Autonomous infrastructure with monitoring in true 3D

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Summary

Just as modern vehicles are becoming smarter and more autonomous, we aim to explore how to make infrastructure more intelligent. The study aims to study automated safety based on LiDAR infrastructure monitoring to ensure the safety of for road users both inside and outside the vehicle. The LiDAR (Light Detection and Ranging) technology is essential for autonomous vehicles and robots, offering a high-resolution digital representation of the physical environment using laser pulses. This spatial awareness is crucial for safe navigation in real-world environments.

To achieve traffic-safe automation, smart infrastructure is proposed, which can complement intelligent vehicles. Fixed LiDAR sensors in the infrastructure can provide comprehensive environmental data to both human drivers and autonomous vehicles, enhancing overall safety.

The pilot study addresses key questions regarding the necessary information from LiDAR for comprehensive environmental understanding and an example of how the system can be designed to achieve automated enhanced safety.

Table of contents

Introduction

Just as modern vehicles are becoming smarter and more autonomous, we aim to explore how to make infrastructure more intelligent. LiDAR (Light Detection and Ranging) technology is one of the most central technologies for self-driving vehicles and autonomous robots, as it provides a high-resolution digital representation of the physical environment using millions of laser pulses. Spatial awareness is essential for these vehicles to navigate safely in real-world environments. One way to ensure traffic-safe automation is to make the infrastructure smart instead of solely relying on intelligent vehicles, the perception abilities of self-driving vehicles are limited, especially where their view is blocked by other vehicles or obstacles (Arnold et al., 2020; Mo et al., 2024). Smart infrastructure is feasible, cost-effective, and powerful, particularly when all activities and traffic occur in confined areas, such as industrial zones. Instead of each vehicle being responsible for its own safety, fixed LiDAR sensors in the infrastructure can provide both human drivers and autonomous vehicles with comprehensive environmental information, which individual vehicles may lack (Arnold et al., 2020).

The goal to reduce human errors

The European Commission's Vision Zero initiative drives the ongoing efforts to enhance road safety and reduce accidents. As highlighted in one of their reports, understanding the factors that contribute to these accidents is a crucial part of the strategy (EU Commission, 2023; (Federal Highway Administration, 2022). Along with other researchers (Afandizadeh & Hamid, 2023; Bucsuházy et al., 2020), they point out that the human factor is responsible for approximately 95% of accidents. This factor is broad, encompassing issues such as insufficient skills, inattention, medical conditions, speeding, and violations of traffic laws (Shetty et al., 2021). As traffic density on roads increases, it becomes harder for drivers to quickly identify both static and moving obstacles, such as trolleys, pedestrians, bicycles, and cyclists. Thus, reliable, real-time obstacle detection systems are crucial for detecting potential collision risks and providing warnings, allowing for timely evasive actions (Shetty et al., 2021; Yu & Marinov, 2020).

Around 50% of failure scenarios occur in urban areas, highlighting the critical need for addressing system failures in these environments. Urban areas account for 38% of failures, while only 7% occur on highways. Interestingly, only about 16% of errors are related to cloudy weather, and just 1% occur during rainy or snowy conditions. Most disengagements (82%) happen in good weather, demonstrating that most errors are not linked to bad weather conditions (Yu & Marinov, 2020). To achieve Vision Zero, the human factor must be addressed, and this requires a wide range of solutions tailored to its diverse causes. Additionally, special attention must be given to improving system performance in urban areas, where failures are more prevalent (Federal Highway Administration, 2022).

Blind spots are a common challenge for drivers, particularly when changing lanes. To check for vehicles in the adjacent lane, drivers typically must turn their head about 90 degrees, taking their eyes off the road ahead for a moment (Arnold et al., 2020; Fukatsu & Sakaguchi, 2021; Shetty et al., 2021). However, during this 1-second glance, the driver loses sight of the road in front, creating a blind zone of approximately 30 meters at a speed of 100 km/h. This brief loss of vision can significantly increase the risk of accidents, as the driver may fail to notice a potential hazard ahead while focusing on the side view (Fukatsu & Sakaguchi, 2021; Yu & Marinov, 2020). Now as LiDAR perhaps cannot provide a solution for diseases and lack in skills, but it could be a great tool for addressing problems such as speeding, breaking traffic rules and lack of attention. LiDAR can be a tool to notify drivers that there is another vehicle speeding or breaking traffic rules and could provide the warnings necessary for them to notify the drivers and be able to get out of the way or stop before heading into a risk zone. Also, LiDAR can provide notifications to drivers not paying attention to the road, warning them of vehicles abruptly stopping or pedestrians walking out in the road.

Increased interest in vehicle-to-infrastructure

The vehicle-to-infrastructure (V2I) field has become an increasingly significant area of research, especially since 2020, as studies on self-driving vehicles and robots expand (Mo et al., 2024; Wu et al., 2023). V2I aims to address the perceptual limitations of individual vehicles and robots and is particularly suitable for confined traffic areas (Mo et al., 2024). Intelligent Traffic Systems Market Growth is projected to reach USD 27.56 Billion by 2030, growing at a CAGR of 12.3% (Straits Research), driven by safety and automation. Even modern vehicles equipped with driver assistance systems—designed to reduce accidents and optimize driving—would benefit from external environmental data. For instance, a LiDAR sensor installed in an industrial setting could greatly enhance safety at a problematic intersection, where the vehicles are known and can be communicated with (Mo et al., 2024; Shan et al., 2020).

There is extensive research on LiDAR in the automotive industry and robotics, where the technology is recognized as suitable for collision avoidance and as a central source for vehicle or robot perception. LiDAR technology has evolved significantly, particularly in the automotive sector, where sensors must be capable of stopping a vehicle at highway speeds upon detecting an object hundreds of meters away. This application is more complex than using LiDAR sensors installed in the infrastructure, such as in an intersection, to warn and manage traffic by detecting risks or collisions.

Knowing the location of vehicles and other objects on the road is a significant contribution to traffic safety and efficiency. By utilizing information from the infrastructure, we can accurately track surrounding vehicles' positions in real-time, allowing for the prediction of potential risks. This information plays a crucial role in the development of autonomous systems that can respond more quickly and precisely to changes in traffic dynamics (Cheng et al., 2020; Shan et al., 2020).

The gap between capability and practical usability

Although there is considerable research in V2I, including LiDAR technology, a complete solution that connects infrastructure perception to communication with the right vehicle or the implementation of suitable actions (like automatic braking) is still lacking. Both research and experience of clients confirm an interest to use LiDAR in infrastructure, as equipping every vehicle with sensors would be too costly and complex. While current traffic monitoring systems can provide highly accurate real-time information, challenges remain in improving the system's reliability, scalability, and security (Creß et al., 2023).

The concept of utilizing LiDAR in infrastructure contributes to safer traffic automation at all stages, from driver-operated to fully autonomous vehicles. This approach provides critical safety information about the overall environment and risks that individual vehicles may not detect.

The project aims to develop a feasibility study addressing the following questions:

- Which information from LiDAR in the infrastructure should be utilized to gain a comprehensive understanding of the environment to avoid accidents and risks?
- How should the system be designed to enhance the safety through automated monitoring?

The study includes an overview of how the problem is solved today, known challenges in implementing LiDAR solution, overview of regulations, behaviours and culture, and proposed technical solution to address the needs. The study is mainly limited to the regulations within Europe, but some conclusions are relevant independently of country.

Overview of Technologies and Research

The Global Goal 3.6 aims to halve the number of global deaths and injuries caused by road traffic accidents by 2020 (*Mål 3: God Hälsa Och Välbefinnande - Globala Målen*, 2024), recognizing the urgent need for safer transportation systems. Road traffic injuries represent a significant public health issue, with millions of lives lost or affected each year. 28% of all fatal crashes and 58% nonfatal crashes are intersection crashes, resulting in $179 billion, or 53% of all economic costs from motor vehicle crashes (Blincoe, et al., 2022). Achieving the safety targets are vital for creating safer communities and ensuring equitable access to mobility for all individuals, ultimately contributing to overall health and well-being.

The challenges of existing solutions

This section summarizes the main problems with existing solutions and how LiDAR technology in infrastructure could address those problems. Current developments in the field are not yet advanced enough to ensure 100% precision and accuracy, indicating that additional effort and innovation are required to overcome existing limitations (Yu & Marinov, 2020).

The total understanding of the surroundings is missing

Signalized intersections are today a common method of managing traffic of vehicles and pedestrians. However, as these intersections often are regulated by sensors in the ground for the vehicles and activations buttons for pedestrians that change the light of the signals, which then are timed based, these types of intersections unfortunately have become hotspots for traffic incidents (Ansariyar, 2023). LiDAR technology emerges as a potential tool to address these incidents, both in a way of monitoring and getting a better understanding of why the accidents occur but also as a solution to hinder the accidents (Ansariyar, 2023; Arnold et al., 2020; Mo et al., 2024; Shan et al., 2020; Srinivasan et al., 2022). The inability to fully understand the scene can lead to incorrect assessments of speed and the seriousness of conflict situations (Mo et al., 2024; Arnold et al., 2020; Wu et al., 2023). As LiDAR can provide awareness in real time, the system has the possibility to signal and communicate and alert drivers or the traffic management system to avoid a possible accident in an early stage (Ansariyar, 2023; Mo et al., 2024; Srinivasan et al., 2022). LiDAR in the infrastructure also provide a bird's perspective that is not possible to achieve with equipping the vehicle with smart sensors.

Real-life scenarios are complex, and conditions are various

A smart system needs to address the challenges posed by extreme weather conditions (rain, snow, fog) and urban-specific situations like shadows, reflections, potholes, and poor lighting. It must also account for unique urban scenarios, such as exhaust emissions, reflections from smooth surfaces, and awareness when opening vehicle doors. Additionally, the system should be capable of detecting emergency service vehicles like ambulances, fire trucks, and police cars that behave differently (Yu & Marinov, 2020).

As cameras have trouble providing good quality data when getting interrupted by bad lightning or no lightning at all (e.t at night) they are not an optimal solution for receiving real-time data (Gupta et al., 2024; Wu et al., 2023). Wu et al. (2023) conducted a comparison between video and LiDAR and their findings show that LiDAR performs similarly to video during the day but does much better than video in low light conditions, like late evening.

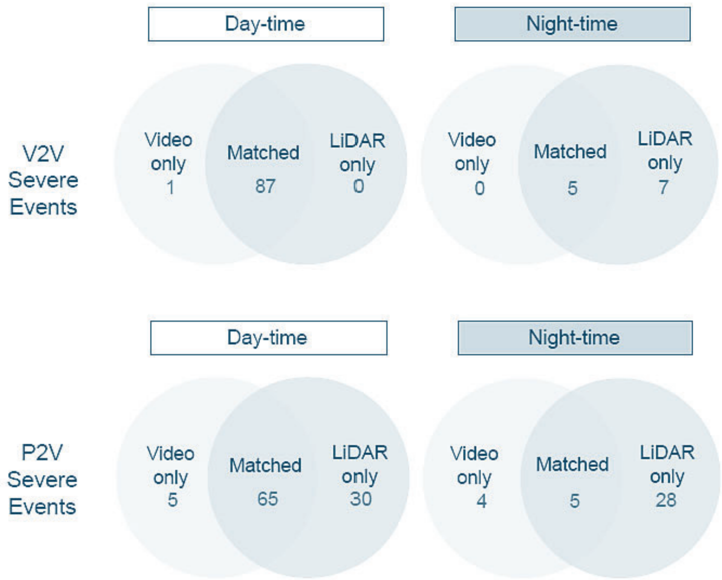

Figure 1. Comparison between LiDAR and video cameras (Wu et al., 2023). An event is a detected object in the scene.

The functions of position identification, distance measurement, and automated braking are crucial for detecting potential risks of failure or collision. However, during driving, reflections of moving cars or cyclists in bus windows or side mirrors can sometimes be misidentified as actual objects, posing a challenge for accurate detection (Yu & Marinov, 2020).

LiDAR technology has been associated with high costs and complexity

Although existing technologies such as cameras and radar are insufficient to compete with the precision of LiDAR technology (Creß et al., 2023; Lv et al., 2019; Wu et al., 2023) it has been the most cost-effective option to fulfill the requirements of driver assistance systems (Yu & Marinov, 2020). LiDAR earlier had the problem of being far more expensive than its counterpart and not been an option to implement. But now as LiDAR is becoming more popular and well known, the price has started to decrease and has made it possible to install LiDAR in traffic (Lv et al., 2019; Srinivasan et al., 2022; Wu et al., 2023). This opens the possibility to transition towards a smart city where you can receive new information or connect the vehicle to the infrastructure and achieve safer traffic through communication between the infrastructure system and the vehicles (Lv et al., 2019; Arnold et al., 2020; Ansariyar, 2023). Another perspective is to compare infrastructure monitoring with having all vehicles equipped with onboard perception, the infrastructure monitoring can be realised with current communications technologies and can reduce the costs of individual vehicles through shared infrastructure resources (Arnold et al., 2020).

Video and radar provide limited information and lack reliability

Sensor technology plays a vital role in the success of intelligent transportation systems (ITS). Early systems primarily relied on induction loops to monitor traffic flow, but these were limited in their ability to analyze individual traffic situations (Creß et al., 2023). As technology advanced, cameras were incorporated to provide more detailed visual analysis of the road environment. Camera-based systems are particularly popular due to their cost-effectiveness and ability to provide advanced object classification and analytics, especially in favorable conditions (Yu &

Marinov, 2020; Wu et al., 2023). Cameras offer a comprehensive view of the environment and can accurately read road signs and color-coded signals. However, their effectiveness is limited by visibility conditions, and they struggle to represent 3D scenes or accurately determine the distance to objects. There is also a big difference between analyzing the traffic to gather insights compared to safety-critical system with the purpose to work in real-time. To overcome this, two cameras can be used to create a 3D point cloud using epipolar geometry, though real-time extraction of 3D details for object detection remains a challenge. Cameras are typically effective at detecting obstacles at short distances, and with real-time depth map extraction and image fusion, they can build a dense map for more accurate obstacle detection and spatial estimation (Yu & Marinov, 2020).

Radar, on the other hand, is effective at mapping over medium to long ranges and excels in poor weather conditions, such as fog or rain, where cameras and LiDAR often struggle. Radar can detect objects up to 150 meters away, far exceeding the 10-meter detection range of human drivers in similar conditions. However, while radar excels in range and reliability under adverse conditions, it lacks the fine resolution necessary for precise object identification, making it less effective for detailed scene analysis (Yu & Marinov, 2020). The combination of video and radar is complementary, although, LiDAR technology offers both the spatial perception and precision when it comes to intelligently understand the surroundings and classify the objects ad events.

Both the camera surveillance and a radar system share the flaw of having a limited field of view which might result in blind spots in the mapping of an area. This is not a problem that LiDAR has as it is able to produce high quality data in a wide area (Cui et al., 2022; Gupta et al., 2024; Wu et al., 2023). Thanks to the high accuracy of LiDAR, it is also able to provide information on roads with multiple lanes compared to a radar system. A LiDAR system can provide information of speed limits in different lanes and possible red-light violations (Yasar et al., 2023). LiDAR offers 360-degree, high-resolution mapping across both short and long ranges, it excels in low-visibility conditions and is unaffected by poor lighting. Due to its superior capabilities in detecting obstacles, creating detailed 3D maps, and providing precise distance measurements, LiDAR is widely used as a standard sensor in many advanced systems (Cui et al., 2022).

Active sensing refers to sensors that emit their own signals, such as RADAR, LiDAR, or ultrasound, which send out laser or radio waves and then detect the reflections. The system or driver can control and manipulate the frequency and direction of these signals. In contrast, passive sensing relies on capturing existing environmental signals, such as light or sound, without emitting any energy. Cameras are a prime example of passive sensors, as they measure the scene based on incoming light without actively transmitting any signals (Yu & Marinov, 2020).

ITS (Intelligent Transportation System)

The need for cities to develop an intelligent transportation system (ITS) and become more intelligent and safer has become more and more important with the increased expansion of urban populations and increase in traffic (Creß et al., 2023; Intertraffic, 2024). Initially, ITS analyzed traffic flow, but since 2010, the trend shifted toward creating highly accurate digital twins of road traffic that can be used to enhance the safety (Creß et al., 2023). In order to develop ITS, LiDAR has become a technology that has been well promoted as the best solution compared to other alternatives (Intertraffic, 2024 & Simon 2024). As LiDAR has been relatively unexplored in this area, it has started to find its way into society in the US where they have started to test using LiDAR in intersections (UDOT 2024 & Andrews 2024). This seems only to be the start as in both these cases they seem satisfied with the solution and the new information provided and they aim to keep using LiDAR and continue installing it in more intersections and covering bigger parts of their cities.

Vehicle and Infrastructure Perception

Mo et al. (2024) and Creß et al., (2023) have made a comprehensive summary about the research within V2I where information from the vehicles and infrastructure is combined to enhance the safety. They demonstrated a system that assisted connected and automated vehicles to detect obstacles that would otherwise remain undetected. By adding sensing data from roadside infrastructure, vehicles gain better awareness of their surroundings. Arnold et al. (2020), Cheng et al. (2020), Cui et al. (2022), and Fukatsu & Sakaguchi (2021) made the same conclusions that cooperative perception is needed. Arnold et al. (2020) and Cui et al. (2022) used 3D LiDAR while Cheng et al. (2020) used GPS to connect the vehicles for double verification of their positions in addition to the vehicles' onboard perception. In contrast to GPS, infrastructure-based LiDAR monitoring has more details and accuracy to prevent collisions by mapping the surroundings. These infrastructure monitoring acts like a global system and helps self-driving systems to understand the environment better, reducing issues caused by blocked views or limited long-distance perception (Arnold et al., 2020; Cui et al., 2022; Fukatsu & Sakaguchi, 2021). As a result, decision-making improves, and road safety is enhanced.

Summary

These are the capabilities needed of a smart monitoring system for traffic safety that complements the drivers' and vehicles' perception.

Purpose	Capability
High reliability under various conditions	• Not sensitive to light and weather conditions • Real-time and minimal latency
Cost-effective	• Easy implementation • Optimized Field of View • Coverage of large areas
High accuracy and precision	• Spatial perception of the environment • High visibility • Detailed and accurate information about each object (dimensions, heading, velocity, class)

Overview of Regulations – The traffic light use case

One of the most basic ITS applications is traffic light control. It can be used for traffic flow optimization as well as indirect improvement of traffic safety through the reduction of traffic jams leading to less driver stress as well as increased safety of VRUs (vulnerable road users). The control of traffic lights is also a much less complicated problem than the dynamic driving task of an autonomous vehicle making it a feasible problem to focus on to evaluate and compare different technologies and their respective shortcomings.

The basis for traffic lights control in Sweden is the Vienna convention from 1968. This is implemented through the TSFS 2014:30, which contains regulations and general advice for road traffic signals. For traffic light specifically, they need to fulfil the functional safety requirements listed in SS-EN 12675:2017.

The hazards to consider are mostly concerning the timing of the transitions between green/yellow/red light and the prevention of green light to conflicting traffic and the failure to display a red light. This can be compared to the complexity of the dynamic driving task of an autonomous vehicle.

Adding ITS systems for traffic light control can thus be implemented in a relatively straight forward way through system partitioning when the lower levels guarantee the fulfilment of the safety requirements, and the higher levels corresponding to the ITS functionality can be implemented without safety concerns, allowing for more rapid development, and even A/B testing in situ. As the V2I standards mature and become implemented, the high-level information the system acquires can also be made available to the vehicles. Additionally, by implementing the ITS system in the infrastructure first and foremost, the advantages it can present will be possible to develop before a V2I has been adopted for the vehicles and without the need to retrofit old vehicles with V2I.

An advantage of using a LiDAR based system in the infrastructure is that the raw data collected from the sensors can be stored for offline verification as well as further functional development, compared to a camera-based system where the data needs to be anonymized in order to comply with the GDPR directive. This means that re-use of the stored data will not be possible to the same extent as in the LiDAR based system as the anonymization will lead to information loss.

Automated perception systems in mixed traffic

This section explores how human drivers interact with automated safety technologies. A major part of the research is from the perspective of autonomous vehicles and smart driver assistance systems; however, it examines broader human-automation interaction that offers valuable insights even for infrastructure-based monitoring systems. By understanding how drivers perceive, interact with, and adapt to automated systems, we can better assess the effectiveness of these technologies in enhancing road safety. An assumption about automated vehicles is that they will never crash with each other, this assumes that only automated vehicles will interact. However, this is unlikely soon for two reasons: the vehicle fleet changes slowly, and even in an ideal automated world, vehicles will still interact with human drivers, pedestrians, animals, weather, and more, all of which could cause crashes (Goodall, 2014; Shetty et al., 2021).

The strategy to avoid accidents with autonomous vehicles is to model nearby vehicle behavior, without such a model, the vehicles might overreact to perceived threats, causing dangerous maneuvers (Goodall, 2014). Still, this behavior is not exactly like how humans drive, causing problems when humans and automated vehicles are in the same area. This also apply to how humans react to safety systems in modern vehicles, the driver reacts if the vehicle is overacting, causing unexpected stops or slow-downs. This underscores the critical need to align the technology's capabilities with the driver's understanding of those capabilities. A misalignment between the two could compromise the safety (Pradhan et al., 2022). In level 2 and 3 automated vehicles, where human intervention is required in emergencies, drivers are tasked with making ethical decisions. However, research indicates that even when vehicles incorporate semi-autonomous features, drivers frequently engage in distracting activities and fail to maintain full attention, thus posing a risk to safety (Goodall, 2014).

From the authors' experience with real safety and traffic related customer cases, there is always a trade-off between autonomous efficiency and safety. One example of feedback comes from a mine's autonomous zones, where concerns have been raised about productivity due to the necessary safety measures for the autonomous machines. With smart infrastructure, the vehicle's perception and navigation could be enhanced. The smart infrastructure could also detect if there are humans entering the autonomous zone where they are not allowed to be if the autonomous vehicles and machines have blind spots. Additionally, the authors received feedback from clients who disabled the safety systems due to their malfunctioning, highlighting the need for reliable automated safety systems that clearly visualize what the system detects for the users involved.

The use case: Intelligent traffic lights

Intelligent traffic lights can provide additional functionality either on a local scale (one crossing) for instance through monitoring VRUs (vulnerable road users) or if incoming vehicles are not slowing down as expected, or on a non-local scale for instance by improving traffic flow through synchronization to generate a green wave.

As the safety aspects can be handled by lower layers, the “intelligent” part allows for a safe test environment where the impact and effect of ITS systems on traffic flow can be evaluated. More specifically for this project, the impact on the system functionality of different sensors can be evaluated in a real-life situation without risk.

Maintaining the safety of a traffic light is not only a lot easier to implement and to partition from the rest of the functionality, it also does not depend on whether the vehicles are equipped with V2I and/or sensors of their own, and the same sensors can be deployed in all crossings that would be under investigation allowed for more consistent testing conditions.

This would require implementing V2I in a selection of vehicles in order to evaluate the impact of sensor choice. If instead the function is first implemented and tested using normal traffic lights the number of available test vehicles will increase making the comparison much easier as more data can be gathered.

Conclusion

In conclusion, researchers provide a detailed overview of the main challenges related to obstacle detection and safety for automated and autonomous vehicles, and they agree that many of these problems can be addressed by using LiDAR monitoring in the infrastructure. Additionally, implementing LiDAR-based ITS can make a big difference in the less complex scenarios already today, by providing information and insights to traffic lights, to improve traffic flow and safety, this without being connected to vehicles. It is important to find a balance between safety and availability as these technologies continue to develop. If the system is too reactive and has too big safety-measures, it will cause traffic flow problems.

Future research

The comparison between different technologies when it comes to sensing is quite conclusive in the literature and the advantages of using LIDAR are by now quite well known. What is not known is how LIDAR vs camera and radar-based solutions compare when it comes to functionality, specifically in ITS systems. It is unknow how a failed event (object not detected) will affect the functionality of the system. It could be that the failed events all correspond to safe situations (for instance a VRU going away from a crossing, not getting closer to it). A possible future research project could take a specific ITS system and supply it with sensing data from different types of sensors and in the specific context compare the impact on the system of the different sensor types.

The simplest use case for such a research project would probably be traffic flow control using traffic lights with centralized control. The safety of the individual crossings would be ensured by the localized controls in every crossing allowing for the centralized control to be implemented without safety requirements. The sensor inputs would then only be used by the centralized control allowing for A/B testing using the different inputs.

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