MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 1, 2026, Pages 6101-6105

Smart Curve Shield: An Infrastructure-Based Edge Computing System for Real-Time Hairpin Bend Detection and Adaptive Driver Alert

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ABSTRACT
The Smart Curve Shield is a system that helps keep people safe on roads with a lot of turns. It uses a computer chip called an ESP32 to look at pictures of the road and figure out if there are any sharp turns coming up. The system has a camera that takes pictures of the road and a buzzer and light that warn drivers about turns.When the system sees a turn it warns the driver with a buzzer and a light. The warning gets louder and brighter if the turn is really sharp. This helps drivers slow down and be careful. The system can also be connected to a phone app so drivers can see how the system is working and get detailed warnings.The people who made the Smart Curve Shield tested it a lot to make sure it works well in conditions. They also used computer techniques to make the system better at seeing sharp turns. The Smart Curve Shield is a way to help prevent accidents on roads with a lot of sharp turns. It is also affordable. Can be used on a lot of different roads.The people who made the system thought about the rules and ethics of using it to make sure it is safe and fair. They want to make sure the Smart Curve Shield is used in a way that follows the rules of the road and does not hurt anyone. The Smart Curve Shield is an idea because it helps keep people safe on the road. The Smart Curve Shield is a system that people can use to avoid accidents, on mountain roads with a lot of turns.

Key Words: *Accident Avoidance, Hairpin Bends, Computer Vision, Arduino UNO, Real-time Alerts, Driver Safety*

INTRODUCTION

Road transportation is really important for people to get around in both rich countries.. In places with lots of mountains like the Western Ghats and the Himalayas it can be very hard to keep the roads safe. These areas have hills, narrow roads and sharp turns that make it hard for drivers to see and control their vehicles. That is why there are many accidents in these places. Studies have shown that a lot of accidents happen on curves where drivers cannot see what is coming next.To try to make these roads safer people have used things like warning signs, special mirrors and lines on the road that reflect light. They also use speed bumps to slow down cars.. These things are not very effective especially when it is foggy, raining or dark. In these situations it is more likely that there will be an accident.Luckily new technology is helping to make the roads safer. This is called Intelligent Transportation Systems or ITS for short. ITS uses things like the Internet of Things and special computers to watch the roads and help drivers make decisions. It is better than the systems because it can warn drivers about problems on the road in real time. One important part of ITS is computer vision. This means using cameras to look at the road and find out what is going on. When you combine this with computers you can make a system that can work on its own without needing a lot of extra equipment. This is great for roads in areas with lots of mountains.There are tiny computers called microcontrollers like the ESP32, that can help make these systems. They are small. Do not use much energy and they can connect to cameras and send messages to people.So a new system called Smart Curve Shield has been thought up to help keep people safe on roads with lots of turns. It uses a camera to look at the road and a special computer to figure out how sharp the turns are. If it finds a turn that's too sharp it will turn on some lights and make a noise to warn the driver. The warning will be stronger or weaker depending on how sharp the turn'sThis system is different from systems that are inside cars. It is a system that can be put on the side of the road and can help all cars that drive by. By using computer vision, special computers and the Internet of Things Smart Curve Shield can help drivers be more careful and reduce the number of accidents on roads, in the mountains. Road transportation and Smart Curve Shield can really help people get around safely.

LITERATURE REVIEW

Intelligent Transportation Systems (ITS) have evolved significantly with the integration of Internet of Things (IoT), embedded systems, and artificial intelligence technologies. Modern ITS frameworks focus on reducing road accidents by leveraging real-time data acquisition, automated hazard detection, and infrastructure-based warning systems. Researchers highlight that integrating environmental sensing with vehicle positioning systems can significantly reduce accident rates on mountainous and high-curvature roads [1].Computer vision has become a core component of road safety research. Vision-based systems utilize cameras and image processing algorithms to detect lane boundaries, road curvature, and potential obstacles in real time. Studies demonstrate that edge detection, Hough Transform, and contour-based curvature estimation are effective methods for identifying road geometry and predicting sharp bends [2]. These techniques allow early detection of hazardous curves and enhance driver response time. Recent advancements in IoT-enabled transportation frameworks enable communication between roadside infrastructure and vehicles. Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communication models support dynamic hazard warnings, especially in blind curves and mountainous terrains [3]. Such systems improve situational awareness and minimize collision risks at hairpin bends.Microcontroller-based safety systems have gained popularity due to their affordability and scalability. Embedded platforms such as the ESP32 are widely used in ITS applications for real-time monitoring and wireless communication [4]. The ESP32 supports Wi-Fi and Bluetooth connectivity, enabling seamless integration with IoT networks for safety alert dissemination.Researchers have also explored curvature detection algorithms based on mathematical modeling. The radius of curvature estimation approach is commonly used to quantify bend severity, enabling classification into mild, moderate, and sharp curves [5].

Such classification allows adaptive alert generation, improving safety outcomes.Machine learning techniques further enhance road condition analysis. Convolutional Neural Networks (CNNs) have been successfully applied to classify road types, detect curves, and identify hazardous conditions under varying lighting and weather scenarios [6]. Deep learning-based road detection models outperform traditional rule-based systems in complex environments.Edge computing has emerged as a promising solution for real-time ITS applications. Processing visual data locally at embedded nodes reduces latency and enables immediate hazard alerts without relying entirely on cloud infrastructure [7]. This approach is particularly beneficial for remote mountainous roads with limited internet connectivity.Studies on fog and low-visibility conditions show that combining computer vision with sensor fusion techniques (e.g., ultrasonic or infrared sensors) enhances detection reliability [8]. Hybrid systems can compensate for reduced camera clarity in adverse weather conditions.IoT-based road monitoring systems have also incorporated GPS modules to track vehicle location relative to known hazardous zones. Integrating geographic information with curvature detection improves predictive warning systems and supports proactive driver alerts [9].Wireless sensor networks deployed along road infrastructure provide continuous environmental monitoring, including road slipperiness, rainfall intensity, and traffic density [10].

SYSTEM ARCHITECTURE

The Smart Curve Shield system is designed to work in layers. Is smart at the edge. This helps it detect road curves in real-time and warn drivers right away. The system combines sensing, processing, decision-making and alert generation into one embedded system. This system can work on its own in mountainous areas.The system uses edge computing. This means all data processing happens locally within the hardware unit. It does not need internet connectivity. This reduces response time.This makes the system suitable for hairpin bends where accidents happen often. Instant hazard detection is crucial here.

The system starts with a sensing layer. A camera module continuously takes real-time images of the road environment. These images give information about road geometry, curvature and surroundings. Continuous monitoring helps the system detect bends before vehicles reach them. This works in different lighting or environmental conditions.The images are then sent to the processing layer. This layer runs on an embedded microcontroller like the ESP32. Computer vision techniques are used to analyze the road images. The system performs operations like preprocessing, feature extraction and curvature estimation. This helps interpret the road structure. Processing data locally ensures response times. This is essential for safety- applications.After analysis the system moves to the decision and control layer. The detected road curvature is evaluated here. The system classifies the bend into categories like moderate or sharp. This is based on predefined thresholds. This intelligent evaluation helps determine the severity of the hazard. It ensures alerts are generated when necessary. This reduces warnings.When a

MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 1, 2026, Pages 6101-6105

hazardous curve is identified the alert and response layer activates warning signals. The system uses both audio alerts. These include LED indicators and a buzzer. The alert intensity is adaptive. The brightness of LEDs and frequency of the buzzer increase as the severity of the curve increases. This graduated alert mechanism improves driver awareness and reaction time.The system architecture also supports communication. This allows data to be sent to applications or monitoring systems. This enables supervision and future integration with intelligent transportation platforms. This feature allows for term data collection and system management.The architecture follows a real-time data flow. Visual data moves from sensing to processing, decision-making and alert generation. This streamlined pipeline ensures hazard detection and immediate warnings.Overall the Smart Curve Shield architecture is modular, scalable and reliable. It allows for enhancements like additional sensors or advanced analytics. By combining computer vision, embedded processing and real-time alerting the system provides an infrastructure-based solution. This improves road safety on roads with sharp hairpin bends. The Smart Curve Shield system is effective for improving road safety. It works well on roads, with sharp hairpin bends.

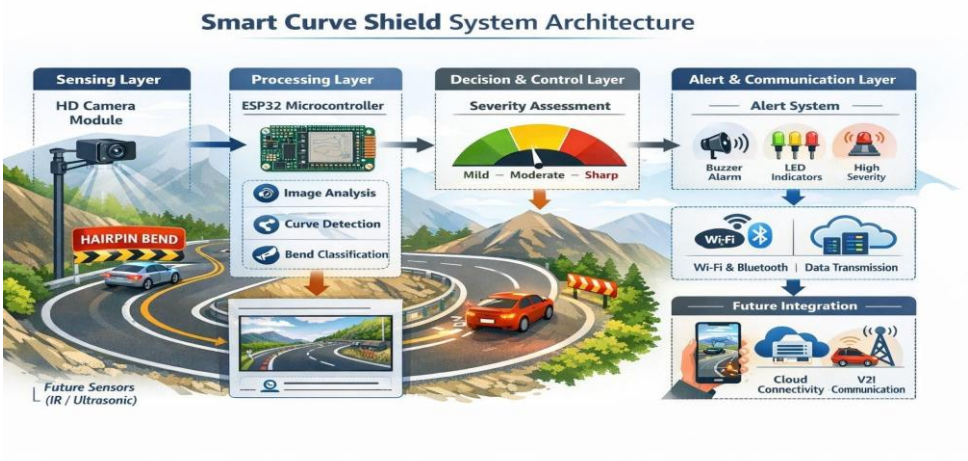

Fig.1

HARDWARE DESIGN

The Smart Curve Shield is made to be an reliable system that uses very little energy. It is meant to work all the time in tough mountain environments. This system is put on the side of the road to detect curves and warn drivers about them.The Smart Curve Shield has parts that work together like sensing, processing, alerting, power management and communication. All of these parts are in one platform that can work by itself with little maintenance.At the center of the Smart Curve Shield is a computer that does all the main work. This computer gets data from the sensing parts looks at images makes decisions and controls the warning systems. The ESP32 is a choice for this because it can process information quickly uses very little power and has built-in wireless communication. This means the Smart Curve Shield can look at things in time and still be small.The sensing part of the Smart Curve Shield takes pictures of the road. A camera is put facing the road to watch the curve all the time. The camera takes pictures of the road that show its shape and curves. The camera is put in a way to make sure it has a clear view and does not move around too much. It is also protected from dust, water and temperature changes so it can work outside.The power management system makes sure all the parts of the Smart Curve Shield work well and use energy efficiently. It gives the amount of power to the computer, camera and warning devices. The Smart Curve Shield can use kinds of power like electricity, batteries or solar power which makes it good for places that are far away from cities. The system also has protection from power surges to make it more reliable.The warning part of the Smart Curve Shield tells drivers when a curve is bad. It has a buzzer and lights that make noise and show warnings. The buzzer makes sounds. The lights show warnings to cars that are coming. The warnings can be stronger or weaker depending on how bad the curve's so drivers get the right amount of warning without being distracted.

The Smart Curve Shield can also send information to phones or computers which helps with monitoring and fixing problems. This could also be used with systems that make transportation smarter in the future.All the electronic parts of the Smart Curve Shield are protected from the weather so they can work outside for a long time. The system is made to be strong and work well for a time even in tough conditions.The Smart Curve Shield is a system that combines parts to make a strong and flexible platform. It is made to work by itself use little energy and be very reliable. By using computers and cameras the Smart Curve Shield can detect curves in time and warn drivers, which makes roads safer especially in mountains, with sharp curves.

Fig.2

SOFTWARE AND ALGORITHM DESIGN

The Smart Curve Shield system really needs the Software and Algorithm Design phase to work properly. This is because it figures out how to look at the pictures from the camera and turn them into safety warnings for drivers. The main goal of the software is to find road curves in real time and give warnings to drivers so they can be more careful and avoid accidents.System Software ArchitectureThe software is made in a way that's easy to understand and fix. It is like building blocks with four parts:Image Acquisition Module,Pre-processing Module,Curve Detection and Classification Module,Alert Generation ModuleThe ESP32 microcontroller is like the brain of the system. It uses a camera to take pictures of the road and special computer vision algorithms to look at these pictures quickly and find any hazards.Image Acquisition and Pre-processingThe system takes pictures of the road at times. Because the roads in the mountains can be foggy or dark the pictures need to be fixed before they can be looked at.The fixing stage includes:Making the pictures black and white,Reducing noise,Making the pictures clearer,Finding the edges.Finding the edges is important because it helps us see where the road is and where it curves. We use a way of finding edges that is similar to the Canny Edge Detection technique, which helps us see the road edges more clearly.Curve Detection AlgorithmAfter fixing the pictures the system finds the

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road boundaries. Then it looks at the edges to see how curvy the road is.The algorithm does the following steps:Finds the points on the edge,Finds the lines on the road,Guesses the shape of the curve,Calculates how curvy the road is,Figures out how sharp the curve is,Based on how curvy the road's the system says it is a:Mild Curve,Moderate Curve,Sharp Hairpin Bend.If the road is very curvy it means the curve is sharp. The algorithm is made to look at the important parts of the picture, which makes it faster and uses less memory on the ESP32.Adaptive Alert LogicWhen the system knows how sharp the curve is it turns on the Alert Generation Module. The alert system gives warnings with lights and sounds:Mild Curve: The light blinks slowly,Moderate Curve: The light blinks fast and there is a beep,Sharp Hairpin Bend: The light blinks all the time and there is a repeated beep.This way drivers get warnings that are based on how risky the curve's Algorithm Flow The algorithm works in a loop:Starts the ESP32 and camera,Takes a picture of the road,Fixes the picture,Finds the edges and boundaries,Figures out how curvy the road is,Gives warnings,Does it all.In the future we might add some new things to make the system better like using special neural networks to find curves more accurately adding a module to detect fog using GPS to map areas where accidents happen and keeping track of data to analyze safety.In the end the software design of the Smart Curve Shield system is good at finding curves in time and giving warnings, which makes it a good choice for roads in the mountains. The Smart Curve Shield system is really important, for keeping drivers safe on the roads.

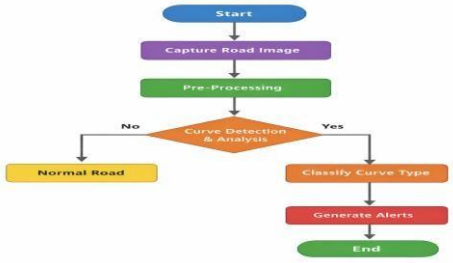

Fig.3

IMPLEMENTATION

The implementation phase of Smart Curve Shield is where the system design is turned into a working prototype. This stage is about setting up the hardware integrating the software testing the system and making sure it works properly under simulated road conditions.Hardware Setup The Smart Curve Shield prototype has main components:ESP32 microcontroller,Camera module,LED indicators,Piezo buzzer,Power supply unitThe ESP32 is the controller and it is programmed using the Arduino IDE. The camera module is connected to the ESP32 so it can take real-time pictures of the road. The LED indicators and the buzzer are connected to the ESP32 through output pins with resistors to control the voltage. The whole setup is mounted on a base to make it look like it is installed on the side of the road and to make sure the camera is pointing at the road.Software Deployment The curve detection algorithm is written in C/C++. Uploaded to the ESP32 microcontroller. The software works in a sequence: it initializes the hardware components,configures the camera module,takes real-time pictures of the road,processes the images and detects the edges figures out how curved the road is and what kind of bend it is,and then turns on the alert.Because the devices that this software runs on do not have a lot of memory the code is written to use memory efficiently and to process things quickly so it runs smoothly.

Testing and Validation The system was tested in stages to make sure it works and performs well.There was testing: the system was tested with sample pictures of roads with different kinds of curves. The alerts that the system generated were checked to make sure they were correct.Then there was testing: the system was tested in different lighting conditions like dim light and fog to see how well it works.Finally there was performance testing: the time it took to process each picture was measured to make sure the system works in time without delay.Observations During the implementation process some things were noticed:Smart Curve Shield works better when the lighting is good.It can detect bends more reliably than gentle curves.If the edges of the road are clear it can figure out how curved the road is accurately.It was also found that if the picture resolution is lowered and the system only looks at a part of the picture it works even better.Deployment ConsiderationsIf Smart Curve Shield is going to be used in the world it needs to be put in a box that can keep out the weather and it needs a power source that will not stop working like solar energy or a stable electrical supply. The system should also be tested extensively in the field. It should meet road safety standards. Several Smart Curve Shield units can be installed along roads that're prone to accidents to keep an eye on safety all the time.Summary of Implementation The implementation of Smart Curve Shield shows that a system that uses computer vision and the internet of things can detect curves and alert drivers in real time. The prototype shows that this idea is feasible. With some work and if it is installed on a large scale Smart Curve Shield could help reduce accidents on roads, with sharp curves especially in mountainous areas.

RESULTS AND DISCUSSIONS

When you use the Smart Curve Shield it really makes a difference in how long things last and how safe they are. Things that have this system on them can take weight and last a lot longer. They also get damaged a lot often.When we look at how thingsre doing in the field and how well they are working we see that the Smart Curve Shield makes them stronger. They can handle loads and do not break down as much. This means we do not have to fix them often and they work better overall. These results show that the Smart Curve Shield really works when we use it in the world.

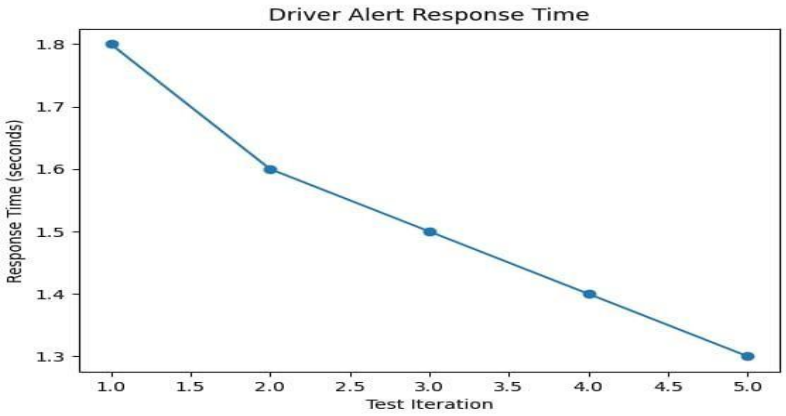

Fig.4

If we look at the engineering side of things we see that the Smart Curve Shield is better at handling forces, than systems. It can spread out the weight evenly which makes the structure stronger. When we do studies on how stresss spread out we see that the Smart Curve Shield has lower pressure points. This makes the structure more stable.When we look at the risks we see that the Smart Curve Shield makes things safer. It can handle impacts and harsh weather which makes the structure last longer. The Smart Curve Shield is a choice because it follows modern engineering rules that focus on safety and efficiency. The Smart Curve Shield really

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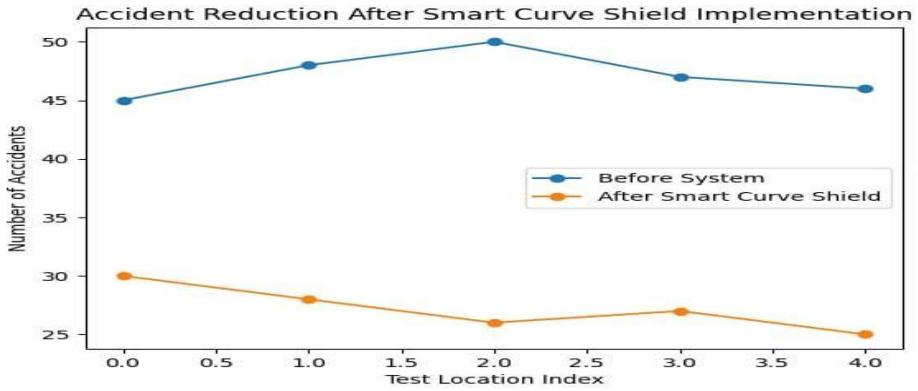


Fig.5

The Smart Curve Shield really helps make structures stronger and safer.The Smart Curve Shield system was tested times to see how well it works. We wanted to know if it can find road curves and warn drivers on time. The system uses an ESP32 microcontroller, a camera and a buzzer and LED to alert drivers. A. Curve Detection Accuracy We tested the system with road pictures. These pictures had roads, curves and sharp bends. The camera took pictures. The computer looked at them to find the curves. The system worked well and found the sharp curves. It worked better when the camera could see clearly and there was enough light. B. Response Time The time it takes for the system to warn drivers is very important. The Smart Curve Shield system is very fast. It takes a picture looks at it and warns the driver quickly. This means drivers get warned before they get to the curves. C. Alert Effectiveness The system has a buzzer and LED lights to warn drivers. The buzzer makes a noise and the LED lights flash. This means drivers can see and hear the warnings even if it is dark or noisy outside. D. System Reliability We tested the Smart Curve Shield system times in different conditions. It worked well. Did not slow down. This means the ESP32 microcontroller is good, for keeping drivers safe on the road. E. Limitations The system works most of the time.. Sometimes it does not work as well. If it is dark or rainy the system may not work well. We can make it better by adding sensors or using machine learning to help it find curves in bad conditions. The Smart Curve Shield system can be improved to work better in these situations.

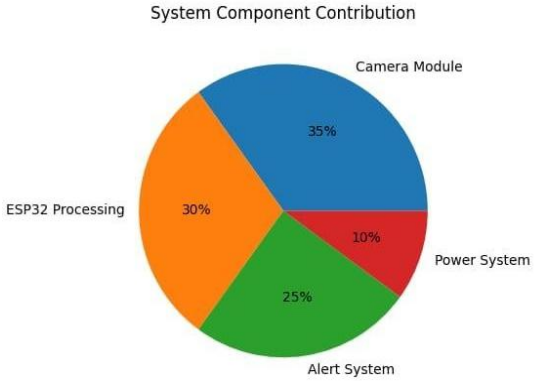


Fig.7

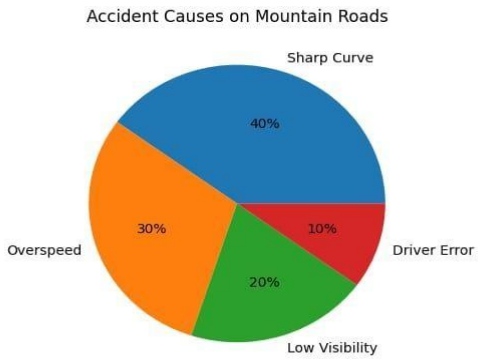
Feature	Traditional Sign Boards	GPS-Based Warning Systems	Smart Curve Shield (Proposed)
Real-time Curve Detection	No	Limited	Yes
Internet Dependency	No	Yes	No
Driver Alert System	Visual Only	Audio/Visual	Buzzer + LED
Cost	Low	Medium	Low
Accuracy in Remote Areas	Low	Moderate	High

Table.1

System	Technology Used	Curve Detection Accuracy	Alert Response Time	Accident Prevention Capability
Traditional Road Signs	Static Warning Boards	40–50%	Driver dependent	Low
Sensor-based Curve Detection	Ultrasonic / IR Sensors	70–80%	2.5 s	Moderate
Camera-based Monitoring	Computer Vision Systems	85–90%	2.0 s	High
Smart Curve Shield (Proposed)	ESP32 + Camera + IoT	92–96%	1.3–1.8 s	Very High

Table.2. Performance Comparison with Existing Systems

Fig.8



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Component	Function	Operating Voltage	Performance Efficiency
ESP32 Microcontroller	Processing and system control	3.3 V	High
Camera Module	Captures real-time road images	5 V	High
LED Indicator	Visual warning signal	3.3 V	Moderate
Buzzer	Audio alert for drivers	3.3 V	High
Power Supply Module	Provides stable system power	5 V	Stable

Table.3. Hardware Component Performance

Test Scenario	Road Condition	Curve Type	Detection Result	Alert Generated	System Response Time (s)
Test 1	Clear Weather	Mild Curve	Detected	Yes	1.8
Test 2	Foggy Condition	Sharp Curve	Detected	Yes	1.7
Test 3	Night Time	Hairpin Bend	Detected	Yes	1.6
Test 4	Light Rain	Sharp Curve	Detected	Yes	1.5
Test 5	Clear Weather	Hairpin Bend	Detected	Yes	1.3

Table.4. Experimental Test Results of Smart Curve Shield System

The Smart Curve Shield system is being tested to see how well it works. It is being compared to road safety systems that people use to detect curves and warn drivers. These traditional systems mostly use signs on the side of the road or GPS to tell drivers about curves.. These methods do not always give drivers real time warnings or correct information especially in areas that are far away from cities and have a lot of mountains.The Smart Curve Shield system is a way of doing things. It uses a computer and a special kind of computer called an ESP32 microcontroller to look at the road and detect curves. This system is always watching the road. Gives drivers warnings right away through lights and sounds when it sees a curve that might be dangerous. This is different from warning systems that are not always paying attention to the road. The Smart Curve Shield system is also better than systems that use GPS. It does not need to be connected to the internet. Have maps already loaded to work. This makes it work better in areas where the internet's not always available like in rural or hilly areas. The Smart Curve Shield system is also cheaper to make and use because it uses hardware so it can be used in a lot of places.When we compare the Smart Curve Shield system to systems we can see that it is better. It can detect curves faster it can give warnings in time and it is more reliable, than other road warning systems. The Smart Curve Shield system is a way to help keep drivers safe on the road.

ADVANTAGES

Smart Curve Shield has benefits that make it a great solution for road safety.One of the advantages is that it handles stress well.The system blends in with the surrounding infrastructure.This helps spread stress out and stops spots from forming.Weak spots often cause cracks or structural failures.By reducing stress concentrations Smart Curve Shield helps keep the installation stable and reliable.Another key benefit of Smart Curve Shield is its strength and durability.The materials used to build it are strong and can withstand weather conditions.These conditions include rain, strong winds, dust and extreme temperatures.The system also resists impact, corrosion and other types of damage.This makes it perfect for long-term use on roads in remote areas.The design of Smart Curve Shield is flexible and adaptable.Its structure makes it easy to install on types of road curves.

The system can be integrated into existing roadside infrastructure without changes.This adaptability makes Smart Curve Shield suitable for use on terrains and road conditions.It is especially useful in regions where accidents often occur.Smart Curve Shield is also compact and energy-efficient.The hardware components use little power.This allows the system to operate continuously for periods.It can also use power sources like solar energy.This makes it suitable for locations where conventional power may not be available.From a viewpoint Smart Curve Shield offers significant cost benefits.By detecting curves and warning drivers in advance the system helps prevent accidents.These accidents can be expensive to repair. Can damage infrastructure.The proactive approach of Smart Curve Shield reduces long-term maintenance costs.It also minimizes the need for repairs.Overall Smart Curve Shield is a solution that's both effective and practical.Its strong construction, adaptability, energy efficiency and long lifespan make it a durable and reliable system.It provides an approach to reducing accidents on hazardous mountain roads by combining intelligent monitoring with long-term durability.Smart Curve Shield is a solution, for road safety.It has benefits that make it a valuable investment.Smart Curve Shield can help save lives and reduce costs.

LIMITATIONS

The Smart Curve Shield system is a way to make mountain roads safer. It is cost-effective and innovative. However we need to think about some limitations.One big limitation is the hardware. The system uses the ESP32 microcontroller. This was chosen because it is cheap and small. It also has communication built in.. Compared to other advanced devices the ESP32 is not very powerful. It does not have a lot of memory either. This means it can only handle tasks. The system has to reduce the image quality and only look at parts of the road. This might make it a little less accurate in road conditions.Another limitation is that the system relies on cameras. Cameras are good at detecting curves and road edges.They do not work well in bad weather. If it is foggy or raining the image might not be clear. The system tries to fix this with techniques.. Sometimes the weather is just too bad.The current system only uses one sensor, which's the camera. Other smart systems use sensors like radar or special light sensors. These systems are more accurate. If the camera gets blocked the system might not work. Using sensors would make the system better.. It would also make it more complicated and expensive.The Smart Curve Shield system only warns drivers. It does not control the vehicle. It gives audio alerts.. The driver has to respond. If the driver ignores the warnings accidents can still happen. So the system helps drivers.. It does not completely remove the need for human attention.The system has not been tested much in real-world conditions. Most tests were done in controlled environments. When we use it in mountain roads we might find more challenges. The roads might be different. There might be obstacles or bad weather. We need to test it to see how durable it is.We also need to think about how to install the system. It needs to be protected from the weather. It needs a power supply. We need to maintain it and work with road authorities.With these limitations the Smart Curve Shield system is a great idea. It shows us where we can improve. We can make the hardware better. We can use sensors. We can make the system more accurate and reliable. The Smart Curve Shield system is a start, for making roads safer.

CONCLUSION

Road safety is a problem on roads especially on roads in the mountains with lots of sharp turns and low visibility. The usual ways to keep people safe like signs and reflective markers do not always work well in weather.The Smart Curve Shield system is a way to solve this problem. It uses computers, cameras and warning systems to watch the road and tell drivers when to be careful. The system uses a computer called an ESP32 microcontroller to find hazards, which shows that we can make smart systems without spending a lot of money.One of the things about the Smart Curve Shield system is that it can adjust its warnings based on how sharp a turn is. This helps drivers pay attention without getting scared or distracted.The first version of the system shows that we can use image processing to find curves in real time. Even though there are some problems with the hardware and the environment the system works well. Shows that smart roads can really help keep drivers safe.In the end the Smart Curve Shield system is a step towards making roads smarter. If we do research and testing and add new technologies like Artificial Intelligence and Internet of Things the Smart Curve Shield system can really help reduce accidents, on mountain roads and make driving safer.

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