



“The Illuminating Whale” A Friendly Light That Saves Lives

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Abstract

The study proposes an innovative emergency signalling architecture based on two autonomous LED devices positioned outside stationary vehicles in order to improve visibility, reduce secondary collisions, and strengthen contemporary road safety governance. The study originates from the growing limitations of traditional passive warning systems, such as the retroreflective triangle, within modern mobility environments characterized by high traffic density, reduced reaction times, distracted driving, and increasingly complex operational conditions. Drawing on the conceptual framework of the *Help Car Roof Project* (Rufa et al., 2023), the proposed system integrates multidirectional LED conspicuity with a red-green chromatic logic, inspired by maritime and aeronautical navigation systems. The theoretical framework combines the *Safe System Approach*, human factors research, cognitive ergonomics, intelligent transportation systems, and contemporary road policing paradigms. The article argues that emergency signalling technologies should no longer be considered simple technical accessories, but rather active components of integrated mobility safety and preventative risk governance. Particular attention is devoted to the operational applications for road policing, emergency responders, roadside assistance personnel, and infrastructure maintenance operators, whose exposure to secondary collisions remains a critical issue worldwide. Finally, the study explores future integration with ITS and V2X systems, highlighting the potential evolution of emergency signalling into intelligent, connected, and anticipatory communication systems capable of improving infrastructural resilience and adaptive mobility safety.

Keywords: Road Safety; Road Policing; Secondary Collisions; Intelligent Transportation Systems (ITS); Emergency LED Signalling

1. Introduction

Road safety has historically been addressed through a combination of infrastructure engineering, user education, vehicle technology development, and enforcement activities (OECD/ITF, 2008; World Health Organization [WHO], 2023). However, despite significant advances in passive vehicle safety, intelligent transportation systems, and emergency medicine in recent decades, secondary collisions involving stationary vehicles continue to represent an extremely critical and underestimated component of contemporary road fatalities (National Highway Traffic Safety Administration [NHTSA], 2022).

Such events occur when a vehicle, already stationary due to a mechanical failure, an accident, a police check, a maintenance operation, or an emergency, is subsequently struck by oncoming traffic. Although these incidents are often statistically absorbed into the broader category of road collisions, they are particularly serious because they occur in operating conditions characterized by reduced predictability, high speed differences between traffic flows, limited manoeuvring space, and extremely compressed decision-making times (Green, 2000).

The issue is increasingly important today in light of the transformation of contemporary mobility systems. Modern road infrastructures are characterized by high traffic density, continuous logistics flows, increasingly widespread night-time mobility, and increased distracted driving related to the use of digital devices and infotainment systems (European Commission, 2020). In this context, the time available to recognize a hazard, correctly interpret it, and adopt a safe manoeuvre is drastically reduced. A driver traveling on a highway at 130 km/h travels approximately 36 meters per second: even a minimal delay in perceiving a risk can therefore lead to catastrophic consequences (Green, 2000).

Traditional emergency signalling systems are increasingly showing their limitations in these new operating conditions. The retroreflective triangle, despite having been the primary regulatory tool for signalling a stationary vehicle for decades, continues to rely on an essentially passive and manual logic (Vienna Convention on Road Signs and Signals, 1968).

Its effectiveness depends on proper positioning, weather conditions, road geometry, the quality of the reflectivity, and the presence of an adequate viewing angle. Even more problematic is the fact that its use requires the user to exit the vehicle and move along the roadway or shoulder in potentially extremely dangerous conditions. Numerous fatal collisions that have occurred while the triangle is being positioned demonstrate the intrinsic vulnerability of this procedure, especially on high-speed infrastructure (NHTSA, 2022).

Furthermore, the triangle primarily provides rearward-facing warning, resulting in poor lateral and multidirectional visibility. In modern traffic environments, characterized by multiple lanes, constant overtaking, and complex visual scenarios, the need for distributed and anticipatory awareness is becoming increasingly critical (Bullough et al., 2024).

The evolution of portable emergency LED systems fits into this scenario. Drawing on the conceptual insights developed in the *Help Car Roof Project* (Rufa et al., 2023), the research proposes a new signalling architecture based on two autonomous LED devices to be positioned outside the vehicle, on the ground or in another convenient location, using suction or magnetic systems. The system integrates a green and red colour scheme designed to increase lateral visibility, improve risk anticipation, reduce user exposure, and strengthen preventative road safety governance.

The choice to place them outside the vehicle, on the ground or in another convenient location, is no a coincidence. This position, in fact, allows for the creation of a distributed and multidirectional light profile, capable of standing out even in heavy traffic or when the vehicle is partially obscured.

Furthermore, the use of a double light source, possibly symmetrical, generates a more recognizable and cognitively effective visual result than centralized systems (Wickens et Hollands, 2000).

Furthermore, it must be considered that emergency signalling technologies should no longer be considered mere technical accessories, but operational components of a broader transformation of mobility governance. Contemporary road safety is increasingly at the intersection of road safety, integrated safety, infrastructure resilience, and road policing (Cestra, 2022). From this perspective, road visibility becomes an active form of risk prevention and management, capable of influencing user behaviour and contributing to the construction of safer and more resilient mobility systems.

2. Discussion

2.1. Theoretical framework

The theoretical framework underlying the LED system to be positioned on the exterior of the vehicle stems from the integration of different scientific and operational fields, including the *Safe System Approach*, human factors, cognitive driving psychology, road policing, and intelligent transportation systems (OECD/ITF, 2008; Stanton et al., 2007). The intersection of these perspectives allows the system to be viewed not as a simple technological innovation, but as part of a broader evolution of contemporary mobility safety management models.

The *Safe System Approach* is currently one of the most influential paradigms in international road safety policies (WHO, 2023). Unlike traditional approaches, which are primarily based on individual driver responsibility, the *Safe System Approach* assumes that human error is inevitable and that transportation systems must be designed to prevent such errors from resulting in fatal or seriously disabling consequences (Reason, 1990). Safety is therefore interpreted as a systemic property resulting from the interaction between infrastructure, vehicles, users, regulations, and emergency systems (OECD/ITF, 2008).

Secondary collisions involving stationary vehicles are a prime example of systemic vulnerability. They arise from the interaction between predictable human cognitive limitations and the road system's insufficient capacity to tolerate these limitations (Reason, 1990). Distraction, fatigue, reduced visibility, cognitive overload, and adverse environmental conditions can compromise a driver's ability to promptly identify an obstacle or operational scenario (Lee, 2008).

The proposed LED system addresses precisely these vulnerabilities. First, it increases the redundancy of hazard communication through active, multidirectional light signalling. Second, it improves anticipatory awareness, allowing drivers to perceive risks from a greater distance. Third, it reduces road user exposure by minimizing the need to manually deploy emergency devices. Finally, it increases systemic tolerance for the inevitable delays in road users' perception and decision-making (OECD/ITF, 2008).

Human factors and cognitive ergonomics also support the rationality of the proposed system. Modern driving exposes drivers to enormous amounts of sensory and cognitive stimuli (Lee, 2008). Risk perception depends not only on the physical visibility of an object, but also on its ability to emerge within the user's field of attention. Cognitive psychology studies demonstrate that dynamic, rotating, pulsating, and peripherally positioned light sources are detected more quickly than static devices placed at ground level (Bullough et al., 2024; Wickens et Hollands, 2000).

The presence of two symmetrical light sources (Figure 1) increases the cognitive recognisability of the sign and strengthens its identification as an intentional warning element (Wickens et Hollands, 2000).



Figure 1. Simmetrical positioning of the device.

The colour differentiation between red and green also introduces a particularly relevant semantic dimension. Red universally communicates urgency, danger, and the need for immediate attention, while green is generally associated with controlled or operational conditions. This distinction allows the system to convey not only the presence of a stationary vehicle, but also implicit information regarding the level of risk of the situation.

The theoretical framework also connects to the evolution of road policing and integrated mobility security. As highlighted by Cestra (2022), contemporary road policing is progressively transcending the traditional concept of traffic policing, taking on a multidimensional function that integrates prevention, emergency management, infrastructural resilience, public safety, and mobility flow governance. Road infrastructures are thus reinterpreted as strategic environments where security, economy, logistical continuity, and human protection converge (Cestra, 2022; European Commission, 2020).

From this perspective, emergency reporting systems become true tools for preventative risk governance. They contribute not only to collision reduction, but also to operator protection, traffic flow stabilization, and the overall resilience of the mobility system.

2.2 Conceptual architecture of the LED system

The conceptual architecture of the proposed system is based on a relatively simple but strategically innovative principle: developing a multidirectional light signal capable of maximizing the visibility of the stationary vehicle while reducing the user's exposure to the roadway (Bullough et al., 2015).

The system consists of two independent LED modules to be positioned outside the vehicle, on the ground, or in another convenient location, and secured using industrial suction cups, magnets, or hybrid stabilization systems. Each module operates independently but can be wirelessly synchronized with the opposite unit, creating a coordinated and symmetrical signal.

The choice to use two separate light sources, rather than a single central source, stems from both geometric considerations and cognitive evaluations. This configuration creates a wider, more laterally distributed light signature, improving visibility even from oblique angles or from side aisles.

From a perceptual standpoint, the presence of two light sources (Figure 2) produces a visual signature that's more easily recognized by the human brain. Drivers tend to interpret bilateral light patterns as intentional and organized signals, increasing the likelihood of early risk identification (Wickens et Hollands, 2000).

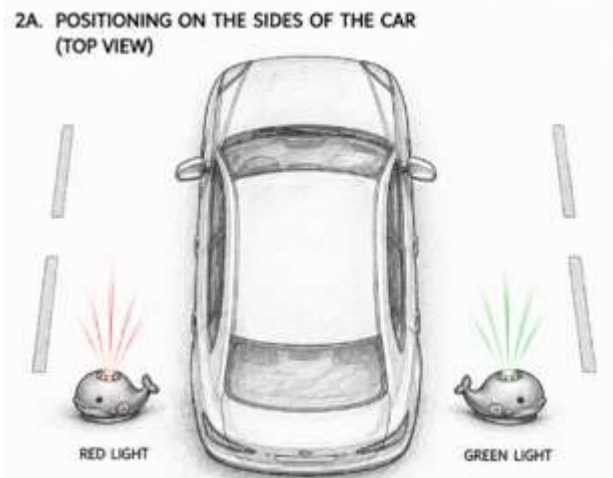


Figure 2. Presence of two lights source.

The use of LED technology further amplifies these advantages. LEDs guarantee high light intensity, low energy consumption, and the ability to create dynamic flashing sequences that increase attention. Unlike passive retroreflective devices, they maintain high visibility even in rain, fog, snow, or darkness (Bullough et al., 2024).

A particularly innovative element concerns the red-green chromatic logic. Green and red perform the same signalling principle as in maritime and air navigation (International Civil Aviation Organization [ICAO], 2018).

The combined use of red and green in the installed LED system is not merely an aesthetic choice or a simple colour differentiation, but is based on a communication logic consolidated for decades in maritime and aeronautical navigation systems. In both these fields, the red-green combination constitutes an international standard for orientation, directional identification, and collision avoidance, based on the human ability to rapidly interpret color-coded light signals even in highly complex operational conditions or reduced visibility (International Maritime Organization [IMO], 2019).

In the maritime sector, navigation lights allow vessel captains to immediately identify the direction, orientation, and mutual trajectory of vessels underway (International Maritime Organization [IMO], 2019). The red light traditionally indicates the port side, while the green light identifies the starboard side. This convention allows for immediate assessment of the relative situation between vessels, helping to prevent collisions, especially during night navigation or in adverse weather conditions. Similarly, in the aviation sector, aircraft use red and green lights on their wingtips to allow recognition of the aircraft's attitude and direction during flight or airport manoeuvres (International Civil Aviation Organization [ICAO], 2018).

What makes the conceptual transfer of this principle to road safety particularly interesting is the fact that both maritime and aeronautical navigation operate in environments characterised by:

- a) high relative speed;
- b) reduced decision-making times;
- c) need for early risk identification;
- d) variable visibility conditions;
- e) strong dependence on light perception.

These same characteristics are increasingly present in modern road systems, especially on high-speed infrastructure (European Commission, 2020). Contemporary roads, in fact, present operational dynamics increasingly similar to those of complex advanced mobility environments, where the ability to rapidly communicate risk situations is of fundamental importance (WHO, 2023).

The application of the red-green principle to road signalling thus introduces a form of "*land navigation*" based on lateral and multidirectional light communication. As in maritime and air navigation, the driver not only perceives the presence of an obstacle, but also acquires implicit information regarding orientation, position, and the nature of the operating situation.

From a cognitive perspective, this approach offers extremely significant advantages. The human brain tends to more quickly interpret culturally consolidated colour schemes that are universally associated with safety and orientation functions (Wickens et Hollands, 2000). Using red as a signal of immediate danger and green as an indicator of stabilization or controlled presence reduces interpretative ambiguity and accelerates the driver's behavioural response.

In the proposed system, red could be used mainly on the traffic-exposed side to emphasize:

- a) immediate risk;
- b) presence of operators;
- c) obstacle on the roadway;
- d) need to slow down.

Green could instead play a complementary role in:

- a) safe area delimitation;
- b) perceptual stabilization;
- c) identification of the protected side;
- d) indirect visual traffic guidance.

This logic introduces an important element of innovation compared to traditional road signalling systems, which generally tend to use a single colour mode without semantic or directional differentiation (Vienna Convention on Road Signs and Signals, 1968).

From a theoretical perspective, the parallel with maritime and air navigation also reinforces the system's positioning within contemporary paradigms of intelligent mobility and road policing. Just as naval and air traffic require standardized light communication systems to ensure safety and interoperability, land mobility is also evolving towards increasingly interconnected ecosystems, in which anticipatory visual communication becomes an integral part of preventative risk governance (European Commission, 2020).

The adoption of a chromatic principle already consolidated in other domains of advanced mobility could therefore facilitate:

- a) intuitive understanding of the system;
- b) international standardization;
- c) future interoperability with ITS and V2X systems;
- d) integration into smart mobility paradigms.

From this perspective, the installed LED system represents not only a new emergency device, but the evolution towards a form of "*navigational*" road signalling, capable of transferring to the terrestrial

domain communication principles already widely validated in the maritime and aeronautical sectors (IMO, 2019; ICAO, 2018).

The possibility of using asymmetric operating modes also appears particularly interesting. The instrument facing traffic could emit a pulsating red light, while the one facing the roadside could use a stabilizing green light. This configuration would be particularly useful during police checks, medical interventions, or maintenance operations, as it would help visually define the operational perimeter and guide driver behaviour.

The system could also integrate accelerometers, impact sensors, GPS modules, and automatic activation capabilities in the event of a collision or sudden deceleration. In the future, these devices could interact with V2X systems, intelligent infrastructure, and traffic management platforms, gradually becoming active communication nodes for intelligent mobility (European Commission, 2020).

From this perspective, the installed LED system should not be interpreted as a simple aftermarket accessory, but as a possible preview of future intelligent signalling architectures integrated into the mobility systems of the future.

The proposed portable emergency signalling device adopts a whale-inspired biomimetic design specifically developed to optimize ergonomic handling, operational intuitiveness, and deployment efficiency under emergency conditions. The whale-shaped configuration is not intended as a purely aesthetic solution, but rather as a functional morphology derived from human factors engineering and cognitive ergonomics principles. (Figure 3)

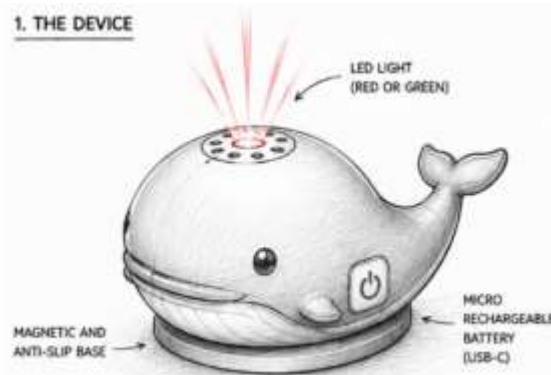


Figure 3. The device draft.

In high-stress roadside scenarios, users frequently experience reduced fine motor control, elevated cognitive workload, diminished situational awareness, and time-pressure decision-making. Under such conditions, conventional geometric emergency devices may become more difficult to grasp, orient, and deploy rapidly. The whale tail structure provides a natural gripping point that can be instinctively seized even in low-visibility conditions, while wearing gloves, or during acute psychological stress. The tail therefore functions as an integrated ergonomic handle specifically designed to facilitate immediate retrieval and positioning during roadside emergencies (Figure 4).



Figure 4. Possible standard dimension and functions of the device.

The central body of the device is intentionally designed with dimensions and tactile characteristics comparable to those of a standard computer mouse. This configuration allows the unit to fit naturally within the palm of the hand, improving grip stability, minimizing slippage risk, and enhancing one-handed operability (Figure 5)

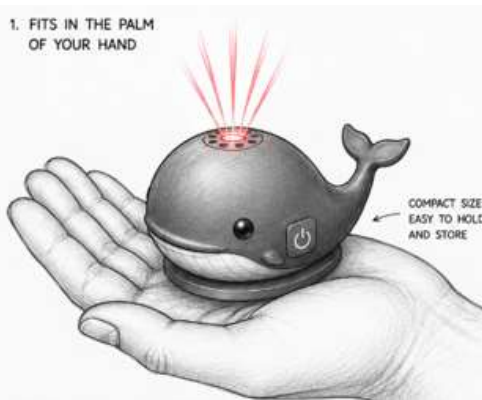


Figure 5. Particular of device's dimension.

The rounded upper surface promotes intuitive tactile recognition and rapid orientation without requiring visual confirmation, which is particularly advantageous during nighttime deployment or adverse weather conditions. From an ergonomic perspective, the smooth convex geometry distributes contact pressure evenly across the hand, reducing muscular strain and facilitating repeated manipulation during operational use. The compact “mouse-like” volume also improves storage efficiency inside vehicle compartments, allowing rapid accessibility without occupying significant space within the passenger cabin (Figure 6).



Figure 6. Easy to grip device design.

The lower section of the device incorporates a wide and stabilized base engineered to maximize ground adherence and positional stability. This enlarged footprint reduces overturning probability caused by aerodynamic turbulence generated by passing vehicles, lateral wind forces, road vibrations, or uneven pavement conditions. Depending on operational requirements, the base may integrate anti-slip materials, magnetic fixation systems, or suction stabilization mechanisms capable of improving anchorage on different roadway surfaces and vehicle structures. Stability represents a critical operational requirement because secondary movement or accidental displacement of emergency signalling devices may reduce conspicuity effectiveness and compromise hazard communication consistency.

One of the most distinctive technical characteristics of the concept concerns the positioning and projection geometry of the LED light source. Rather than emitting light horizontally or frontally, the system projects luminous signalling upward from the curved dorsal section of the whale body, reproducing the visual dynamics of a whale's blowhole spray. This biomimetic solution serves several functional objectives simultaneously. First, the elevated upward projection increases multidirectional visibility and improves long-range conspicuity by creating a vertically distributed luminous plume capable of emerging above surrounding visual clutter. Second, the dorsal emission geometry enhances peripheral detection and attentional capture, particularly under nighttime or reduced-visibility conditions. Third, the "whale blow" luminous effect generates a highly recognizable visual signature that differs substantially from conventional automotive lighting patterns, thereby reducing perceptual ambiguity and improving hazard recognition speed among approaching drivers (Figure 7).

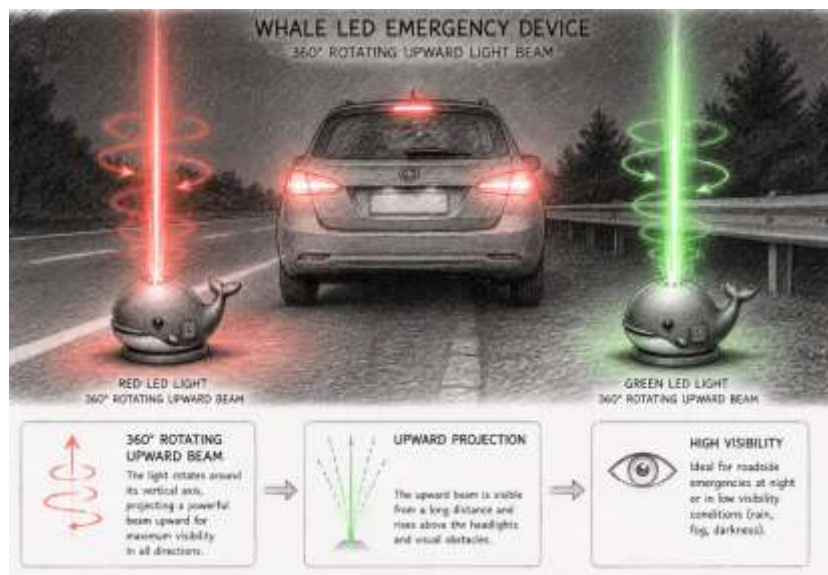


Figure 7. Whale rotating up lights.

From a cognitive and operational perspective, the whale-inspired architecture combines ergonomic efficiency, intuitive manipulation, aerodynamic stability, and distinctive visual communication within a single integrated roadside safety device. The concept therefore represents an example of biomimetic industrial design applied to road safety engineering, where natural morphological solutions are adapted to improve usability, conspicuity, and operational performance in emergency mobility environments.

2.2. Benefits for road safety

The installed LED system has numerous potential advantages in terms of road safety, especially with regard to the prevention of secondary collisions, the protection of vulnerable road users and the improvement of early risk perception (WHO, 2023).

One of the most important benefits is reducing road users' exposure to the road. The traditional warning triangle forces the driver to exit the vehicle and walk through often extremely dangerous stretches of road, especially on highways, in tunnels, or in conditions of poor visibility (NHTSA, 2022).

The proposed system, however, allows for immediate activation directly from the vehicle or immediately after stopping. In the future, the need for manual intervention could be almost completely eliminated, drastically reducing the risk of the driver or passengers being hit.

Another key advantage is multidirectional visibility. Traditional systems primarily produce rearward warnings, while the proposed system generates distributed lateral conspicuity, improving hazard recognition even from side lanes or oblique angles (Bullough et al., 2024).

Detection distance is also significantly improved. External light sources are more noticeable, especially in heavy traffic, rain, fog, or obstructed vision (Bullough et al., 2024).

The dynamic nature of LEDs also helps increase attentional capture. The human brain tends to perceive intermittent or pulsating light stimuli more quickly than static, retroreflective objects (Wickens et Hollands, 2000). This is particularly important in an era of increasing distracted driving (Lee, 2008).

The red-green colour scheme further enhances the system's effectiveness. Red induces an immediate perception of danger and encourages speed reduction, while green allows for the communication of controlled or less critical operational situations. This semantic modulation reduces perceptual ambiguity and facilitates cognitive interpretation of the scene (IMO, 2019).

The system also offers significant operational advantages for road police forces, emergency responders, and maintenance workers. Increased lateral conspicuity could improve operational safety and reduce the risk of secondary collisions involving exposed personnel along the roadway (Cestra, 2022).

From a *Safe System* perspective, the proposed system ultimately contributes to creating a more "forgiving" road environment, more tolerant of inevitable human error (OECD/ITF, 2008). Rather than relying solely on the driver's perfect attention, it introduces perceptual redundancy, anticipatory communication, and greater systemic resilience, helping to transform emergency reporting into an active component of preventative road safety governance.

2.3. Integration with *Intelligent Transportation Systems*

The progressive digitalization of mobility systems is profoundly transforming the relationship between vehicles, infrastructure, emergency management, and road safety governance (European Commission, 2020). Roads are no longer just physical corridors for transportation, but are becoming intelligent operating ecosystems characterized by continuous information exchange, predictive management capabilities, sensor integration, and real-time communication between infrastructure and users. In this evolving scenario, road emergency reporting technologies must also evolve from passive warning tools to connected and interoperable safety systems capable of actively participating in traffic management and risk mitigation.

The proposed LED architecture offers particularly significant potential in this regard, as its modular structure naturally lends itself to integration with *Intelligent Transportation Systems* (ITS) and *Vehicle-to-Everything* (V2X) communication environments (European Commission, 2020). Although the current conceptual model primarily emphasizes visual signalling and lateral conspicuity, future developments could transform these devices into true intelligent mobility nodes, capable of generating, transmitting, and receiving operational safety information.

One of the most promising developments involves automatic hazard communication. In contemporary traffic systems, many collisions occur not because the hazard is invisible, but because hazard information reaches drivers too late (WHO, 2023). A stationary vehicle perceived solely by sight can leave drivers with only a few seconds of reaction time, especially on high-speed infrastructure (Green, 2000). If LED devices were integrated with V2X platforms, system activation could simultaneously generate digital alerts broadcast to nearby connected vehicles. Drivers would then receive advance warnings directly on their on-board displays, navigation systems, or head-up displays before they even visually detect the immobilized vehicle.

This anticipatory communication becomes even more important in the context of autonomous and semi-autonomous vehicles. Future mobility systems will increasingly depend on vehicles' ability to exchange operational information in real time (European Commission, 2020). An intelligent emergency warning system could provide automated driving systems with precise geolocalized data regarding obstacles on the road, accident scenarios, or the presence of roadside operators. This would enable early lane adjustments, speed reductions, and safer traffic flow management.

Another important aspect concerns integration with emergency management systems. The proposed devices could synchronize with existing *eCall* infrastructures, automatically transmitting emergency information upon detection of a collision or sudden deceleration (European Commission, 2020). This capability would not only improve the efficiency of post-crash rescue operations, but would also strengthen the protective function of road signals during the critical interval between the occurrence of the event and the arrival of emergency responders.

Integration with smart infrastructure also presents considerable opportunities. *Smart roads* equipped with environmental sensors, variable message signs, adaptive speed management systems, and traffic monitoring platforms could dynamically interact with activated emergency systems (European Commission, 2020).

For example, turning on the LED lights could automatically determine:

- a) dynamic speed limit reductions;
- b) activation of danger messages on electronic panels;
- c) temporary changes in lane management;
- d) predictive congestion management interventions;
- e) activation of emergency corridors.

These interactions would transform road signage from an isolated visual phenomenon to an integral part of an adaptive mobility governance ecosystem (European Commission, 2020).

The proposed system could also contribute to the development of predictive safety models. Aggregated and anonymized data on emergency device activations could allow authorities to identify areas with recurring mechanical failures, particularly critical infrastructure sections, weather vulnerabilities, or operational bottlenecks. In this sense, the devices could function not only as preventative safety tools, but also as distributed sensors to support advanced transportation intelligence systems.

Naturally, the evolution towards connected systems would make cybersecurity and interoperability issues central. Any intelligent emergency reporting infrastructure would require robust encryption protocols, secure authentication mechanisms, and harmonized technical standards at the European level to prevent misuse or false alerts (European Commission, 2020). However, the potential benefits in terms of

preventative security and anticipatory communication fully justify further research and experimentation in this direction.

Ultimately, the integration of LED systems into smart mobility ecosystems reflects a broader paradigm shift in road safety governance. Safety depends less on isolated technologies and more on interconnected systems capable of continuous information exchange, adaptive response, and predictive risk management (OECD/ITF, 2008). In this context, road visibility is evolving from a simple passive condition to an active communication process embedded in the very architecture of smart mobility.

2.5. Operational applications for Road Policing and emergency services

The operational implications of the LED system extend far beyond standard civilian roadside assistance scenarios. One of the most strategically relevant aspects of the concept is its application in road policing, emergency response, infrastructure maintenance, and roadside operational safety (Cestra, 2022). Modern road infrastructures represent highly dynamic operating environments in which police officers, emergency responders, maintenance workers, and vehicle recovery personnel frequently perform tasks in extremely high-risk conditions (WHO, 2023).

Roadside fatalities remain a persistent problem worldwide. Road police officers conducting checks, accident investigations, or emergency response often operate just meters from high-speed traffic. Firefighters, medical personnel, highway maintenance crews, and tow truck drivers are similarly at risk. In many cases, secondary collisions involving roadside workers occur not because drivers intentionally ignore the rules, but because they fail to perceive the scene early enough to safely adjust their behaviour (NHTSA, 2022).

In this context, visibility becomes a critical factor in operational protection. Traditional emergency lighting systems installed on vehicles, while effective in many circumstances, still have several limitations. Roof-mounted light bars primarily provide front and rear warnings. In heavy traffic or complex road geometry, the operational scene can remain partially obscured until the final moments before interacting with an approaching driver (Bullough et al., 2024). LED systems positioned outside the vehicle, on the ground, or in another convenient location, offer a complementary protective function, generating extended lateral visibility capable of increasing early detection of danger.

For road policing, in particular, the proposed architecture integrates perfectly with the evolution from "*traffic policing*" towards broader "*road policing*" paradigms, as described by Cestra (2022). Contemporary road policing increasingly integrates prevention, emergency management, infrastructural resilience, mobility governance, and integrated safety. In this framework, road signalling systems become not simple technical accessories, but real operational tools capable of directly contributing to the creation of safer intervention environments and better regulation of traffic flows.

The possibility of using asymmetric signalling modes is particularly interesting. During a roadside check or highway intervention, the LED facing traffic could emit high-intensity red flashes to maximize attention and prompt a reduction in speed, while the LED facing the shoulder or protected area could emit green stabilization signals. This configuration creates a sort of dynamic visual management of the operational corridor, guiding drivers and reinforcing the correct interpretation of the scene (IMO, 2019).

EMS services could also benefit significantly from increased lateral conspicuity. Ambulance crews frequently operate in volatile traffic conditions during the most critical minutes following accidents or medical emergencies. Improved multidirectional visibility could contribute to safer extraction operations, more effective scene stabilization, and reduced vulnerability of healthcare workers (WHO, 2023).

Road maintenance operations represent another particularly relevant application area. Maintenance operators often work in temporary or mobile operating configurations where traditional traffic management systems may be insufficient or difficult to deploy quickly. LED systems, positioned outside the vehicle, on the ground, or in another convenient location, could therefore provide flexible additional visibility for short-term interventions, temporary obstacles, or rapid risk mitigation operations.

Tow truck drivers are also a highly vulnerable professional group. Recovery operations frequently occur at night, in difficult weather conditions, or on high-speed highways. The use of multidirectional signalling systems could significantly increase the visual safety perimeter around immobilized vehicles and recovery operators (NHTSA, 2022).

From an operational perspective, the proposed system reflects the shift toward preventive and adaptive safety models. Rather than relying solely on static rules or driver attention, the architecture aims to create a more communicative operating environment capable of proactively influencing road user behaviour. This approach fully integrates with *Safe System* philosophies and contemporary integrated mobility safety paradigms (OECD/ITF, 2008).

Finally, the concept of LEDs positioned outside the vehicle, on the ground, or in another convenient location, could contribute, both symbolically and operationally, to the evolution of the professional identity of road policing and mobility safety governance. Visibility, prevention, anticipatory communication, and operational safety are increasingly central dimensions in modern road intervention strategies (Cestra, 2022). Technologies capable of strengthening these dimensions could therefore play a significant role in the future development of safer, smarter, and more resilient mobility systems (European Commission, 2020).

2.6. Research paths and experimental validation

Although the theoretical and operational rationale for an LED system to be positioned outside the vehicle, on the ground or in another convenient location, appears particularly promising, its actual scientific validation necessarily requires extensive multidisciplinary empirical research (Stanton et al., 2007). The complexity of contemporary road environments requires that any new safety technology be evaluated not only from a technical perspective, but also with respect to its behavioural, perceptual, operational, and systemic implications (OECD/ITF, 2008).

One of the main priorities is evaluating performance in terms of visibility and early hazard recognition. It will be necessary to experimentally verify whether LED systems, to be positioned outside the vehicle, on the ground or in another convenient location, are actually capable of increasing detection distance, improving reaction times, and promoting faster risk identification compared to traditional retroreflective triangles or existing light devices (Bullough et al., 2024).

Such studies could be developed both through experiments in real environments and through advanced driving simulators capable of reproducing highly complex operational scenarios, including:

- a) adverse weather conditions;
- b) night driving;
- c) heavy highway traffic;
- d) galleries;
- e) congested urban environments;
- f) high cognitive load scenarios.

Driving simulators are a particularly important tool because they allow researchers to analyse driver behaviour under realistic conditions without exposing participants to actual risks (Lee, 2008).

Through these methodologies, it would be possible to accurately measure variables such as:

- a) braking start distance;
- b) reaction time;
- c) residual speed;
- d) lane deviation;
- e) evasive trajectories;
- f) gaze distribution;
- g) visual fixation times.

The use of eye-tracking technologies could also provide extremely useful information about the system's ability to capture peripheral attention and emerge within the driver's field of attention. This aspect is particularly important in light of the growing phenomenon of distracted driving and the high number of visual stimuli present in modern traffic environments (Wickens et Hollands, 2000).

The red-green colour logic also requires specific experimental validation. Although the theoretical rationale, borrowed from maritime and aeronautical navigation systems, appears particularly robust (IMO, 2019; ICAO, 2018), it will be necessary to empirically verify whether drivers actually interpret the signals as intended.

The studies will therefore have to analyse:

- a) semantic understanding of colours;
- b) subjective perception of risk;
- c) perceived urgency;
- d) behavioural adaptation;
- e) possible cognitive overload.

Another area of research concerns the influence of environmental conditions on system performance. Heavy rain, fog, snow, light reflections, urban lighting, or unusual road geometries could significantly alter the perceptual effectiveness of LED devices. It will therefore be necessary to compare system performance in different operating contexts, evaluating its robustness and reliability (Bullough et al., 2024).

Operational validation also appears particularly important in the context of road policing and emergency services. Field studies conducted with road police patrols, highway operators, emergency medical services, and maintenance teams could allow for the evaluation of:

- a) increased perceived safety;
- b) improved conspicuity of operational scenes;
- c) reduction of the risk of secondary collisions;
- d) traffic stabilization;
- e) impact on the behaviour of drivers.

These studies could be integrated with questionnaires, operational interviews and psychometric tools aimed at analysing the subjective perception of safety by operators (Stanton et al., 2007).

Another area of research concerns the system's integration with *Intelligent Transportation Systems* and *V2X* systems. Connected experimental environments could allow testing the effectiveness of combining visual signalling and anticipatory digital communication (European Commission, 2020). Looking ahead, it will be important to understand whether the integration of visual warnings and automatic transmission of emergency data produces superior synergistic effects compared to traditional systems.

Cost-benefit analyses will also be essential. Although the system appears relatively inexpensive compared to other advanced road safety technologies, institutions and public decision-makers will require quantitative evidence regarding:

- a) implementation costs;
- b) operational life;
- c) maintenance;
- d) reliability;
- e) expected reduction of secondary collisions;
- f) economic and social benefits.

These aspects take on particular relevance in the context of Safe System policies, which are increasingly oriented towards evidence-based approaches and systemic effectiveness evaluations (OECD/ITF, 2008).

Finally, further research activities will have to concern regulatory and standardization aspects. The introduction of new signalling architectures may require changes to European and international standards relating to:

- a) allowed colours;
- b) light intensity;
- c) activation protocols;
- d) interoperability;
- e) approval;
- f) cybersecurity in connected systems.

Ultimately, future research should not be limited to the technical evaluation of the device alone, but should consider the system within the broader transformation of mobility safety governance. The evolution towards intelligent, connected, and multidirectional emergency reporting systems represents part of a deeper shift involving infrastructure, behaviours, technologies, and road policing models (Cestra, 2022; European Commission, 2020).

3. Conclusions

The development of advanced road emergency signalling systems is part of a broader transformation of contemporary mobility, road safety, and integrated risk governance paradigms (European Commission, 2020; WHO, 2023). Modern road infrastructures are no longer simply spaces for the movement of people and goods, but complex operational environments that combine public safety, logistical continuity, infrastructure resilience, emergency management, and intelligent mobility (Cestra, 2022). In this context, managing roadside emergencies takes on increasingly strategic importance.

The proposed LED system, to be positioned outside the vehicle, on the ground, or in another convenient location, reflects this paradigm shift, reinterpreting emergency signalling not as a simple passive regulatory requirement, but as an active component of preventative road safety governance.

Traditional signalling devices, such as the retroreflective triangle, were developed in historical contexts characterized by lower traffic density, lower average speeds, and relatively less complex infrastructure environments (Vienna Convention on Road Signs and Signals, 1968). Modern mobility networks, however, feature much higher levels of operational intensity, reducing the time available for risk perception and management (Green, 2000).

From a policy perspective, this requires rethinking the very concept of emergency signalling. Safety can no longer rely solely on static, passive devices that require the user's physical exposure to the roadway (WHO, 2023). On the contrary, future road safety strategies should be oriented towards systems:

- a) anticipatory;
- b) adaptive;
- c) intelligent;
- d) multidirectional;
- e) interoperable;
- f) capable of compensating for human cognitive limitations.

The proposed architecture appears highly consistent with the objectives pursued by the European Commission and the European *Vision Zero* strategies, based on the *Safe System Approach* and systemic risk reduction (OECD/ITF, 2008; European Commission, 2020).

By improving early visibility, reducing user exposure and strengthening danger communication, the system contributes to:

- a) increase systemic tolerance for human error;
- b) reduce kinetic risk;
- c) protect vulnerable users;
- d) improve mobility resilience.

Its application in protecting roadside workers is particularly significant. Road police forces, emergency responders, maintenance workers, and vehicle recovery workers continue to operate in extremely vulnerable conditions (NHTSA, 2022). Secondary collisions remain one of the main critical issues in contemporary road safety. Technologies capable of increasing the conspicuity of operational scenes and promoting early traffic slowdown can therefore generate significant benefits in terms of both public safety and employment protection (WHO, 2023).

The system also integrates perfectly with the evolution of road policing. Contemporary road policing is no longer limited to traditional traffic enforcement, but takes on a multidimensional function that integrates prevention, emergency management, infrastructural resilience, integrated security, and intelligent governance of mobility flows. In this framework, advanced signalling systems become strategic tools for preventative risk management.

The conceptual connection with maritime and aeronautical navigation systems also appears particularly interesting. The combined use of red and green draws on light communication logics already widely validated in complex mobility environments characterized by:

- a) high speed;
- b) reduced decision-making times;
- c) need for advance identification;
- d) strong dependence on light perception (IMO, 2019; ICAO, 2018).

The introduction of such principles into the road domain could facilitate future international standardization processes and interoperability with *ITS* and *V2X* ecosystems (European Commission, 2020).

The theoretical and operational advantages of the system fully justify further experimentation and research. In particular, the conceptual insights developed within the *Help Car Roof Project* demonstrate how innovative signalling technologies may contribute to reducing secondary collision risks and improving operational visibility in high-risk roadway environments (Rufa et al., 2023).

In conclusion, the LED system to be positioned outside the vehicle, on the ground, or in another convenient location, should not be seen simply as a new emergency accessory, but as the expression of a broader conceptual evolution of mobility safety. Future road safety will increasingly depend on systems capable of proactively communicating, dynamically adapting to operational contexts, and reducing dependence on perfect human performance (Reason, 1990).

From this perspective, emergency signalling evolves from a passive function to an active component of preventative road safety governance and integrated mobility safety. The proposed system therefore represents a potential preview of future intelligent signalling architectures destined to characterize 21st-century mobility ecosystems (Rufa et al, 2023; Cestra, 2022; European Commission, 2020).

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Contribution statement

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Declaration of competing interests

The Authors report no competing interests.

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