast of vehicle developments, empowering partners to expect and relieve potential challenges proactively. Moreover, this granular understanding of vehicle directions empowers the refinement of urban foundation and transportation approaches, cultivating economical and flexible urban situations competent of obliging the advancing needs of cutting edge society.

In substance, the direction of a vehicle rises above simple spatial development, epitomizing a wealthy embroidered artwork of worldly elements and vital decision-making. As independent vehicles proceed to multiply and reshape the texture of urban versatility, the craftsmanship and science of direction arranging and modeling will stay vital apparatuses in the journey for more secure, more astute, and more effective transportation frameworks.

ADAS

Progressed Driver-Assistance Frameworks are electronic frameworks that offer assistance the driver whereas driving the vehicle by giving exact perusing of the information collected from street environment utilizing different hardware to guarantee street security. When planned with a secure human-machine interface, they are aiming to increment driver security and generally street security. Most mishaps happen due to human mistake which can be effectively dodged by the utilize of fake insights along with electronic innovation. The ADAS are expecting to maintain a strategic distance from street mischances which ordinarily occur due to human blunder by utilizing electronic innovation. The utilize of this kind of framework in vehicles is awesome for applications like daze spot observing, lane-keep help and forward collision caution. The utilize of ADAS is a most to guarantee street security and appropriate activity management.[1]

Advanced driver-assistance frameworks (ADAS) are advances that help drivers with the secure operation of a vehicle. Through a human-machine interface, ADAS increment car and street security. ADAS utilize robotized innovation, such as sensors and cameras, to identify adjacent impediments or driver blunders, and react appropriately. ADAS can empower different levels of independent driving.[2]

Mixed Traffic Environments

Blended activity situations allude to roadways where different sorts of vehicles share the same space, counting conventional human-driven vehicles, bikes, cruisers, people on foot, and progressively, independent vehicles. These situations show interesting challenges and elements due to the contrasting speeds, sizes, behaviors, and vulnerabilities of the distinctive street. To securely and productively explore in complex urban activity, independent vehicles must make mindful forecasts in connection to encompassing traffic-agents (vehicles, bikes, people on foot, etc.). A challenging and basic assignment is to investigate the development designs of diverse traffic-agents and anticipate their future directions precisely to offer assistance the independent vehicle make sensible route decision.[1] Productive activity control can reduce activity clog, decrease fuel utilization, and move forward activity security. With the improvement of communication and robotization innovations, customary. vehicles (RVs), associated vehicles (CVs), and associated and mechanized vehicles (CAVs) will coexist on urban streets in the close future. [2] Heterogeneity is one of those characteristics which separate activity conditions of a creating nation from other created countries. The heterogeneity which speaks to the differing qualities among vehicle categories is suspected to have antagonistic impacts on path teach, blockage potential, and street users’ safety.[3]

Overview

Motivations

The motivations behind the study on trajectory prediction of vehicles in urban areas are multifaceted and address several critical aspects of autonomous vehicle technology and its integration into real-world settings.

Safety Enhancement: The primary motivation lies in improving the safety of autonomous vehicles operating in mixed traffic environments. By accurately predicting the trajectories of other road users, such as human-driven vehicles, cyclists, and pedestrians, autonomous vehicles can proactively anticipate and respond to potential collision scenarios.

Human-Autonomous Vehicle Interaction: In mixed traffic environments, human drivers often rely on implicit communication cues, such as eye contact and hand gestures, to negotiate interactions with other road users. Autonomous vehicles must be able to interpret and respond to these social cues effectively to navigate safely and smoothly. Therefore, the thesis aims to develop interactive trajectory prediction models that enable autonomous vehicles to anticipate and adapt to the behavior of human road users, fostering more natural and intuitive interactions on the road.

Traffic Flow Optimization: Effective trajectory prediction algorithms can contribute to optimizing traffic flow and reducing congestion in mixed traffic environments. By accurately forecasting the movements of different vehicles and anticipating potential bottlenecks or conflicts, autonomous vehicles can adjust their trajectories dynamically to minimize disruptions and maintain smooth traffic flow, thereby enhancing overall efficiency and mobility.

Real-World Deployment Challenges: Despite significant advancements in autonomous vehicle technology, deploying these vehicles in real-world environments poses numerous challenges, including unpredictable human behavior, complex traffic scenarios, and varying environmental conditions. By addressing the specific challenges of trajectory prediction in mixed traffic environments, the thesis aims to develop practical solutions that can facilitate the safe and efficient integration of autonomous vehicles into diverse urban and suburban settings.

Regulatory and Policy Implications: The successful deployment of autonomous vehicles hinges not only on technological advancements but also on regulatory frameworks and policy decisions that govern their operation. By providing insights into the capabilities and limitations of interactive trajectory prediction models, the thesis can inform policymakers and regulatory agencies in developing standards and guidelines for the safe and responsible deployment of autonomous vehicles in mixed traffic environments.

Overall, the thesis on interactive trajectory prediction of autonomous vehicles in mixed traffic environments is driven by the overarching goal of advancing the state-of-the-art in autonomous vehicle technology and accelerating the transition towards safer, more efficient, and more sustainable transportation systems. By addressing key challenges and opportunities in trajectory prediction, the research contributes to realizing the full potential of autonomous vehicles in reshaping the future of mobility.

Objectives

The objectives of the thesis on trajectory prediction of vehicles in urban areas are designed to address the complexities and challenges inherent in the integration of autonomous vehicles into real-world settings. These objectives encompass both technical advancements and practical applications, aimed at enhancing the safety, efficiency, and usability of autonomous vehicle technology in mixed traffic environments. The key objectives include:

Develop Accurate Trajectory Prediction Models: The primary objective is to develop advanced machine learning and predictive modeling techniques capable of accurately forecasting the trajectories of diverse road users, including human-driven vehicles, cyclists, and pedestrians. These models should incorporate factors such as historical data, environmental conditions, and social interactions to improve prediction accuracy and reliability.

Enhance Human-Autonomous Vehicle Interaction: Another objective is to enhance the interaction between autonomous vehicles and human road users by developing intuitive and socially-aware trajectory prediction algorithms. This involves analyzing and interpreting human behavior cues, such as gestures, eye contact, and body language, to anticipate and respond to the intentions of other road users effectively.

Improve Safety and Collision Avoidance: A key objective is to improve safety and collision avoidance capabilities of autonomous vehicles through proactive trajectory prediction and risk assessment. By accurately identifying potential collision scenarios and hazardous situations in advance, autonomous vehicles can take preemptive actions, such as adjusting speed or changing lanes, to mitigate risks and ensure safe navigation in mixed traffic environments.

Optimize Traffic Flow and Efficiency: The thesis aims to optimize traffic flow and reduce congestion in mixed traffic environments by developing trajectory prediction models that facilitate smoother interactions between autonomous vehicles and other road users. By dynamically adjusting trajectories based on real-time traffic conditions and congestion patterns, autonomous vehicles can contribute to improving overall traffic efficiency and mobility.

Validate and Evaluate Performance: An essential objective is to validate and evaluate the performance of the developed trajectory prediction models through extensive simulations and real-world testing scenarios. This involves assessing prediction accuracy, responsiveness, and reliability under diverse environmental conditions and traffic scenarios to ensure the robustness and effectiveness of the proposed approaches.

Overall, the objectives of the thesis are aligned with the overarching goal of advancing the state-of-the-art in autonomous vehicle technology and facilitating the seamless integration of autonomous vehicles into diverse urban and suburban landscapes. By addressing these objectives, the research contributes to realizing the potential benefits of autonomous vehicles in improving road safety, traffic efficiency, and mobility for society as a whole.

Challenges

The primary focus of this thesis revolves around the intricate task of trajectory prediction within a diverse and dynamic mixed traffic environment. This environment comprises various types of road agents, including but not limited to buses, trucks, motorcycles, pedestrians, and even animals. In addition to these diverse entities, the presence of traffic infrastructure elements such as traffic lights, traffic signs, and speed breakers further complicates the prediction task.

The challenges inherent in this scenario stem from the complex interactions and behaviors exhibited by the different road agents. Each type of agent possesses its own set of movement patterns, intentions, and responses to external stimuli. For instance, buses and trucks may have slower acceleration and deceleration rates compared to motorcycles, while pedestrians and animals exhibit unpredictable movements.

Furthermore, the dynamics of traffic signs and signals add another layer of complexity. Deciphering the intentions of road agents in response to these signals, such as stopping at a red light or yielding at a stop sign, requires a nuanced understanding of traffic rules and behavioral norms.

The ultimate goal of this thesis is to develop robust prediction models capable of accurately forecasting the trajectories of various road agents within this heterogeneous environment. These predictive capabilities are crucial for the successful implementation of autonomous driving systems and Advanced Driver Assistance Systems (ADAS). By effectively anticipating the movements of surrounding agents, autonomous vehicles can make informed decisions to ensure safe and efficient navigation through mixed traffic scenarios.

Thesis Organization

Conclusion

In this chapter, we've provided a comprehensive overview of the study to come, offering a preliminary look at the tasks that lie ahead. Through our discussion, we've highlighted the inspiration behind the research, articulated the objectives we seek to accomplish, and identified the challenges that will be further explored in subsequent chapters. By laying this groundwork, we've set the stage for a more in-depth examination of the motivations driving our inquiry, the specific goals we aim to achieve, and the obstacles we anticipate encountering. This introductory discussion serves as a foundation upon which we will build a deeper understanding of the complexities inherent in our research domain and the strategies required to address them effectively.

Chapter 3

Literature Review

Introduction

Related Works

"TraPHic\_Trajectory\_Prediction.pdf" introduces a novel LSTM-CNN hybrid network for trajectory prediction in dense traffic scenarios. The paper addresses the limitations of existing models by incorporating factors such as velocity, turning radius, and local density to enhance prediction accuracy. By leveraging the strengths of both CNNs and LSTMs, the proposed model achieves a significant 30% improvement in accuracy on dense datasets, particularly showcasing its effectiveness on a new Asian urban dataset. Unlike traditional approaches, this model can handle heterogeneous road agents without explicit behavior assumptions, making it versatile for various traffic conditions.

The paper contributes to the field by bridging the gap in accurate trajectory forecasting, especially in dense traffic environments. While existing datasets like ApolloScape and NGSIM simulations offer diverse scenarios, this paper's approach provides a unique perspective on traffic prediction. By drawing inspiration from RNNs and LSTMs for sequence modeling, the model showcases the potential of combining different neural network architectures for more effective traffic prediction. However, the paper acknowledges limitations in the application of generative models like VAEs and GANs due to challenges in back-propagation during training. Despite this, the successful utilization of generative models for trajectory prediction in pedestrian crowds and sparse traffic scenarios demonstrates the paper's innovative contributions to the field.

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The paper introduces TrafficPredict, a novel LSTM-based algorithm for predicting trajectories of heterogeneous traffic agents in urban environments. The main contribution lies in proposing a new approach to handle trajectory prediction scenarios where different types of traffic agents, such as vehicles, bicycles, and pedestrians, interact with each other. To model these interactions, the authors introduce a 4D graph structure that captures spatial and temporal relationships between agents, as well as similarities and differences between agent categories.

The proposed architecture consists of two main layers: an instance layer and a category layer. The instance layer aims to capture the movements and interactions of individual agents using LSTM networks and attention mechanisms. The category layer, on the other hand, learns the movement patterns and similarities of agents within the same category, providing guidance to refine the predictions for individual instances. By integrating information from both layers, the algorithm can leverage the collective knowledge of agent interactions and category-specific patterns.

To facilitate research in this area, the authors have collected and released a new large-scale trajectory dataset in urban traffic, featuring various traffic agents and interactions. Experimental results on this dataset demonstrate improved accuracy compared to previous state-of-the-art methods, with about 20% improvement in average displacement error and final displacement error.

Despite these contributions, the paper acknowledges some limitations. The accuracy of the proposed method may vary based on traffic conditions and the duration of observed past trajectories. Additionally, the method does not explicitly consider constraints such as lane directions, traffic signals, and traffic rules, which could potentially further improve prediction accuracy. The evaluation is also limited to a specific urban environment, and the performance may need to be validated in different traffic scenarios and environments. Furthermore, the paper does not provide a detailed comparison of computational efficiency and scalability with other methods, nor does it discuss the potential challenges in extending the method to handle a larger number of traffic agent categories or more complex interactions.

Overall, the paper presents a novel approach for trajectory prediction in heterogeneous traffic scenarios, contributing to modeling spatial and temporal relationships, learning category-specific patterns, and providing a new dataset for evaluation. However, there are opportunities for further improvements and validations in different traffic environments and conditions.

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Recurrent Meta Neural network

The thesis paper titled "Interactive Trajectory Prediction for Autonomous Driving via Recurrent Meta Program Induction Network" by Chiyu Dong, Yilun Chen, and John M. Dolan presents a novel approach for predicting the trajectory of surrounding vehicles in autonomous driving scenarios. The authors highlight the importance of accurately predicting the future trajectories of neighboring vehicles for autonomous cars to interact and cooperate effectively in complex driving situations such as lane changes and merging.

The paper provides a comprehensive literature review of existing methods for interactive trajectory prediction and cooperative driving, categorizing them into rule-based, optimization-based, and probabilistic/learning approaches. The authors critique the limitations of these methods, such as the lack of consideration for interactions among vehicles, the need for manually designed probabilistic models and reward functions, and the inability to handle continuous action spaces or sequential information effectively.

The authors propose a Recurrent Meta Induction Network (RMIN) framework to address these shortcomings. The RMIN is based on the Conditional Neural Process (CNP), which uses a set of demonstration examples and an additional observation as inputs to predict the corresponding output. However, the original CNP does not consider the sequential information in the inputs due to permutation invariance requirements. The RMIN overcomes this limitation by replacing the original demonstration sub-net with a recurrent neural cell, allowing it to capture sequential information in the historical trajectories of surrounding vehicles.

The proposed method is evaluated on real trajectory data from the NGSIM dataset, specifically focusing on lane-change scenarios. The results demonstrate that the RMIN outperforms traditional kernel methods and the original CNP in terms of mean error in both longitudinal and lateral trajectory prediction. The authors attribute this improvement to the RMIN's ability to capture sequential information and the use of a fully connected network as the generator, which explicitly models the relationships among positions in the predicted trajectory.

Overall, the paper presents a novel and effective approach for interactive trajectory prediction in autonomous driving scenarios, addressing the limitations of existing methods and demonstrating its superiority through experimental results on real-world data.

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Driver Behavior Paper:

The paper starts with a comprehensive writing audit, covering considers on driving behaviors from the areas of social brain research and transportation inquire about. These thinks about have characterized drivers based on their levels of forcefulness and carefulness, regularly connecting these behaviors with components such as driver age, identity characteristics, and reactions to surveys. Be that as it may, the creators highlight the require for an approach that can recognize driver behaviors exclusively from sensor information, as would be required for independent driving systems.

The creators at that point examine earlier work related to direction highlights, independent car route, and adjustment to human driver behaviors. They distinguish restrictions in existing strategies, such as the failure to handle nonstop activity spaces, the require for physically outlined probabilistic models and remunerate capacities, and the need of thought for consecutive data in trajectories.

To address these confinements, the creators propose a novel set of direction highlights, counting a path taking after metric and a relative speed metric, that can be effortlessly extricated from vehicle directions. They conduct an expand web-based client ponder to build up a data-driven mapping between these highlights and six driver behaviors: forcefulness, carelessness, debilitating behavior, carefulness, cautiousness, and timidity.

Through figure investigation, the creators distinguish a inactive variable that summarizes these behaviors and can be utilized to degree the level of mindfulness required when driving close other vehicles. They join this mapping, called the Direction to Driver Behavior Mapping (TDBM), into an existing independent driving calculation, AutonoVi, to empower more secure real-time route by maintaining a strategic distance from possibly unsafe drivers.

The paper presents exploratory comes about illustrating the viability of the proposed approach in terms of made strides direction expectation exactness and more secure route choices compared to standard strategies.

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Motion of road agent paper:

The paper presents a deep learning approach for predicting the future motion of vulnerable road users (VRUs) like pedestrians and bicyclists for autonomous driving applications. It builds upon recent work using rasterized images of the surrounding context as input to convolutional neural networks (CNNs) for motion prediction.

Traditional approaches for VRU motion prediction have relied on hand-crafted models like the social force model and Inverse Reinforcement Learning that attempt to encode interactions between actors and obstacles. However, the need to manually design features makes them difficult to scale to complex environments.

Many recent deep learning methods have applied recurrent models like LSTMs for motion prediction, incorporating factors like neighboring actor interactions through pooling or attention mechanisms. Some work has included static scene context by concatenating CNN features from scene images with actor states. However, most prior work does not fully leverage rich map data available in autonomous driving.

A key novelty of this paper is encoding high-definition map data like lane geometry, crosswalks, and traffic light states directly into the rasterized input images. The authors explore several variations of the rasterization pipeline and their impact, such as pixel resolution, rotating the frame to the actor's perspective, and different schemes for encoding map elements.

On the modeling side, the paper proposes a new efficient CNN architecture called FastMobileNet designed for fast inference speed on GPUs. It also introduces a spatial feature fusion technique to combine the rasterized context with other actor state features like velocity and acceleration.

Through extensive experiments, the authors demonstrate the benefits of their approach over baselines like unscented Kalman filters and Social-LSTM models, both in terms of prediction accuracy and inference speed. They also provide insights into which rasterization choices are most impactful for VRU prediction.

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Map Driver Intention.pdf

The paper addresses the problem of estimating a driver's intended maneuver at road intersections for applications like advanced driver assistance systems and autonomous driving. It focuses on incorporating contextual information from digital maps and handling uncertain observations.

Previous work on maneuver intention estimation can be broadly categorized into discriminative and generative approaches. Discriminative methods like learning prototype trajectories from data are limited in generalizing to arbitrary intersections. Generative approaches explicitly model the process between intention and vehicle behavior, but often do not leverage map context.

Some works have used probabilistic representations like Bayesian filters, probabilistic finite state machines, and hierarchical hidden Markov models to model maneuver evolution. However, they either do not utilize map information or only consider topological characteristics like lane connectivity.

The European PReVENT-INTERSAFE project incorporated intersection topology but not geometry for probabilistic intention estimation. On the other hand, modeling approaches based on Gaussian processes have included geometric context like road borders, but assume accurate lane-level positioning which may not be realistic.

In contrast, the proposed approach uses a Bayesian network to probabilistically combine uncertain observations of the vehicle's behavior (position, orientation, turn signal) with both topological information like lane connectivity as well as geometric characteristics like lane shapes and paths extracted from a detailed digital map representation.

The key novelties are: 1) Jointly exploiting topological and geometric map context, and 2) Handling uncertainties in observations through virtual evidence in the Bayesian network instead of hard lane assignments. This allows reliable intention predictions even when the driver's behavior is inconsistent or ambiguous.

The method is evaluated on real traffic data, including scenarios with inconsistent driver behavior. A tailored evaluation procedure assesses if the system can reliably estimate maneuver intention when sufficient evidence is available while maintaining high uncertainty when observations are contradictory.

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BAT

This thesis paper proposes a novel behavior-aware trajectory prediction model (BAT) for autonomous driving that incorporates insights from traffic psychology, human behavior, and decision-making. The authors highlight the critical need for accurate trajectory prediction of surrounding vehicles to enable fully autonomous driving.

The paper reviews prior work in trajectory prediction, categorizing approaches as physics-based, statistics-based, and deep learning-based. Physics-based methods use principles of physics and mechanics but often exhibit lower accuracy. Statistics-based approaches describe trajectories using predefined maneuver distributions and tend to perform better than physics-based ones. Deep learning methods like RNNs, CNNs, and Transformers have generally demonstrated superior performance, especially for long-term prediction.

The authors argue that mimicking human-like comprehension and response to surrounding traffic scenarios could be a breakthrough. They hypothesize that accounting for driver behaviors in the decision-making process of autonomous vehicles can enhance driving performance, motivating a deeper analysis of driver behavior for trajectory prediction.

The paper incorporates findings that drivers exhibit certain behavior patterns that are predictable, persistent, and consistent based on their driving styles. It also notes that humans tend to perceive their surroundings in relative terms like "slightly ahead and to the right" rather than absolute coordinates, suggesting polar coordinates may better represent human perception for trajectory prediction.

The proposed BAT model consists of behavior-aware, interaction-aware, priority-aware, and position-aware modules to capture driver behavior, vehicle interactions, relative importance of agents, and ego vehicle positioning respectively. A novel pooling mechanism using polar coordinates is introduced to align with human observation instincts.

The authors evaluate BAT across multiple real-world datasets (NGSIM, HighD, RounD, MoCAD) and show its superior performance over state-of-the-art baselines in terms of prediction accuracy and efficiency, even when trained on reduced data. Ablation studies confirm the importance of the key model components. Visualizations demonstrate BAT's ability to interpret driving behavior like humans for reliable trajectory predictions.

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Mixed Autonomy

The paper presents a novel trajectory prediction model called GaVa (Graph Attention for Vehicle Anticipation) for autonomous vehicles in mixed-autonomy traffic environments.

Traditional approaches to trajectory prediction have largely relied on computational methods like time-series analysis. In contrast, GaVa incorporates findings on how human drivers allocate visual attention based on factors like speed, proximity, and orientation. It introduces an "adaptive visual sector" mechanism that mimics how a driver's central field of view dynamically adjusts with speed.

The paper reviews prior work using deep learning for trajectory prediction, including Long Short-Term Memory (LSTM) networks, Convolutional Neural Networks (CNNs), and Graph Neural Networks (GNNs). Models combining CNNs and LSTMs or utilizing multi-head attention have shown promising results.

Research on visual behavior in driving is also covered, such as how a driver's visual field changes with speed, with slower speeds allowing a broader focus. Eye-tracking studies have confirmed drivers concentrate on the central region for vehicle control but shift attention for maneuvers like lane changes.

The proposed GaVa model contains several novel components inspired by this prior work: a Context-Aware Module for capturing temporal dependencies, an Interaction-Aware Module using CNNs and Graph Attention Networks to model spatial interactions between agents, a Vision-Aware Module incorporating an adaptive visual sector based on speed, and a Priority-Aware Module using a Transformer encoder-decoder for multi-trajectory prediction.

The authors evaluate GaVa on the NGSIM, HighD, and MoCAD datasets, outperforming state-of-the-art baselines by at least 15.2%, 19.4%, and 12.0% respectively across prediction horizons. Ablation studies validate the importance of components like the Interaction-Aware and Vision-Aware Modules.

**Conclusion:**