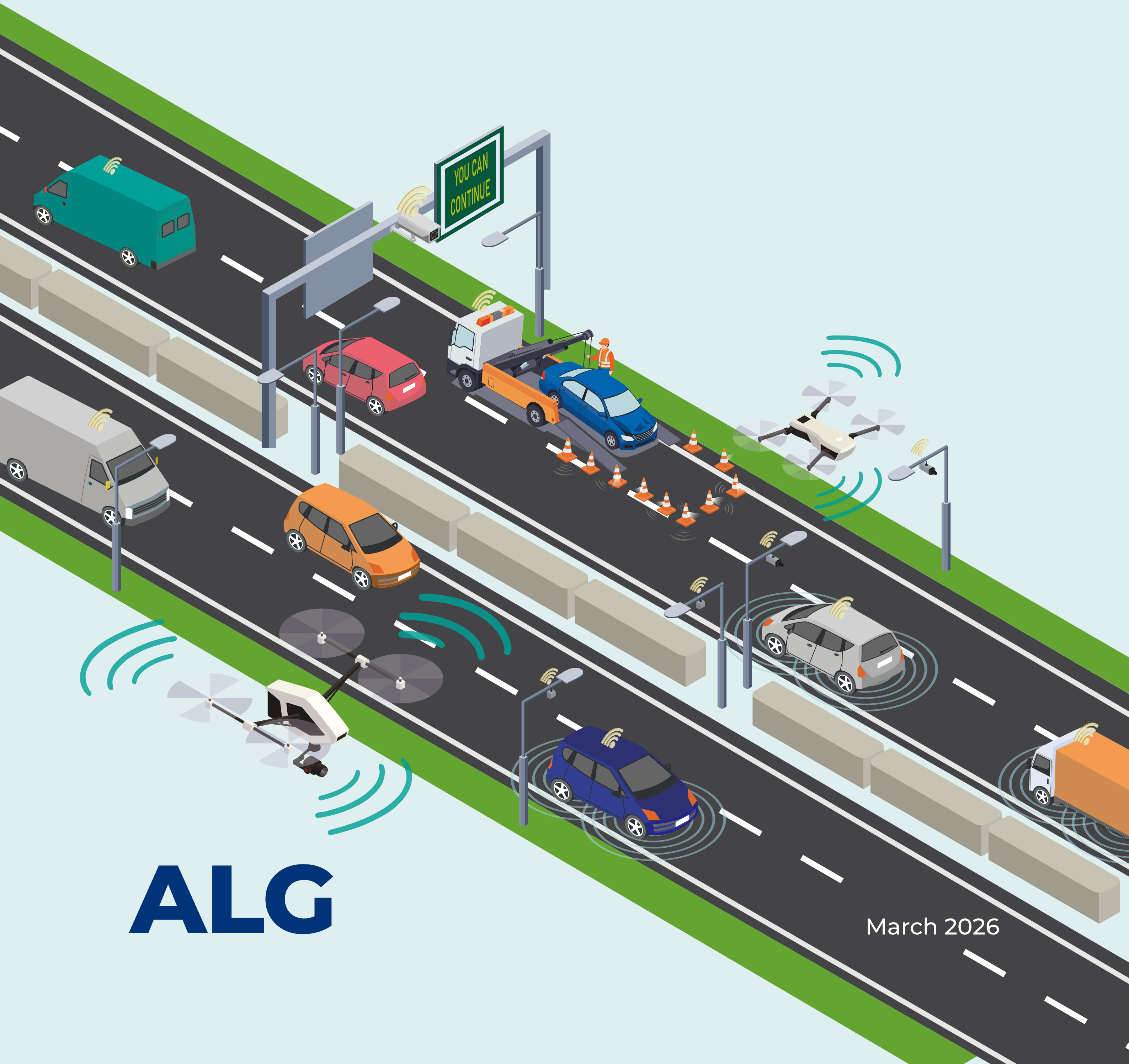
# THE FUTURE OF HIGHWAYS: INFRASTRUCTURE POWERED BY TECHNOLOGY

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March 2026

# CHALLENGES IN THE HIGHWAY SECTOR VS. TECHNOLOGY READINESS

The highway sector is facing an increasingly complex and demanding operating environment. Growing traffic volumes, aging infrastructure, safety concerns, and new mobility patterns (among others) are placing unprecedented pressure on highway operators.


Most pressing challenges in the highway industry





**Funding constraints.** Fleet electrification is contributing to declining fuel levy revenues, while aging infrastructure approaching the end of its design life continues to drive maintenance costs upward. Predictive maintenance and performance-based maintenance models with advanced analytics can help to optimize intervention costs.

**Capacity limitations.** Increasing traffic volumes in constrained corridors, coupled with limited space and budget for capacity expansion, lead to congestion and reduced service levels. This results in significant user dissatisfaction and substantial economic losses, which can be mitigated through active traffic management measures and coordinated driving enabled by connected and autonomous vehicles.

**Toll revenue leakage.** Uncollected tolls and fraud from carpool imposters (falsely declaring themselves as high-occupancy vehicles) can lead to significant revenue losses, especially in Express Lanes, undermining financial sustainability. This challenge reinforces the need for automated, technology-driven tolling and enforcement solutions.

**Work zone safety.** Executing maintenance activities safely without disrupting traffic flow is a major challenge for highway operators. Work zones increase the risk of accidents for both maintenance crews and road users, highlighting the need for advanced traffic management solutions that minimize personnel exposure.

**Road user safety**. Increasing congestion and traffic density on highway corridors contribute to higher accident rates. This underscores the need for enhanced safety, monitoring, and rapid incident-response capabilities.

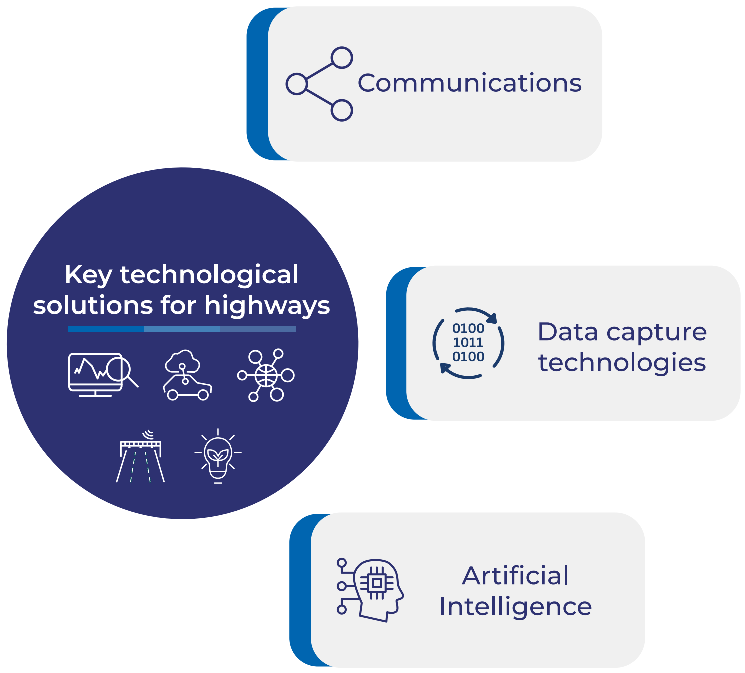
**User experience.** Toll-paying users expect minimal delays, real-time traffic information, and fast incident response. Intelligent traffic management, real-time monitoring, and rapid-response systems enable operators and public authorities meet these growing expectations.

**Environmental sustainability.** Societal pressures, regulatory requirements, and funding eligibility criteria are pushing operators to reduce emissions, manage noise, optimize energy use, and improve resilience to climate change. As a result, agencies are increasingly adopting innovative materials and energy-efficient technologies to meet these requirements without compromising performance or budgets.

Against this backdrop, the adoption of new technologies is prompting operators to reconsider traditional approaches to the operation and maintenance of tolled highways and freeways. By leveraging emerging technologies and innovative solutions, operators can address growing challenges and external pressures, using these tools to bridge critical gaps across the industry.

As a result, the highway sector has reached a critical inflection point. Technologies that were once experimental, cost-prohibitive, or operationally immature now reliable, scalable, and economically viable. Advances in artificial intelligence (AI), combined with new data capture technologies (high-resolution cameras, drones, fiber-optic infrastructure, etc.) and communications have unlocked capabilities that were not realistically achievable a few years ago.

Today, these technologies have matured enough to be deployed at scale and integrated into day-to-day highway operations. Acting now would enable operators to capitalize on the maturity of these technologies, manage transition risks in a controlled manner, and position their highway networks for sustainable, data-driven operations in the years ahead.




Key technological solutions for highways

> **AI and advanced analytics** have emerged as cross-cutting platforms capable of processing, correlating, and interpreting the vast volumes of **data captured by cameras, drones, sensors, and fiber-optic systems** (among other) across highways. At the same time, advances in **communications infrastructure** now enable the reliable, real-time transmission of this data across road networks and users at relatively lose cost.



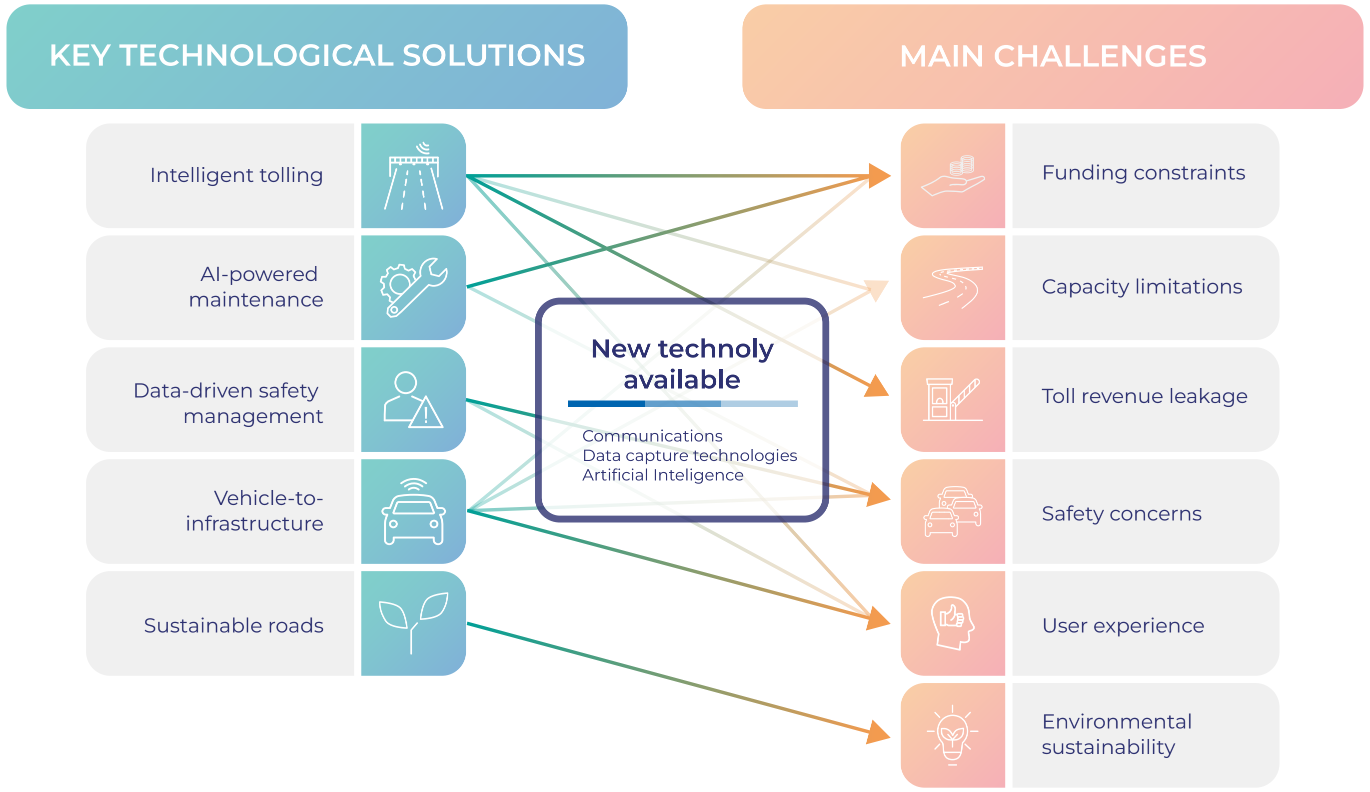


From an infrastructure manager perspective, the scope for directly enabling autonomous vehicles remains limited, beyond supporting their ability to correctly interpret the surrounding environment. In this context, maintaining high-quality horizontal signage and clear lane markings is essential, particularly in work zones, where inconsistent or degraded markings can negatively affect vehicle perception systems and compromise safe automated driving.

# EMERGING TECHNOLOGIES TO ADDRESS HIGHWAY CHALLENGES

Building on this digital foundation, the integration of advanced analytics, new data-capture devices, and enhanced connectivity are enabling a new generation of sector-specific solutions. In this context, the most impactful and mature solutions transforming the highway sector are categorized into five major innovation groups:

**NEW TECHNOLOGY AVAILABLE: COMMUNICATIONS, DATA CAPTURE TECHNOLOGIES AND ARTIFICIAL INTELLIGENCE**




The potential of technological innovations for highways





**Intelligent tolling.** Increasing availability of real-time traffic data (including vehicle location and imaging) combined with V2I communication enables the implementation of more reliable and flexible tolling schemes, which ultimately support innovative mobility strategies, optimize traffic flow, and create new funding opportunities for the highway sector.

**AI-powered road maintenance.** By capturing data more efficiently, reliably, and at higher frequency, AI-powered road maintenance enables a shift from reactive, calendar-based approaches to data-driven, condition-based strategies. Leveraging automated asset monitoring systems combined with advanced analytics, operators can anticipate failures, optimize maintenance interventions, extend asset life, and ultimately reduce O&M costs.

**Data-driven safety management** focuses on enhancing safety across the highway network, for both road users and maintenance crews. Solutions such as real-time traffic monitoring, advanced incident detection, and predictive traffic management play a critical role in minimizing accidents, improving response times, and maintaining service levels, particularly in heavy traffic environments.

**Vehicle-to-infrastructure** communication enables direct communication between highway infrastructure and vehicles. By providing real-time information on traffic conditions, incidents, weather, and speed recommendations, these solutions enhance situational awareness for drivers, improve safety, and lay the foundation for connected and autonomous vehicle ecosystems.

**Sustainable roads** aim to reduce the environmental footprint of highway operations while increasing infrastructure resilience to climate change. They include energy-efficient infrastructure, renewable energy, adaptive lighting, and recycled materials designed to lower emissions, optimize energy use, and support long-term sustainability goals.

The strategic deployment of these technological solutions can effectively address the critical challenges confronting the highway sector.

# Intelligent tolling

By combining real-time traffic data, vehicle-to-infrastructure communication, and advanced algorithms, intelligent tolling enables flexible and dynamic pricing schemes that improve traffic flow, enhance user experience, and open new revenue opportunities. Modern solutions integrate various capabilities to create a seamless and efficient tolling ecosystem.

This includes:

- Dynamic pricing algorithms
- GNSS tolling
- Automated vehicle occupancy identification
- Car wallet



## Dynamic pricing algorithms

Dynamic pricing algorithms adjust toll rates in real time in response to traffic demand and service levels. Their primary objective is to preserve a minimum traffic speed to ensure reliable travel time performance in congested corridors, while maximizing toll revenue.

These algorithms are foundational to managed lanes and congestion pricing programs, where toll rates adjust continuously to regulate traffic flow and travel speeds.

Beyond congestion management, dynamic pricing also enhances revenue performance by capturing users' willingness to pay during peak periods, thereby strengthening the financial sustainability of managed lane facilities and enabling flexible pricing schemes. Its implementation relies on robust traffic data, continuous monitoring systems, and well-established pricing methodologies, positioning dynamic tolling as a mature, proven, and dependable instrument in modern highway operations.

In the United States, some illustrative examples include managed lanes on the I-66 in Virginia, and I-105 and SR-91 in California (amongst many others), where toll rates are continuously adjusted to regulate demand, maintain traffic flow, and optimize revenue generation. These corridors illustrate the role of dynamic pricing as a core element of intelligent tolling systems.

Key benefits:

- Evidence from Express Lanes in the U.S. suggests that dynamic pricing can reduce travel times by up to 40%[1] in heavily congested environments.

- At the same time, dynamic pricing has been associated with toll revenue increases of around 20%[2], by capturing users' higher willingness to pay during peak hours.

[1] Investigating the impacts of I-66 Inner Beltway dynamic tolling system
[2] Colorado's Dynamic Tolling Boosts Traffic Flow

## GNSS tolling

GNSS tolling enables toll calculation and payment without the need for physical toll plazas or gantries. GNSS tolling relies on onboard units to determine vehicle position and apply charges based on the actual distance traveled, road segments used, or predefined charging zones.

Deployment patterns vary significantly by region. In Europe, GNSS tolling is used as a primary tolling mechanism on selected motorways across multiple countries. In the United States, large-scale adoption of fully GNSS-based tolling remains limited due to privacy, regulatory, and user-acceptance considerations.

Illustrative examples of GNSS tolling in Europe include corridors such as the German Federal Motorway Network, Belgium, Hungary and the Chez Republic. In the United States, electronic toll collection systems based on roadside infrastructure remain predominant, while GNSS tolling continues to be evaluated for future large-scale implementation.

Key benefits:

- With the shift to GNSS technology, experience in Europe shows a 50%[3] reduction in tolling system operating costs, while simultaneously enabling an expansion of the tolled network by nearly 90%[3].

- Germany's GNSS truck tolling system reports toll revenue leakage below 1%[4], indicating highly accurate billing and revenue capture.

[3] Satellite positioning innovations in tolling
[4] Toll Collect





## Automated vehicle occupancy identification

Toll revenue leakage remains a structural issue on express lanes where exemptions/discounts are in place for high-occupancy vehicle (HOVs), as some drivers falsely claim HOV status to avoid paying for tolls. Automated vehicle occupancy identification addresses this issue by using advanced sensing and analytics to support HOV compliance and protect toll revenues.

This technology relies on artificial intelligence applied to video and image data to automatically estimate vehicle occupancy and identify potential carpool imposters. In many cases, achieving acceptable accuracy at free-flow speeds, which limits the use of fully automated enforcement due to the risk of false positives. As a result, these systems are typically integrated into broader tolling and enforcement frameworks rather than as a standalone solution, where automated detection supports manual verification processes.

For example, automated HOV detection in the U.S. is used only in some Express Lanes such as the I-405 and the SR-167 in Washington State, where it supports the validation process with manual enforcement agencies.

Key benefits:

- Evidence from Express Lanes suggests that carpool imposters can represent up to 30-35% of total traffic (since more than 50% of HOV traffic falsely declare themselves as high-occupancy vehicles).

- Therefore, in environments with visual enforcement, the implementation of automated HOV detection technology can reduce toll revenue leakage on express lanes by ~65-70%.

- Vehicle occupancy detection technology can reach 95% accuracy at free-flow speed.



## Car Wallet

As tolling systems continue to evolve toward fully digital and barrier-free operations, ensuring reliable vehicle identification and payment compliance has become a growing challenge for highway operators. While transponder-based systems are widely available and generally effective, especially in the United States, leakage associated with pay-by-plate enforcement remains a structural issue.

Car wallet solutions address this gap by embedding payment functionality directly within the vehicle's onboard software, linking vehicle identification with a registered payment method to enable automatic toll transactions.

In this model, toll payments can be processed in free-flow environments and extended to other mobility-related services such as parking, fuel stations, electric vehicle charging, or future road usage charging schemes. By shifting payment into the vehicle itself, car wallet solutions reduce reliance on external identifiers such as license plates and support more direct and automated payment flows. From an operator perspective, the primary value lies in improving payment reliability and reducing revenue leakage in digital tolling environments, while generating new revenue opportunities.

Car wallet solutions remain at an early stage of maturity for highway tolling applications. While technical feasibility has been demonstrated through controlled pilots, broader deployment is constrained by regulatory frameworks, interoperability requirements, and the need for alignment across vehicle manufacturers, toll operators, and payment platforms. Partial adoption limits network-wide effectiveness, meaning conventional transponders or alternative payment mechanisms are still required in parallel.

Current implementations are therefore limited to early-stage use cases and controlled deployments, typically developed in collaboration with vehicle manufacturers, toll operators, or technology providers. These initiatives still focus on technical validation and institutional readiness rather than routine operational deployment across highway networks.

Key benefits:

- All-electronic toll systems can significantly reduce revenue leakage.

- The introduction of car-wallet technology establishes a new service ecosystem in the transportation field. By supporting seamless payments for tolling, refueling/charging, parking, and service-area transactions, it enables the development of new commercial opportunities and business models along the road network.



## AI-powered road maintenance

Automated and predictive maintenance introduces a data-driven approach to asset management, shifting from reactive interventions to proactive lifecycle optimization. LiDAR technology, inspection cameras, drones, and pavement-embedded sensors provide continuous visibility into the condition of pavements, bridges, and roadside assets. By leveraging high-frequency and automated asset monitoring, operators can anticipate failures, optimize interventions, extend asset life, while reducing operation and maintenance costs.

This includes:

- Image-based AI inspection systems
- LiDAR-based AI inspection systems
- Pavement-integrated sensors
- Self-healing pavements

## Image-based AI inspection systems

Highway operators manage large road networks where frequent and consistent condition monitoring is required, while traditional manual inspections are costly, inefficient and prone to human error. Image-based AI inspection systems respond to this need by enabling large-scale visual inspections at traffic speed, without disrupting operations.

Cameras mounted on inspection vehicles capture images or video of the roadway condition and surrounding environment, which are processed in real time using artificial intelligence to identify pavement surface defects and visible anomalies on roadside assets. Typical applications include the detection of pavement cracks, potholes, surface wear, and localized damage, as well as the condition of road markings, signage, barriers, and vegetation height. Compared to LiDAR-based approaches, image-based inspections offer lower geometric precision but allow simpler deployment, lower costs, and higher inspection frequency across extensive networks.

This technology is well established and widely deployed for network-level condition screening, supported by mature camera hardware and continuously improving AI/ML models. In highway operations, they typically serve as a first assessment layer, helping operators identify sections that require more detailed inspection using higher-precision technologies.

In terms of implementation, image-based AI inspection systems are deployed on operational road networks in both Europe and the United States. As an illustrative example, agencies such as the Utah Department of Transportation are using image-based AI inspection solutions to support automated monitoring of pavement condition and road markings across the state highway network.

Key benefits:

- Research indicates that these innovative inspection systems can reduce inspection costs by 30-40%[5] compared with traditional manual methods (while defect identification time reduces by around 30%[6]).
- In turn, the preventive approach enabled by AI-based inspection technology can reduce total maintenance costs by up to 30%[7], while avoiding unexpected lane closures.

[5] The Benefits and Challenges of Artificial Intelligence in Road Infrastructure Maintenance
[6] Pavement Inspection Systems Market Size, Growth
[7] AI-Powered Road Asset Management: Automated Inspection & Predictive Maintenance

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## LiDAR-based AI inspection systems

For certain maintenance, asset management, and engineering activities, visual condition data alone is not sufficient, implying that a higher level of geometric accuracy is required. In these cases, LiDAR-based inspections enable the construction of detailed three-dimensional representations of the pavement surface and roadside environment, supporting engineering-grade analysis and targeted maintenance decisions.

Laser scanning sensors mounted on inspection vehicles generate precise geometric data at traffic speed by emitting laser pulses and measuring their return time. This data is used to assess pavement cracking, rutting, and localized surface defects, as well as to characterize the geometry and condition of structures (bridges, viaducts, etc.) and roadside assets such as traffic signals, poles, gantries, and cabinets. Compared to camera-based inspections, LiDAR provides substantially higher geometric accuracy, at higher cost and typically lower inspection frequency. Recent advances in solid-state LiDAR are progressively reducing costs and complexity, facilitating broader deployment.

LiDAR is a mature measurement technology with long-standing use in surveying and infrastructure engineering. In highway applications, it is primarily deployed in targeted, high-precision inspection campaigns rather than for continuous, network-wide monitoring, and is commonly used to complement image-based inspections where further detailed geometric information is required.

In terms of implementation, LiDAR systems are in use in multiple highway corridors in both the United States and Europe. In the United States, these systems are applied on toll road networks such as the Pennsylvania Turnpike to collect detailed three-dimensional data on pavement condition and roadside assets. In Europe, similar solutions are deployed on motorway corridors such as the M6 motorway (UK), to support detailed road mapping and asset inventory activities.

Key benefits:

- LiDAR delivers superior geometric accuracy for volumetric assessments, with field evaluations indicating that LiDAR-derived measurements are roughly 10%[8] more accurate than those obtained through conventional cross-section surveying methods.
- Recent advancements in LiDAR technology, particularly the development of solid-state LiDAR, have reduced acquisition costs by roughly 60%[9] compared to earlier mechanical systems, making technology increasingly competitive as prices continue to fall with ongoing innovation.

[8] LiDAR vs Surveying In the Field: Choosing the b est option
[9] Energy-Harvesting Pavement Materials: A Review of Technologies for Sustainable Infrastructure

## Pavement-integrated sensors

Understanding how pavements behave structurally over time is a recurring challenge for highway operators, particularly when assessing fatigue, load effects, and long-term deterioration patterns that are not visible at the surface. Pavement-integrated sensors address this gap by embedding sensors within the pavement structure to capture direct, in-situ measurements of mechanical and environmental conditions.

Embedded sensors can measure variables such as strain, deformation, temperature, humidity, and traffic loads, providing data that supports structural assessment and the development of more informed maintenance and rehabilitation strategies. Unlike surface-based inspections, these systems focus on internal pavement behavior rather than visible defects.

While sensing technologies are technologically mature, their use within operational environments remains limited. Adoption is constrained by the need to install sensors during construction or major rehabilitation works, as well as by durability requirements and the complexity and cost of deploying and managing sensors at network scale.

As a result, pavement-integrated sensors are currently implemented mainly through pilot projects, test sections, and research-oriented applications. These initiatives are primarily used to evaluate data value and system performance and are not yet considered scalable solutions for routine and network-wide pavement monitoring.

Several U.S. DOTs, including those in Wyoming and Utah, are exploring the use of distributed acoustic sensing (DAS) combined with AI-driven computer vision to monitor highways. This technology converts standard fiber optic cables into thousands of distributed vibration sensors, capable of detecting strain and acoustic signals in real time. Its applications include monitoring pavement conditions, traffic counts, detecting roadway slides, and more.

Key benefits:

- Pilot deployments indicate potential maintenance cost reductions of up to ~20%[10], enabled by earlier detection of pavement deterioration through continuous sensor data.

- Initial pilots show a material reduction in emergency repairs, in some cases approaching 50%[10], driven by earlier identification of defects and preventive interventions.

- Early implementations suggest work-order response times could be reduced by around 30–35%[10] compared with traditional inspection-based maintenance.

[10] Intelligent pavement management systems: Integrating IoT sensors for real-time monitoring



## Self-healing pavements

Early-stage cracking is a key driver of long-term pavement deterioration, as small defects can rapidly evolve into structural damage if not addressed in time. Self-healing pavements aim to mitigate this issue by incorporating technology and materials capable of autonomously repairing micro-cracks, extending pavement service life and reducing the need for early maintenance interventions.

Self-healing mechanisms are typically based on induction heating, using conductive fibers to locally soften the binder, or on encapsulated rejuvenating agents that are released when cracking occurs, partially restoring material cohesion.

These approaches target pavement damage at its earliest stages, before surface defects become visible or structurally critical.

Self-healing pavements have demonstrated promising performance under laboratory conditions and in highly controlled pilot-scale applications, confirming the technical feasibility of autonomous crack repair mechanisms. However, deployment in operational highway networks remains limited, as further validation is still required regarding long-term durability, performance under real traffic loads, constructability at scale, and cost-effectiveness within standard pavement maintenance programs. Therefore, current applications are mainly focused on controlled demonstration projects that support the assessment of their potential integration in operational environments.

Key benefits:

- Field results indicate that induction-based self-healing asphalt can extend pavement service life by approximately 25%[11] relative to traditional asphalt.

- The extended service life translates to an estimated 40%[11] reduction in life-cycle $CO_2$ emissions when compared with conventional pavement systems, as fewer full-depth overlays and disruptive repair operations are required over the pavement's lifespan.

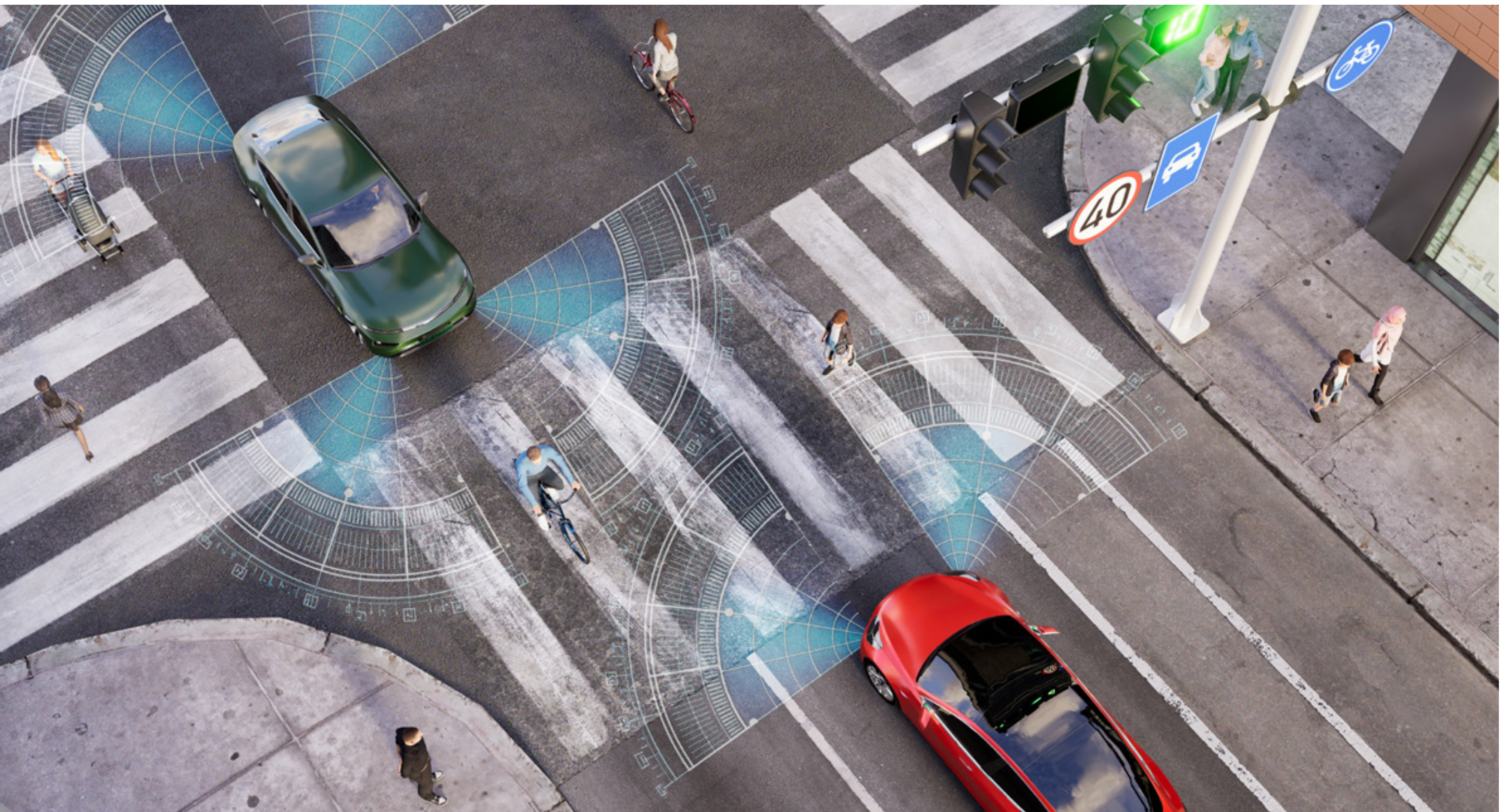
[11] Epion | self-healing asphalt

# Data-driven safety management

Focused on protecting both road users and maintenance crews, these solutions employ real-time monitoring and predictive analytics to reduce accidents and improve response times. Thus, advanced traffic management tools allow operators to respond dynamically to congestion and risk profiles to proactively mitigate accidents, reduce secondary events, and improve emergency response times.

This includes:

- Automatic Incident Detection
- AI-powered incident prediction & traffic management
- Smart work zones
- Drone patrolling
- Robotics for highway works

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## Automatic Incident Detection

Traditional incident detection methods based on manual monitoring or isolated sensors are often limited in coverage and effectiveness. Automatic Incident Detection (AID) systems address this need by enabling continuous, real-time monitoring of traffic conditions using artificial intelligence, to minimize response times and reduce secondary accidents.

AID solutions analyze video streams and traffic data from roadside cameras, ITS sensors, and complementary sources such as GPS or mobility platforms to automatically identify abnormal situations, including stopped vehicles, wrong-way driving, pedestrians on the roadway, and sudden congestion. Compared to manual monitoring, AI-based detection allows incidents to be identified consistently and at scale, providing earlier alerts and optimizing operations. Most AID solutions are software-based and deployed using edge computing architectures (no need for Cloud), ensuring low latency and real-time performance without requiring major additional roadside infrastructure.

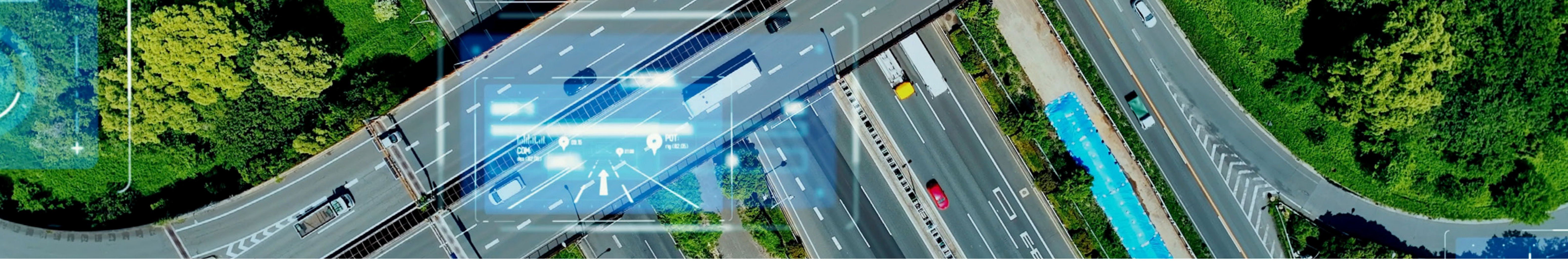
This represents a mature and reliable technology under live-traffic conditions. In highway operations, AID systems are typically used to support Traffic Management Centers by shortening incident detection times and improving situational awareness for a proportionate response.

In terms of implementation examples in the United States, AI-based incident detection has been implemented on high-capacity urban freeways such as the I-405 in California. In Europe, similar systems are in operation on toll motorways such as Olympia Odos in Greece, integrated into day-to-day traffic management and incident response activities.

Key benefits:

- AID enables incident identification nearly 50%[12] faster than traditional methods.
- Earlier detection reduces the risk of secondary crashes by about 40%[13].
- By providing earlier and more reliable incident alerts, the system allows traffic agencies to position highway patrol units more effectively and display advanced warnings on dynamic message signs, contributing to a ~15%[14] reduction in crash occurrence.

[12] Improving incident detection through the use of real-time data analytics and AI
[13] Roadways TrafficVision
[14] Raising Awareness of Artificial Intelligence for Transportation Systems Management and Operations



## AI-powered incident prediction & traffic management

Proactive traffic management requires anticipating how traffic conditions may evolve in order to mitigate congestion and prevent accidents. Congestion and accident prediction solutions combine artificial intelligence with digital twin models to analyze historical and live traffic data together with exogenous variables such as weather conditions, incidents, work zones, and demand patterns, with the objective of identifying high-risk situations before accidents occur.

These systems process data from traffic sensors, cameras, GPS, connected vehicles, and external sources to anticipate risk conditions. At the same time, digital twins allow operators to test scenarios and assess the potential impact of preventive measures such as dynamic speed limits, lane management strategies, variable messages, or infrastructure interventions prior to implementation, supporting proactive safety-oriented traffic management.

AI-powered incident prediction models are moderately mature and increasingly integrated into traffic management environments. However, the use of reliable digital twins for proactive accident prevention remains limited, as converting existing infrastructure and traffic data into robust 3D models requires consistent and structured data that is often not available.

In practice, these solutions are deployed in selected corridors rather than across entire networks. In the United States, AI-powered incident prediction models are operational on highways such as the I-95 (California) to support proactive traffic and safety management. In Europe, similar approaches have been implemented on urban motorway networks such as the M-50 in Ireland, where they support the anticipation of congestion and hazardous conditions.

Key benefits:

- AI-based congestion and accident prediction has been associated with reductions of up to ~15%[15] in overall accident rates, by anticipating high-risk traffic conditions and enabling earlier operational responses.
- The use of predictive analytics and digital twins enables operators to respond up to 25%[15] faster to congestion build-ups and accident-prone situations, by forecasting traffic evolution and supporting proactive traffic management decisions.
- Evidence from traffic systems powered by AI in North East England report a reduction in delays of 13.7%[16] after creating a digital twin of the road network.

[15] Solutions | Valerann
[16] Tees Valley AI 'traffic twin' helping to reduce delays



## Smart work zones

Reducing accident risk in active highway work zones remains a priority for public authorities and private highway operators, particularly under traffic conditions. Smart work zone safety systems address this need by automatically detecting vehicle intrusions and unsafe situations involving workers. These solutions combine long-range radar with AI-based video analytics to monitor approaching traffic and identify irregular vehicle behavior in real time. The radar enables early detection at long distances, while cameras provide short-range confirmation, improving reliability under adverse weather or low-visibility conditions.

Most systems operate using edge computing architectures, processing data locally to minimize latency and enable near-instantaneous alerts. Sensorized cones or mobile units installed on work equipment define protected work areas, while additional proximity detection technologies (using Bluetooth) can monitor interactions between workers and construction machinery. Alerts are delivered directly to workers through connected wearables, enabling immediate and intuitive responses without relying on manual intervention.

Smart work zone safety systems present a high level of maturity, supported by well-established sensing technologies and proven real-time analytics. In highway operations, they are increasingly integrated into maintenance and construction activities carried out under live traffic conditions, where rapid detection and alerting are critical to enhance workers' safety.

Alerts are also sent to drivers approaching work zones via V2X communication to notify them of lane closures ahead and encourage speed reduction

In terms of implementation examples, these systems are already deployed in operational environments in the United States. Agencies such as the Florida DOT are applying smart work zone safety solutions across interstate resurfacing and maintenance projects, demonstrating their operational readiness and applicability to large-scale use cases.

Key benefits:

- Smart Work Zone deployments are associated with reductions of around 15%[17] in overall work zone crashes.
- Data from vehicle manufacturers show that alerts via V2X communication have led to a 17%[18] reduction in speed among drivers approaching work zones.
- Injury-related crashes within work zones observed a reduction of up to 60%[17] in deployments using Smart Work Zone technologies.

[17] Developments in traffic safety technology
[18] Evaluation of Digital Alert Systems Associated with Emergency Response Vehicles and Compliance with Move Over Law | IDEALS

## Drone patrolling

Drone patrolling uses unmanned aerial vehicles to support traffic monitoring, incident verification, and response coordination on highways, in response to the need for enhanced road safety and faster incident response capabilities.

Drones can be deployed on demand or as part of planned patrol schemes to provide aerial visibility of traffic conditions, accidents, stopped vehicles, congestion, and hazardous situations. Live video and imagery captured by drones are transmitted in real time to Traffic Control Centers, complementing fixed roadside infrastructure and enabling operators to assess incidents remotely, coordinate emergency and maintenance services, and prioritize response actions more effectively.

Drone platforms and onboard sensing technologies are technically mature and widely used in other sectors (particularly in emergency services through the drone-in-a-box concept). In highway operations, their use for patrolling and incident response is moderately mature, with adoption still shaped by regulatory constraints, safety procedures, airspace management, and operational integration with traffic management workflows.

In terms of implementation, deployment is progressing mainly through structured and agency-led programs rather than network-wide rollouts. In the United States, agencies such as the Ohio Department of Transportation are developing drone-as-first-responder programs, where drones are dispatched early during incidents to provide real-time situational awareness to traffic operators and emergency services.

Key benefits:

- Drone deployment for incident response can reduce crash-related road closure times by up to ~75%[19] through faster initial response.

- Collaborative patrol strategies that integrate drones with ground vehicles can reduce total response routing time by approximately 9–16%[20] versus vehicle-only patrols.

[19] A Report Shows Unmanned Aircraft Systems Can Reduce Road Closure Times by 75 Percent When Deployed for Traffic Incident Management (TIM) saving $350 per minute

[20] Traffic Patrolling Routing Problem with Drones in an Urban Road System



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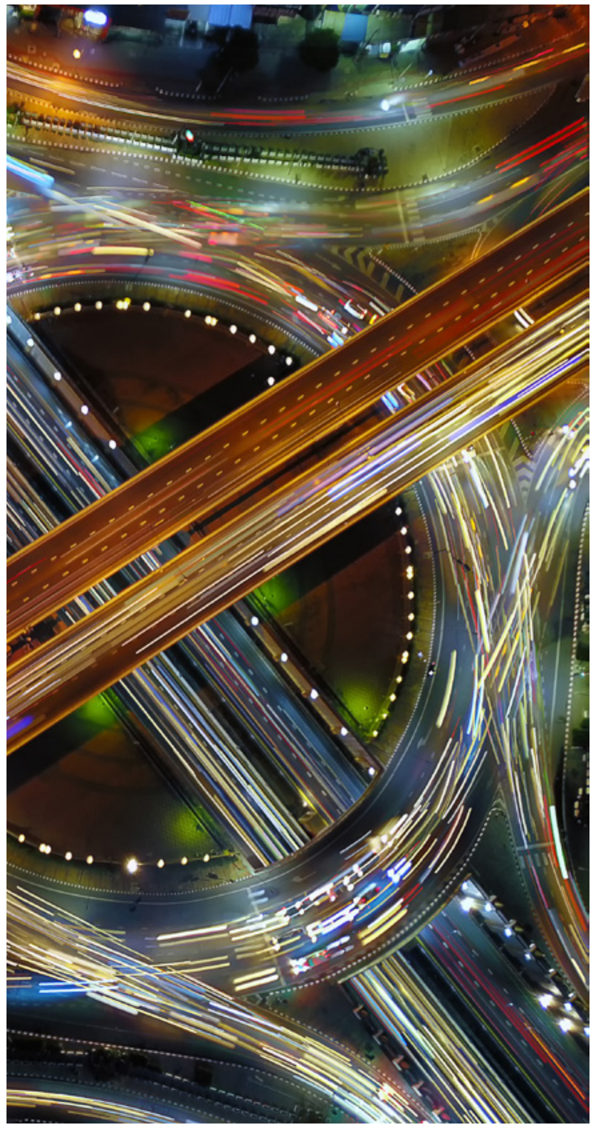


## Robotics for highway works

Robotics for highway works aim to automate specific inspection and maintenance tasks traditionally performed by maintenance crews, particularly in environments with high exposure to traffic or confined spaces. Typical applications include drainage and culvert inspection and cleaning, localized pavement interventions such as crack sealing, winter maintenance activities, and other targeted conservation tasks, which significantly reduce personnel exposure and accident risks.

These systems are designed for task-specific operations rather than continuous or network-wide deployment. They are typically operated by existing maintenance crews, requiring limited training and enabling relatively rapid adoption.

Robotics for highway works remain at a low level of maturity, with most solutions at pilot or early commercial stages and limited operational deployment. Current implementations focus on improving worker safety by reducing exposure to live traffic and hazardous environments.

In terms of implementation, deployments to date are largely limited to pilot initiatives. In the United States, agencies such as the Ohio Department of Transportation have tested robotic solutions for maintenance-related tasks, particularly focused on drainage and culvert inspection.

Key benefits:

- Based on manufacturer estimates, robotic crack sealing is estimated to achieve 30%[21]-50%[22] reduction in direct operating costs per mile relative to conventional crew operations.

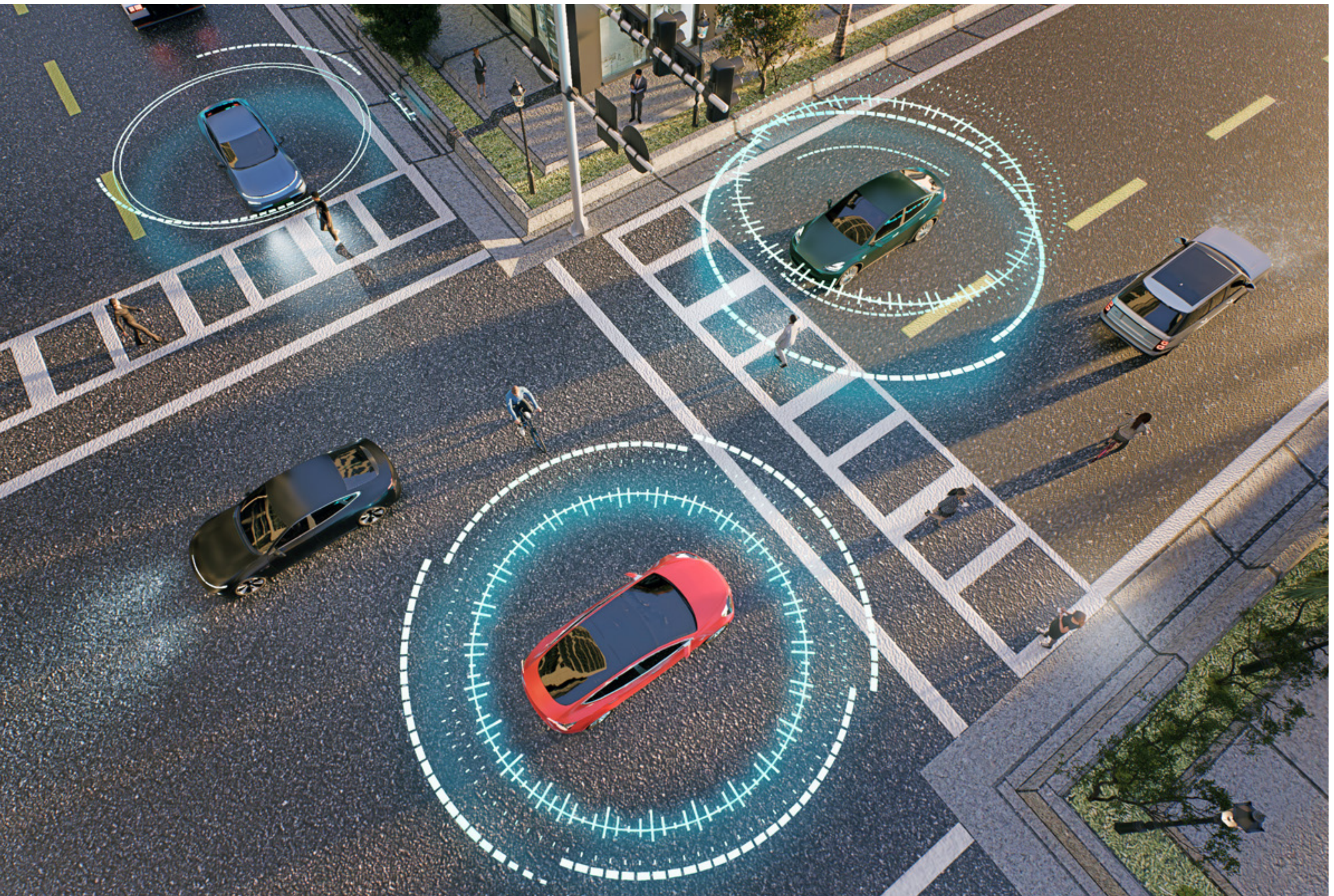
- These solutions are expected to deliver significant safety and operational benefits, including a 50%[21] reduction in fatal accidents in high-risk maintenance scenarios.

[21] Improving road worker safety with automated, robotic systems

[22] Crunching the Numbers: The Real ROI of Automated Crack Sealing vs. Traditional Methods

# Vehicle-to-infrastructure communication

Infrastructure-to-vehicle communication is a critical enabler of connected and autonomous mobility. Through V2I (vehicle-to-infrastructure) and C-V2X (cellular vehicle-to-everything) technologies, highways can transmit trusted, low-latency information on speed regulations, hazards, work zones, and traffic conditions directly to vehicles. In return, anonymized vehicle data enhances situational awareness and supports more precise traffic management.



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## V2I and V2X technology

Improving traffic safety and operational efficiency increasingly depends on real-time coordination between vehicles and road infrastructure. Connected vehicle systems enable this interaction through vehicle-to-infrastructure (V2I) and cellular vehicle-to-everything (V2X) connectivity, allowing vehicles to receive timely information on traffic conditions, incidents, road works, and hazards.

This technology supports applications such as safety warnings, incident notifications and work-zone alerts. The same connectivity also enables traffic operators to dynamically adjust roadside systems, including variable message signs and digital signage, and to coordinate traffic control strategies to manage rerouting during incidents or congestion. These functions rely on the interaction between onboard units, roadside units, traffic management centers, and connected traffic control devices, using low-latency communication over 4G and 5G networks.

Connected vehicle systems based on V2I and V2X present a moderate level of maturity and are already deployed in operational traffic environments to support safety and traffic management applications.

In terms of implementation examples, connected vehicle communication systems have been deployed at limited scale on selected corridors in both the United States and Europe. In the United States, V2I and V2X connectivity has been implemented on corridors such as the Interstate 94 in Michigan, supporting safety-focused connected vehicle applications and operational testing. In Europe, similar deployments have been carried out on motorway corridors such as the A9 Autobahn in Germany, where V2X infrastructure supports the testing and validation of connected and autonomous vehicle use cases.

Key benefits:

- Estimates indicate that the implementation of V2X technologies can reduce accident rates by 13[23]–20%[24], as continuous real-time communication between vehicles, road users, and infrastructure enables smoother interactions and earlier hazard detection.

- Through platooning systems, fuel consumption for heavy vehicles can be reduced by up to 10%[25] in real highway conditions.

- The implementation of V2X technology across more than 4,000 intersections in London has resulted in a 40%[26] reduction in intersection delays and collision risks through dynamic speed adjustment and conflict-point warnings.

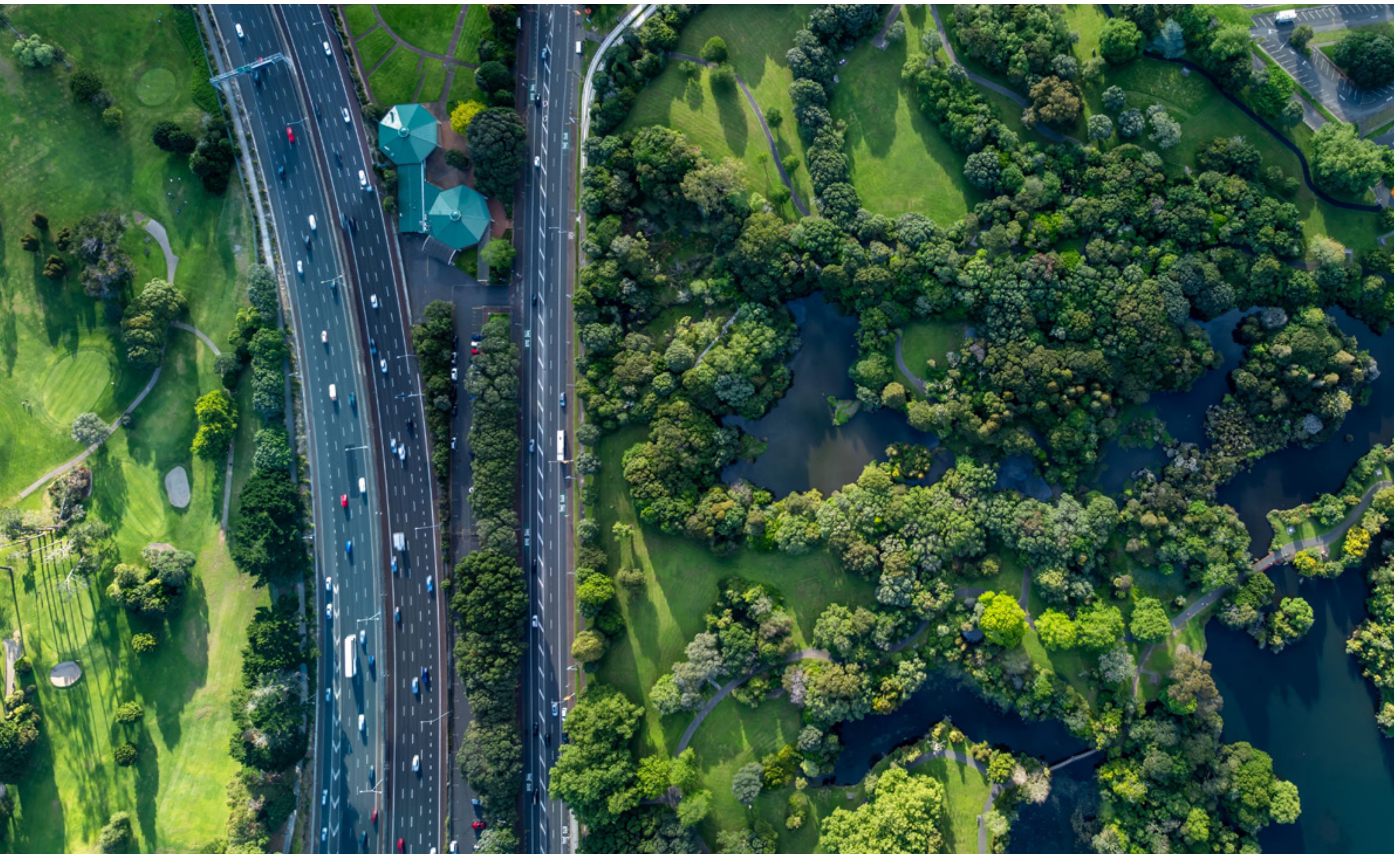
[23] V2X: Vehicle-to-Everything Solutions
[24] Accident reduction of up to 20% with Connected Vehicle C-ITS Technology
[25] Illinois Study Found Automated Truck Platooning Powered by an Artificial Intelligence Model Can Reduce Average Fuel Consumption by 10 Percent and Delivery Cost by 26.5 Percent
[26] Vehicle-to-Everything (V2X) Technology

# Sustainable roads

Sustainable road strategies embed environmental performance into the design, construction, and operation of highway infrastructure. This includes adopting low-carbon and recycled materials, energy-efficient and adaptive lighting systems, and integrating renewable energy sources. Together, these measures support regulatory compliance, long-term resilience to climate change, and alignment with national and international sustainability targets.

This includes:

- Green pavements
- Roadway energy generation
- Adaptive lighting systems



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## Green pavements

Reducing the environmental footprint of road infrastructure has become a key objective in pavement design and construction. Recycled, modular, and low-temperature pavement solutions address this objective by reducing material consumption, energy use, and greenhouse gas emissions across the pavement lifecycle:

- **Recycled Asphalt Pavement (RAP)** involves reusing reclaimed asphalt from existing roadways in the production of new asphalt mixtures. By incorporating milled pavement into new layers, operators reduce the need for virgin aggregates and bitumen, lowering material costs, energy consumption, and greenhouse gas emissions.
- **Modular pavements** consist of prefabricated pavement elements manufactured off-site and assembled on-site. This approach enables faster installation, reduced traffic disruption, improved quality control, and easier maintenance or replacement of individual sections, making it particularly suitable for high-traffic corridors or urban environments.
- **Low-temperature pavements** (also known as warm-mix asphalt technologies) are produced and laid at lower temperatures than conventional asphalt. This reduces fuel consumption during production, lowers emissions and improves working conditions for crews.

Although these solutions are technically proven, deployment remains largely project-driven rather than systematic. Adoption is typically linked to specific sustainability requirements, pilot programs, or favorable local conditions, as long-term durability under real traffic and climate conditions is still under evaluation by several agencies.

In the United States, pilot deployments and targeted testing have been conducted on corridors such as the I-90 in Illinois (Chicago), as well as through specialized testing programs monitored by agencies including the Arizona Department of Transportation. While these initiatives have produced positive results across multiple regions to date, many agencies remain cautious to fully adopt the technology at scale (because of pavement durability concerns).

In Europe, green pavement techniques have been applied on motorway corridors such as the A2 Motorway (Netherlands) as part of individual construction or rehabilitation projects.

Key benefits:

- Low-temperature asphalt mixtures are associated with energy savings of around 4%[27] during asphalt production, by lowering heating requirements during construction.

- The use of recycled materials into pavement mixtures can reduce material and production costs by approximately 25–35%[28], decreasing the demand for virgin raw materials.

- Modular and prefabricated pavements can reduce on-site intervention times by up to ~50%[29], limiting traffic disruptions and lane closures during construction/ rehabilitation works.

[27] The Future Is Warm
[28] Evaluation of Low-Temperature Performance of Recycled Asphalt Mixture with Different Thermal History Reclaimed Asphalt Pavement
[29] Comparative Analysis Between Pre-Cast Concrete Pavement and Cast-In-Place for Tertiary Road Construction in San Simon, Pampanga

## Roadway energy generation

The use of road infrastructure as a source of renewable energy has attracted increasing interest in recent years. Roadway energy generation solutions aim to produce electricity directly within the roadway by integrating photovoltaic elements into pavement surfaces or by capturing energy from traffic-induced movement.

- **Solar pavements** integrate photovoltaic cells into or alongside roadway surfaces to generate electricity from sunlight. The energy produced can be used to power roadway lighting, traffic management systems, electric vehicle charging infrastructure, or fed back into the grid.
- **Kinetic energy** systems capture mechanical energy generated by moving vehicles (such as pressure or vibration) and convert it into usable electrical energy. Installed beneath or alongside roadways, these systems can provide localized power for sensors, lighting, or monitoring equipment.

In practice, these approaches are intended to supply local power to roadside equipment and auxiliary infrastructure rather than to act as large-scale energy sources. While technical feasibility has been demonstrated in controlled environments, broader application remains constrained by durability under actual traffic loads, energy efficiency and long-term maintenance requirements. This indicates that these solutions are still at an early stage of development.

As a consequence, implementation to date has been limited to experimental and project-specific installations focused on technical validation, with no evidence yet of routine or scalable deployment across highway networks.

Key benefits:

- A prototype of a solar-integrated bike path generates 50 to 70 kWh per square meter annually[30], which is less than 50% of the energy output of conventional solar panels, highlighting the need for further advancements in the actual feasibility of these models.

- Highway pilot projects have demonstrated that solar-integrated noise barriers can generate renewable electricity, with the long-term goal of creating energy self-sufficient highways[31].

[30] 6 Months Later, Here's What's Happened to the Netherlands' Solar Bike Paths
[31] Swiss Federal Roads Office (FEDRO)



## Adaptive lighting systems

The need to improve roadway safety while reducing energy consumption and operating costs has driven growing interest in more intelligent lighting solutions for highway infrastructure. Conventional static lighting operates at fixed intensity levels regardless of traffic and environmental conditions, which can lead to unnecessary during low-demand periods and insufficient adaptability in higher-risk nighttime or low-visibility scenarios.

Adaptive lighting systems address this limitation by dynamically adjusting illumination levels based on real-time traffic, weather, visibility, time of day, incidents, and work-zone activity. These systems combine LED luminaires with sensors, connectivity, and control platforms to modulate light output, improving nighttime operating conditions while optimizing energy use.

In terms of implementation, adaptive lighting systems are not yet deployed uniformly across highway networks. In the United States, illustrative examples can be found on sections of I-35 in Texas, while in Europe similar solutions have been implemented on motorway corridors such as Germany's A9 Autobahn.

Key benefits:

- Although adaptive lighting systems involve higher investment, their lower energy use and reduced maintenance needs show an overall midterm cost reduction of about 24%[32] (as energy consumption reduces between 20-40%[32]).

- This technology has also been shown to reduce nighttime pedestrian-injury crashes by up to 42%[33] at intersections, highlighting the safety potential of enhanced and adaptive lighting systems that adjust illumination based on real-time conditions.

[32] Guidelines for The Implementation of Reduced Lighting on Roadways
[33] Proven Safety Countermeasures: Lighting

# Summary of emerging technologies

These technologies, as described above, have the potential to transform the highway industry by leveraging the recent and unprecedented advances in artificial intelligence and communication technologies:

## Overview of the key technological solutions for highways

### Smart tolling
- Dynamic pricing algorithms
- GNSS-based and app-based tolling payment
- Fraud management & automated vehicle occupancy identification

### Sustainability and green roads
- Recycled, modular, and low-temperature pavements
- Embedded or kinetic solar energy generation
- Adaptive lighting systems

### Infrastructure-to-vehicle communication
- Connected and autonomous vehicles
- Car Wallet

### Automated and predictive maintenance
- Image-based AI inspection systems
- Detailed inspections and inventory using LiDAR
- Robotics for highway inspection and maintenance works
- Smart pavements
- Self-healing pavements

### Smart traffic and safety management
- Automatic Incident Detection (AID)
- Congestion and accident prediction using AI and digital twins
- Smart work zones
- Drone patrolling and incident response





The following table summarizes the main technological solutions for the highway sector with the greatest potential to address the most pressing challenges faced by the industry:

| TECHNOLOGY | MATURITY STAGE | LEVEL OF IMPLEMENTATION | KEY BENEFITS |
|---|---|---|---|
| **INTELLIGENT TOLLING** | | | |
| DYNAMIC PRICING ALGORITHMS | High | **Widely implemented in conventional tolls and Express Lanes** (I-66, I-25 and SR-91 USA) | · About ~40% decrease in travel times<br>· ~20% increase in toll revenues |
| GNSS TOLLING | High | **Implemented in some highways** (German Federal Motorway Network Europe and I-66 USA) | · Roughly 50% decrease in toll operating costs |
| AUTOMATED VEHICLE OCCUPANCY IDENTIFICATION | Medium/High | **Implemented in some highways** (I-405 and SR-167 USA) | · Between 65-70% decrease in toll revenue leakage on Express Lanes |
| CAR WALLET | Very low | **Under development** | · Decrease in revenue leakage<br>· New business models |
| **AI-POWERED ROAD MAINTENANCE** | | | |
| IMAGE-BASED AI INSPECTION SYSTEMS | High | **Implemented in some highways** | · 30% decrease in maintenance costs<br>· 30% decrease in defect identification time |
| LIDAR-BASED AI INSPECTION SYSTEMS | High | **Implemented in some highways** (Pennsylvania Turnpike USA and M6 UK) | · 10% increase in defect identification accuracy |
| PAVEMENT-INTEGRATED SENSORS | Low | **Implemented at a pilot level** | · 20% decrease in maintenance costs<br>· 50% decrease in emergency repairs |
| SELF-HEALING PAVEMENTS | Very low | **Under development** | · 25% increase in pavement service life<br>· 40% decrease in $CO_2$ emissions |

| TECHNOLOGY | MATURITY STAGE | LEVEL OF IMPLEMENTATION | KEY BENEFITS |
|---|---|---|---|
| **DATA-DRIVEN SAFETY MANAGEMENT** | | | |
| AUTOMATIC INCIDENT DETECTION | Medium/High | **Implemented in some highways** (I-405 USA and Olympia Odos Greece) | • 50% faster incident identification<br>• 40% less risk of secondary crashes<br>• ~15% decrease in crash occurrences |
| AI-POWERED INCIDENT PREDICTION & TRAFFIC MANAGEMENT | High | **Implemented in some highways** (I-95 USA and M-50 Dublin) | • ~15% decrease in accident rates<br>• 25% faster operator response to congestion and accidents |
| SMART WORK ZONES | High | **Implemented in some highways** (Florida DOT, USA) | • 15% decrease in work zone crashes<br>• 60% decrease in injury-related crashes |
| DRONE PATROLLING | Medium/High | **Implemented on a small scale** (Ohio DOT, USA) | • 75% decrease in crash-related lane closure times<br>• 9-16% decrease in incident response time |
| ROBOTICS FOR HIGHWAY INSPECTION AND MAINTENANCE WORK | Medium/Low | **Implemented on a small scale** (Ohio DOT, USA) | • 30-50% decrease in operating costs<br>• 50% decrease in fatal accidents in high-risk maintenance scenarios |
| **VEHICLE-TO-INFRASTRUCTURE COMMUNICATION** | | | |
| V2I AND V2X TECHNOLOGY | Medium/Low | **Implemented on a small scale** (I-94 USA and A9 Autobahn Germany) | • 13-20% decrease in accident rates<br>• 40% decrease in intersection delays<br>• 15% fuel savings through platooning |
| **SUSTAINABLE ROADS** | | | |
| GREEN PAVEMENTS | Low | **Implemented in some highways** (I-90 USA and A2 Netherlands) | • 4% energy savings<br>• 25-35% decrease in material and production costs<br>• 50% decrease in on-site construction time |
| ROADWAY ENERGY GENERATION | Very low | **Under development** | • Lower emissions<br>• Higher energy efficiency |
| ADAPTIVE LIGHT SYSTEMS | Medium | **Implemented in some highways** (I-35 USA and A9 Autobahn Germany) | • 20-40% decrease in energy consumption<br>• 42% decrease in nighttime pedestrian-injury crashes |

Main technology solutions

In summary, these technologies can help highway operators tackle operational, safety, and financial challenges while supporting resilient and sustainable highway operations. Thoughtful implementation can transform technology from a simple tool into a strategic driver of long-term performance and service excellence.



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# SUCCESSFUL CASE STUDIES

## How have operators effectively implemented new technologies in their operations?

While the potential of technology in toll highway operations is clear, real-world examples demonstrate how these innovations can be successfully applied. Across the globe, operators have leveraged emerging technologies to improve safety, efficiency, and customer experience.

This section highlights selected case studies that illustrate best practices, lessons learned, and measurable benefits, providing practical insights into how technology can be effectively integrated into highway operations and maintenance.

Automated HOV detection systems on I-66 (Virginia) by Indra[34]

## Dynamic tolling and HOV detection on the I-66 in Virginia, USA (Indra)

Indra has implemented a free flow tolling system with integrated High Occupancy Vehicle (HOV) detection on the I-66 Outside the Beltway highway in Virginia. The solution enables dynamic pricing based on real-time traffic conditions and vehicle occupancy, improving flow management, fair toll enforcement, and enhanced operational efficiency.

The system uses overhead sensors that combine 3D LiDAR, computer vision, and AI-based analytics to detect occupancy, classify vehicles, and apply toll rates without relying on pavement-based equipment or physical barriers.

It also supports flexible pricing rules and configurable business logic, allowing adaptation to future policy changes and vehicle classification needs.

In addition to tolling and HOV detection, the deployment incorporates vehicle-to-infrastructure communication capabilities through CV2X technology and forms part of a broader effort to enable connected and intelligent highway operations. The project has received industry recognition and is considered a relevant reference for the integration of advanced sensing and pricing technologies in managed lanes environments.

[34] Automated HOV detection systems on I-66 (Virginia) by Indra



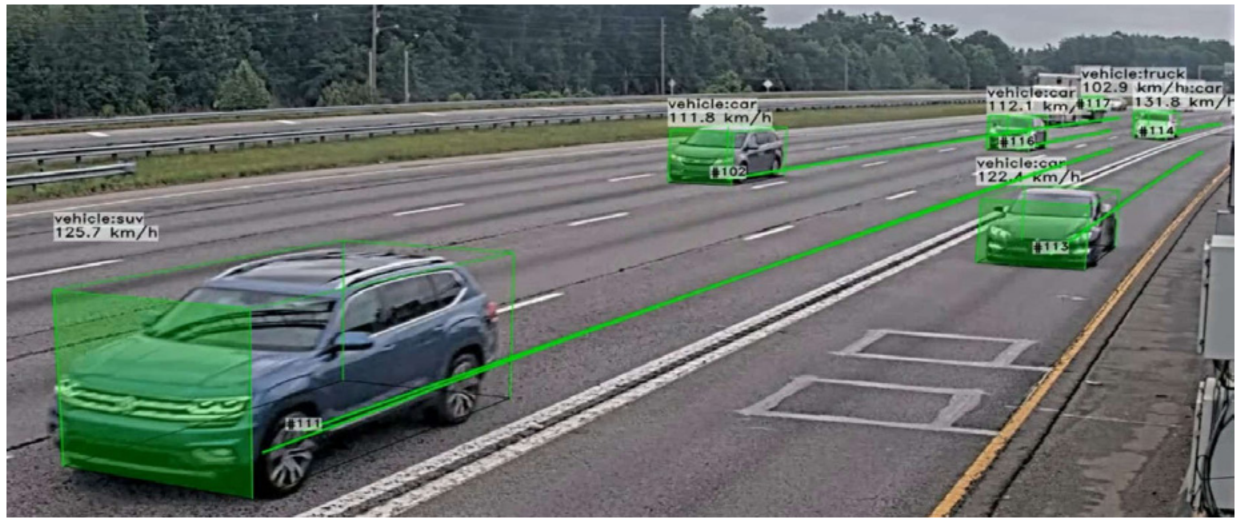


## Implementation of Automatic Incident Detection technology in Greece (Invision)

Invision has deployed an Automatic Incident Detection solution on the Olympia Odos toll motorway in Greece. The system integrates AI-based video analytics with the operator's existing ITS camera infrastructure using an edge-based architecture, minimizing additional hardware requirements and reducing deployment costs.

The deployment covers approximately 120 roadside cameras and provides real-time, geolocated incident detection to the traffic control center. The solution achieves approximately 97% detection accuracy, enabling reliable incident identification at corridor scale with a very low rate of false alerts.

In parallel, the project includes adaptive lighting systems that dynamically adjust lighting levels based on traffic conditions and visibility. The platform also provides additional traffic management functionalities, including vehicle counts by category, speed and traffic flow indicators, as well as alerts related to road works and weather conditions, supported by a live 3D visualization digital twin for real-time corridor monitoring.



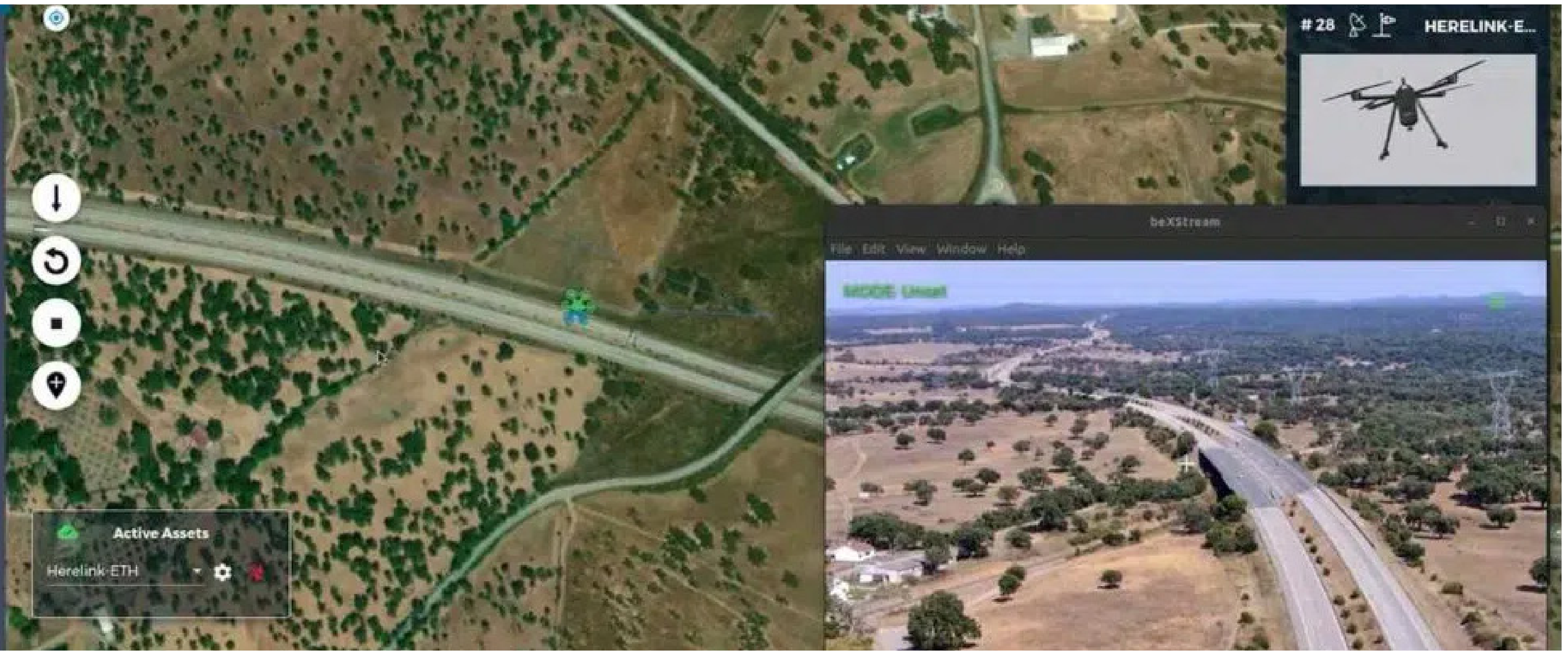

Automated Incident Detection technology

## Drones as first responders in Portugal (Beyond Vision)

Beyond Vision has developed and deployed an AI-powered drone solution as part of a pilot program on a toll motorway in Portugal, aimed at supporting traffic monitoring, infrastructure inspection, and incident response. The initiative focuses on evaluating how drones can complement traditional highway operations and enhance situational awareness.

The drones provide real-time aerial monitoring of traffic conditions and road infrastructure, supporting the identification of congestion, incidents, and potential safety issues. They are also used for proactive inspection of critical assets such as bridges, tunnels, and road surfaces, enabling early detection of defects and supporting maintenance oversight. In incident scenarios, drones transmit live video and data to operators, reducing response times and improving coordination.

In parallel, transportation administrations such as Ohio DOT have been developing the concept of drones as first responders over recent years, defining operational frameworks and regulatory approaches. As a result, initial operational deployments in this area are expected to materialize progressively from 2026 onwards.




Drone patrolling technology





## Smart work zones implementation in Florida DOT (SmartCone)

SmartCone has developed a smart work zone safety solution designed to automatically detect vehicle intrusions and unsafe situations involving workers in highway construction and rehabilitation environments. The system combines long-range radar with AI-based video analytics to provide early detection of irregular vehicle behavior approaching active work zones.

Long-range radar enables vehicle detection at distances of up to approximately 1 mile (1.6 km), while camera-based analytics provide complementary detection at shorter ranges of around 300 feet (90 m). This multi-sensor approach allows earlier warning than camera-only solutions and offers higher robustness under low visibility, rain, or adverse lighting conditions.

The solution operates using an edge computing architecture, with all processing performed locally, enabling alerts to be issued within approximately 130 milliseconds from detection. SmartCone units are installed on work equipment or mobile supports and use sensorized-cones to define safe working areas. The system also includes proximity detection between workers and construction machinery using Bluetooth-based technologies.

Alerts are delivered directly to workers through connected wearables, such as smart watches, using vibration, audio, color, and text signals designed to trigger an immediate and intuitive response.

In the United States, the Florida Department of Transportation is deploying this technology across interstate resurfacing projects planned for 2025, reflecting the operational maturity and readiness of smart work zone safety systems.

## Automated inspection cameras to evaluate the condition of more than 4,000 km of highways in Spain (Gemminis)

Gemminis deployed an AI-based road inspection solution to assess the condition of more than 4,000 km of highways in Catalonia (Spain) within approximately 20 days, demonstrating its ability to monitor large road networks efficiently.

The solution uses bifocal cameras with integrated GPS to capture georeferenced images at free-flow speed, which are processed using artificial intelligence to detect and classify pavement defects, obstacles on the roadway, vegetation height, and the condition and visibility of road signs. Inspection data is processed in real time and visualized through GIS and business intelligence platforms.

The system achieves decimetric-level accuracy, which is sufficient for systematic infrastructure inspections, and captures approximately one image per meter at speeds of up to 100 km/h, enabling rapid, traffic-neutral condition screening at network scale.

# LOOKING TO THE FUTURE

## How can the highway sector adapt to the technological era?

As the highway sector faces multiple challenges, the adoption of emerging technologies is becoming essential. Capturing their full value requires a structured, strategic approach rather than isolated deployments.

To enable a successful transition, private highway operators, Departments of Transportation, and Public Tolling Authorities should establish a Strategic Technology Plan that defines a clear and actionable roadmap for technology adoption and implementation.

This roadmap can be structured around four key steps:

- **Identify requirements** covering all value-added chain including safety, infrastructure design, maintenance, operations, and tolling, among others. These requirements should focus on improving safety, efficiency and user experience, while identifying operational inefficiencies.
- **Select appropriate technologies.** Select technologies that effectively address these requirements. This analysis will consider both the characteristics of the highway (infrastructure, traffic, user profile...) as well as the technology itself: proven use cases, maturity, integration requirements, and measurable operational improvements. Where relevant, opportunities to enable new business or revenue models can be developed.
- **Define the implementation approach** by translating technology choices into concrete execution plans, including rollout by operational area, geographic deployment across the network, partnership models established with technology providers, and whether to pursue exclusive, country-specific, or multi-vendor arrangements.
- **Plan phased deployment.** Determine what will be implemented in the short, medium, and long term, aligned with budget availability, technology and operation constraints, and organizational readiness.

By following a structured roadmap that links needs, technologies, and deployment timelines, the highway sector can modernize its operations strategically while managing risk, budgets, and organizational complexity, ultimately enhancing efficiency, resilience, and service quality.

ALG


**Cesar Valero**
MSc. in Civil Engineering and an MBA, Partner at ALG
cvalero@alg-global.com

**Pau Boix**
MSc in Transport and Business Management, Engagement Manager at ALG
pboix@alg-global.com

**Miguel Armesto**
MSc. in Civil Engineering, Consultant at ALG
marmesto@alg-global.com

**Ashlee Sprock**
MA in Economics, Consultant at ALG
ansprock@alg-global.com