- CIRCUIT -

Holistic approach to foster CIRCUlar and resilient transport InfrasTructures and support the deployment of Green and Innovation Public Procurement and innovative engineering practices

– Deliverable D2.4 -

Real-Time traffic management on smart mobility system

Project details	
Project reference no.	101104283
Project Acronym	CIRCUIT
Project Full title	Holistic approach to foster CIRCUlar and resilient transport InfrasTructures and support the deployment of Green and Innovation Public Procurement and innovative engineering practices
Call ID **Topic**	HORIZON-CL5-2022-D6-02 HORIZON-CL5-2022-D6-02-06
Duration	48 Months
Coordinator	Thierry Goger (FEHRL)

	Participant Legal Name	Country
1	FORUM DES LABORATOIRES NATIONAUX EUROPEENS DE RECHERCHE ROUTIERE FEHRLAISBL – FEHRL	Belgium
2	INFRA PLAN KONZALTNIG JDOO ZA USLUGE - INFRA PLAN	Croatia
3	INGEO BV – INGEO BV	The Netherlands
4	ANAS SPA – ANAS	Italy
5	ZAVOD ZA GRADBENISTVO SLOVENIJE – ZAG	Slovenia
6	EUROPEAN UNION ROAD FEDERATION – ERF	Belgium
7	ACCIONA CONSTRUCCION SA – ACCIONA	Spain
8	INSTITUTO ESPAÑOL DEL CEMENTO Y SUS APLICACIONES – IECA	Spain
9	BETON - LUCKO DOO ZA GRADITELJSTVO PROIZVODNJU TRANSPORT I TRGOVINU– BL	Croatia
10	OBCINA CRNA NA KOROSKEM – CRNA	Slovenia
11	RIGHT-CLICK – RC	Spain
12	UNIVERSIDAD DE CANTABRIA – UC	Spain
13	DIGITALTWIN TECHNOLOGY GMBH – DTT	Germany
14	SVEUCILISTE U ZAGREBU GRADEVINSKI FAKULTET – UNIZAG GF	Croatia
15	MINISTERIO DE TRANSPORTES Y MOVILIDAD SOSTENIBLE (MITMS)	Spain
16	INGEVITY HOLDINGS SRL – NGVT	Belgium
17	ALGORAB – ALGORAB	Italy
18	HRVATSKE AUTOCESTE D.O.O. – HAC	Croatia
19	WATERSCHAP HOLLANDSE DELTA – WSHD	The Netherlands
20	UBERBINDER LIMITED – UBERBINDER	United Kingdom

Document Details	
Title	Deliverable D2.4 Real-time traffic management on smart mobility system
Work Package	WP2
Date of the Document	02/05/2025
Version of the document	V1
Responsible partner	UC
Contributing Partner	-
Reviewing Partner	ZAG, DTT
Status of the document	Final
Dissemination level	Public

Authors list		
José Luis Moura Berodia	Universidad de Cantabria	Joseluis.moura@unican.es
Borja Alonso Oreña	Universidad de Cantabria	Borja.alonso@unican.es
Andrés Rodríguez Gutiérrez	Universidad de Cantabria	Rodriguezan@unican.es
Maira Milena Delgado Lindeman	Universidad de Cantabria	Maira.delgado@unican.es
Alba Ledesma Prieto	Universidad de Cantabria	Ledesmaa@unican.es
Raquel González Fernández	Universidad de Cantabria	Gonzalezfr@unican.es

Document History			
Version	**Date**	**Comments**	**Author**
01	11-04-2025	Draft 1	**SUMLAB- UNICAN**
02	26-04-2025	Draft 2	**Reviewers** **DTT, ZAG**
1.0	28-04-2025	Final	**SUMLAB- UNICAN**

Table Of Contents

List Of Tables

List Of Figures

List Of Abbreviations and Definitions

Abbreviation	Definition
ACC	Adaptive Cruise Control
AEMET	State Agency for Meteorology (Spain)
AID	Automatic Incident Detection: System that identifies incidents such as accidents or stationary vehicles through pattern recognition or sensor analysis.
ANPR and ALPR	Automatic Number Plate Recognition: Technology that automatically captures and processes vehicle license plates for monitoring and compliance.
API	Application Programming Interface
C-ITS	Cooperative Intelligent Transport Systems
CCAM	Connected, Cooperative and Automated Mobility
CCTV	Closed-Circuit Television
CEF	Connecting Europe Facility
CEN	European Committee for Standardization
CIRCUIT	Holistic approach to foster CIRCUlar and resilient transport InfrasTructures and support the deployment of Green and Innovation Public Procurement and innovative engineering practices
CO_2	Carbon dioxide
CORDIS	Community Research and Development Information Service
DATEX II	European standard for the electronic exchange of traffic and travel data, supporting interoperability across systems.
DGT	General Directorate of Traffic (Spain)
DMS	Dynamic Message Signs
DSRC	Dedicated Short-Range Communications
EU	European Union
ETSI	European Telecommunications Standards Institute
FEHRL	Forum of European National Highway Research Laboratories
GDPR	General Data Protection Regulation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HDR	High Dynamic Range
HOV	High-Occupancy Vehicle
IDS	Intrusion Detection System
IMD	Average Daily Index: refers to the number of conches circulating at a given point throughout the day.
IoT	Internet of Things
ITS	Intelligent Transportation Systems
ITS-G5	Wireless communication standard for ITS
LIDAR	Light Detection and Ranging

LTE	Long-Term Evolution
MaaS	Mobility as a Service
MITECO	Ministry for Ecological Transition and the Demographic Challenge.
MITMA	Ministry of Transport, Mobility and Urban Agenda (Spain)
MQTT	Message Queuing Telemetry Transport
NAP	National Access Point: Plataforma nacional que da acceso a datos de transporte y movilidad para compartir e integrar servicios.
NGVT	Ingevity Holdings SRL
NTP	Network Time Protocol
OCR	Optical Character Recognition
PIARC	World Road Association
Reversible Lanes	Lanes whose direction of traffic can be changed to adapt to demand.
SCADA	Supervisory Control And Data Acquisition
Smart Intersection	Road intersection equipped with sensors and communication systems that adapt traffic lights in real-time and prioritise certain modes of transport.
SRTI	Safety-Related Traffic Information
SUMlab	Sustainable Urban Mobility Laboratory
TMP	Traffic Management Plan: Operational strategy during planned or unforeseen events to minimize disruptions and maintain mobility.
Traffic Management	Set of strategies and tools to optimise traffic and information flow, improving mobility, safety and environmental sustainability.
UTC	Urban Traffic Control Centre: Centralised traffic control centre in urban environments.
V2I	Vehicle-to-Infrastructure: Communication between vehicles and road infrastructure elements (such as traffic lights, signs, toll booths, and sensors)
V2N	Vehicle-to-Network: Communication between vehicles and cellular or cloud networks.
V2P	Vehicle-to-Pedestrian: Communication between vehicles and pedestrians (through smartphones or wearable devices).
V2V	Vehicle-to-Vehicle: Direct communication between vehicles to share data like speed, location, and direction.
V2X	Vehicle-to-Everything: A communication framework that enables vehicles to exchange information with other vehicles, infrastructure, networks and pedestrians.
Variable Message Signs (VMS) / PMV	Variable Message Signs: Electronic signs that provide real-time information about traffic conditions, incidents or road works.
VIP	Video Image Processing
WDR	Wide Dynamic Range

Disclaimer:

CIRCUIT has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101104283.

This document reflects only the authors' views. The European Commission and CINEA are not responsible for any use that may be made of the information contained therein.

1. Introduction

1.1. Global Context and Study Rationale

This report examines key traffic management strategies, the implications of emerging technologies, the role played by urban planning, and the current challenges in mobility. Intelligent Transport System (ITS) contribution to traffic management is also explored.

Achieving a transport system that is both sustainable and functional stands as the primary objective of traffic management. As a key driver of societal development, transport must be managed in a way that improves mobility, reduces congestion, enhances road safety, and optimises infrastructure use for both freight and passenger movement.

Traffic management follows a straightforward structure: data is collected (always anonymously) to provide real-time insight into road conditions. The collected data is analysed to generate instructions or deliver the information that supports effective decision-making related to driving and traffic operations. These systems help reduce emissions, improve safety, provide real-time alerts, automate toll collection, and support the development of shared mobility and transport applications, among other uses, as illustrated in Figure 1.

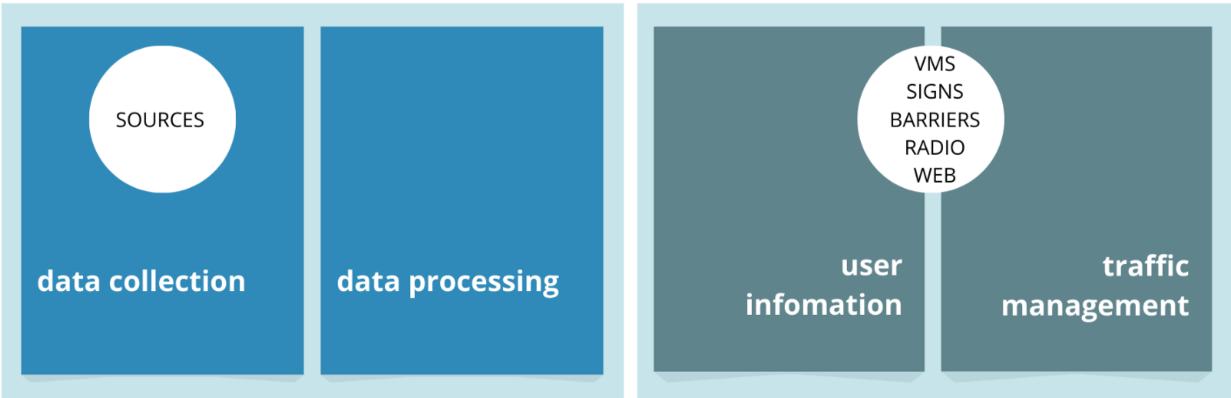

Figure 1 Traffic management scheme flow from data collection and processing to user information dissemination and traffic control.

Recent technological developments such as the IoT, the widespread use of smartphones, edge computing, machine learning techniques, innovations in electric battery design, and the decreasing cost of sensors are opening up new opportunities to improve transport infrastructure and services from a sustainability perspective.

Traffic management refers to a set of strategies and tools used to control and optimise the flow of vehicles, people, and information within a defined area. It plays a key role in both local urban settings and wider transport networks. The objective is to minimise traffic-related issues and enhance the overall safety and efficiency of transport systems.

In urban settings, traffic management according to recent trends relies increasingly on intelligent systems designed to dynamically regulate the flow of vehicles, pedestrians, and cyclists. These systems incorporate technologies such as adaptive signalling, in-road sensors, real-time monitoring platforms, and optimisation algorithms. Beyond improving mobility and reducing congestion, they play a key role in lowering pollutant emissions and enhancing the energy efficiency of the transport system. Effective data management, both in terms of volume and speed, enables the application of mechanisms such as traffic prioritisation, incident management, and dynamic resource allocation, helping to keep the network operational even under high demand.

The primary aim of this report D2.4 is to provide an up-to-date overview of real-time traffic management within the context of intelligent mobility systems. In line with the strategic objectives of the European Commission, specifically the Sustainable and Smart Mobility Strategy and the European Green Deal (Fetting, 2020), the report analyses current technologies and systems, the evolution of ITS infrastructure, available data sources, and the operational, strategic, and road safety challenges involved. It also includes real-world applications, case studies, and emerging trends that are reshaping urban and interurban traffic planning.

Within the European Union, the decline in fatal traffic accidents has been associated, among other factors, with the deployment of Intelligent Transport Systems (ITS). Work on the harmonisation of traffic information services and user access began in 1992. One of the first major initiatives was Eureka 147 (European Broadcasting Union, 1992), which laid the foundation for what is now the EPEG (Expert Group on Transport Protocol) (*TPEG | EBU Technology & Innovation*, no date), tasked with defining common standards for the interoperability of ITS services across Europe.

Since then, the European Union has pursued a strategy centred on the digitalisation of transport and the adoption of technologies that contribute to road safety, operational efficiency, and environmental sustainability. Directive 2010/40/EU (European Union, 2010), establishing the framework for the deployment of ITS in road-transport and its interface with other modes, has played a central role in advancing these systems. It has fostered cooperation among Member States and promoted the integration of platforms at the European level.

In this context, initiatives such as DATEX II (the European standard for the exchange of traffic and road data) (NAPCORE, 2021) and the establishment of National Access Points have supported the development of a shared digital infrastructure. These instruments facilitate services such as real-time information provision, dynamic traffic control and vehicle-to-infrastructure (V2X) communication. Backed by funding mechanisms such as Horizon Europe and the Connecting Europe Facility (CEF), these efforts form part of the European Commission's Sustainable and Smart Mobility Strategy.

1.2. Alignment with Project Objectives

This deliverable D2.4 "Real-Time Traffic Management on Smart Mobility System" is aligned with the overarching objectives of the CIRCUIT project. CIRCUIT seeks to develop a holistic approach supported by digital solutions and guidelines to foster circular, sustainable, resilient, and smart transport infrastructures. This document directly contributes to these goals by analyzing and proposing advanced real-time traffic management strategies that integrate digital technologies, ITS, and data-driven decision-making processes to enhance mobility, safety, and environmental performance.

Through the exploration of cutting-edge technologies such as V2X communication, IoT platforms, and real-time traffic information systems, this deliverable supports CIRCUIT's ambition to integrate smart and adaptive solutions into the design, operation, and maintenance of transport infrastructures. The methodologies and case studies presented promote the optimization of traffic flows, reduction of congestion, and minimization of environmental impacts, aligning with CIRCUIT's emphasis on sustainable mobility, digitalization, and innovation across the construction and operation value chain.

Moreover, this document reflects the project's holistic vision by considering multimodal transport integration, resilience in traffic management strategies, and the use of data analytics to support predictive and adaptive interventions. In doing so, it not only advances the deployment of green and innovative public procurement practices but also sets a foundation for the development of infrastructures that are better prepared to meet future mobility challenges, including the integration of autonomous vehicles and the promotion of circular economy principles in transport planning

Aligned with KER 8 of the project, as part of the present study, a pilot project is proposed to detect vehicles entering a motorway in the wrong direction via an exit ramp. The project proposes the installation of cameras and sensors at critical motorway exit points, with the aim of monitoring vehicle travel direction in real-time. Upon detecting such a prohibited manoeuvre, which poses an immediate risk to road safety, the system is expected to automatically issue alerts both to drivers travelling on the motorway, through dynamic signage, and to traffic control centres, from which intervention protocols with law enforcement agencies will be activated.

Furthermore, this deliverable is specifically framed inside WP2, which addresses the implementation and validation of innovative solutions for traffic management. The document contributes to this work package by detailing strategies and tools that enhance real-time operational capabilities and integration with digital traffic platforms. These contributions are essential for WP2's goal of enabling smart, safe, and sustainable infrastructure operation by leveraging ITS and intelligent decision-support systems

1.3. Current Issues in Traffic Management

A Multimodal Mobility and Transport System is as dynamic as the territory in which it operates. It must be continuously updated as cities grow, the number of vehicles increases, or new modes of transport emerge. At the same time, traffic management is required to deal with the limitations of existing infrastructure, maintenance-related roadworks, unforeseen events such as accidents, adverse weather conditions, and a range of other circumstances that may disrupt circulation.

Within this context, there is a growing need for platforms capable of integrating large volumes of data, supporting real-time decision-making, and adapting to specific environments and systems. Among the key challenges identified are traffic accidents, road congestion, and environmental pollution. Collectively, the overarching goal is to improve mobility and reduce the negative impacts of traffic on quality of life, particularly in urban areas.

Each of the sources reviewed for this report, including websites, theses, and academic articles, examines different aspects of traffic management. The main issues identified by (Toh *et al.*, 2020) include traffic accidents, congestion, the generation of pollution and air emissions and fuel costs.

The World Health Organization recommends a set of strategies to reduce the increasing rate of accidents and improve road safety, including the implementation of speed monitoring systems and smart traffic signals based on neural networks (Organization & Partnership, 2023).

In the report published by the Spanish *Dirección General de Tráfico, 2024* (Nuria Herraiz, 2024), the focus is placed on reducing the negative effects of traffic on air quality and improving mobility in urban environments to enhance the efficiency of vehicle circulation.

Another example is the publication *Traffic and Transportation Technology Trends(Janne Lautanala, 2025)*, which examines traffic congestion in urban areas, a persistent issue in densely populated environments. In this context, traffic optimisation is pursued through the application of advanced simulation tools, with the aim of reducing travel times and enhancing mobility.

The World Road Association(PIARC, 2016) also refers to pollution and its effects on urban mobility, although the emphasis is placed on developing systems to improve vehicle guidance. This is approached through technological solutions such as simulation platforms and real-time traffic monitoring systems. Table 1 summarises monitoring systems currently used in traffic management, highlighting their descriptions, benefits, and associated technologies.

Table 1 Monitoring systems

Monitoring System	**Description**	**Benefits**	**Associated Technologies**
Surveillance Cameras	Cameras installed at strategic locations to visually monitor traffic in real-time.	Visual identification of incidents, congestion and unexpected events.	Conventional cameras, AI-enabled smart cameras.
Roadway Sensors	Sensors embedded in the pavement or elevated positions that measure vehicle presence, speed and count.	Accurate data on traffic density and speed.	Inductive sensors, radar, LIDAR, and ultrasound.
GPS and Vehicle Data	Location and speed data generated by vehicles and mobile applications.	Detailed traffic information from thousands of users.	GPS, applications such as Google Maps and Waze.
Intelligent Signalling Systems	Real-time dynamic adjustment of traffic signals based on traffic flow conditions.	Traffic flow optimisation and congestion reduction.	Smart traffic signals, dynamic signage.
Monitoring and Data Analysis Platforms	Systems that collect and analyse real-time data to produce reports and alerts.	Clear visibility of traffic conditions and rapid decision-making.	Data analytics software, AI, and dashboards.
Drones and Autonomous Vehicles	Drones flying over traffic areas or autonomous vehicles monitoring road conditions.	Aerial visibility and traffic data from autonomous vehicles.	Drones, sensors in autonomous vehicles.
System Integration	Interconnection of various transport systems and monitoring platforms to manage mobility.	Efficient coordination of urban systems and rapid response.	Integration platforms, Intelligent Transport Systems (ITS).
Smart Weather Stations	Equipment installed on roads to collect environmental and weather-related data.	Supports traffic management under adverse weather conditions.	Temperature, humidity, wind, visibility sensors, and RWIS stations.
Automatic Number Plate Recognition (ANPR)	Automatic capture of license plates for vehicle tracking.	Access control, violation detection, and mobility pattern analysis.	ANPR cameras, OCR software, and vehicle databases.
Urban Environmental Sensors	Monitoring of air quality and noise levels in high-traffic urban areas.	Assessment of environmental impact and development of sustainable mobility policies.	CO_2, NO_2, $PM_{2.5}/PM_{10}$ sensors, and acoustic IoT sensors.
Floating Vehicles	Vehicles equipped with sensors that travel through the network to collect dynamic data.	Mobile coverage and real-time incident detection	GNSS sensors, onboard cameras,

		on non-sensored segments.	telemetry, V2X connectivity.

LIDAR: Light Detection and Ranging; AI: artificial intelligence; GPS: Global Positioning System; RWIS: Road Weather Information System; ANPR: Automatic Number Plate Recognition; OCR: Optical Character Recognition; GNSS: Global Navigation Satellite System; V2X: Vehicle-to-Everything.

2. Advanced Traffic Management Systems and Technologies

Traditionally, traffic management focused on adapting existing infrastructure to match demand, whether for freight transport or passenger mobility. However, the contemporary concept of traffic management is centred on minimising the problems associated with traffic. With recent innovations in ITS, enhanced connectivity, software advancements, and data management applications, traffic management today is driven by a new paradigm: managing to reduce, specifically to reduce congestion, travel times, fuel consumption, emissions, and costs.

According to PIARC(PIARC, 2016), the core objectives of contemporary traffic management include improving safety across the road network, optimizing traffic flow on major roads and highways, reducing urban and interurban congestion, and efficiently handling incidents to minimize delays and mitigate adverse impacts such as congestion, weather conditions, roadworks, emergencies, and disasters. Effective management of maintenance and construction works is also crucial to minimizing safety risks and congestion impacts. Providing travelers with timely and accurate information enhances their journey experience, while improving interfaces between passenger and freight transport modes aims to eliminate bottlenecks caused by inadequate road design and ensure adequate public transport services.

Moreover, transport networks are structured according to a road hierarchy, and their management is carried out by municipalities, regional authorities, and the national transport ministry, as well as by public and private sector operators. Coordination between agencies and private companies is essential.

2.1. Adaptive and Dynamic Traffic Control

Adaptive and dynamic traffic control relies on real-time data collection and analysis to efficiently regulate vehicular flow. By utilising sensors, cameras, networked communication systems, and AI algorithms, it is possible to predict congestion issues, respond to incidents promptly, and enhance mobility within urban areas and highways.

Spatial levels

Traffic management cannot be understood as a homogeneous policy uniformly applicable across all territories. Mobility issues and potential solutions are conditioned by factors such as the characteristics of the physical environment, land-use classification, urban development patterns, road network connectivity, and travel distances. Therefore, for each geographical level, adaptive and dynamic control strategies must be analysed and organised.

At least four fundamental scales for traffic management can be identified: urban, inter-urban, inter-regional and cross-border. Each presents specific challenges, differentiated resources, and strategic goals that necessitate distinct technical and organisational approaches, although there may be overlaps.

Urban Traffic Management: In urban areas, where the road network is embedded within a dense fabric, traffic control focuses on optimising intersections, prioritising modes of transport, and minimising conflicts between different types of users. Common challenges include recurrent congestion, traffic violations, illegal parking, and conflicts between vehicles and pedestrians. Management in this context must be sensitive to the social environment, urban life, and the quality of public space.

Interurban and Metropolitan Traffic Management: Interurban travel is characterised by high-intensity flows connecting peripheral zones with urban centres. This type of mobility, usually commuting, causes predictable congestion at certain points and times. Management at this level requires the integration of working hour policies, metropolitan public transport systems, and technologies that support early detection of congestion or incidents.

Interregional Traffic Management: At this scale, complexity increases due to the need for coordination between operational systems across different regions or autonomous communities. Key aspects include the interoperability of toll systems, the harmonisation of technical standards, and the joint management of logistics corridors. Shared data platforms enable a strategic view of the overall network and facilitate coordinated responses to large-scale events.

Cross-border Traffic Management: In areas where traffic crosses national borders, the challenges are even more significant. Beyond operational aspects, there are regulatory, linguistic, and administrative differences. Cross-border management requires institutional cooperation frameworks, common technical protocols, and coordinated surveillance systems. Freight transport corridors are commonly used, equipped with smart control points and technologies that ensure safety without compromising traffic fluidity.

The geographic scale not only determines the nature of the challenges but also the tools and management models required to tackle them. An adaptive and dynamic traffic control system must be designed with an awareness of this diversity and with the flexibility to respond effectively to each territorial context. Table 2 presents the main features, management objectives, and technologies associated with different spatial levels of traffic management.

Table 2 Spatial levels of traffic management

Spatial level	Main features	Management objectives	Main technologies
Urban	High-density, multi-mode, complex nodes	Reduce traffic congestion, road safety, and accessibility	Adaptive traffic signal systems, inductive loop detectors, and centralised traffic signal control.
Interurban	High-speed, road links, pendular mobility	Traffic flow under peak-hour conditions, incident management, and travel times.	Variable Message Signs (VMS), average speed enforcement systems, ramp metering
Interregional	Coordination between regions, freight transport	Interoperability across regions.	Shared platforms, integrated corridor management.
Border crossings	Different regulations, languages and technical systems	International security and logistics	Bilateral protocols, traffic data exchange, and smart border control.

Urban traffic control

Traffic control in urban environments represents one of the most complex challenges in adaptive traffic management(Paniagua, 2019). The high density of vehicles, the coexistence with pedestrians, cyclists and other modes of transport, as well as the concentration of economic, institutional and residential activities, generate a changing, multifactorial and constantly evolving scenario.

The main objective of urban traffic control is not only to maintain traffic flow, but also to ensure road safety, reduce pollution, prioritise sustainable modes and optimise the use of limited space. To achieve this, control systems must act in an integrated, coordinated and real-time manner.

Urban Traffic Control Centres (UTC) are the operational core of these strategies. These are facilities where data from sensors, cameras, traffic lights, public transport networks and user information platforms converge. These centres are responsible for making both automated and supervised decisions that have a direct impact on the functioning of the urban mobility system. An interior of a modern UTC is shown in Figure 2.

Figure 2 Santander Traffic Control Center, Cantabria, Spain (El Diario Montañés, 2024)

An essential component of CTUs is adaptive traffic signal management. Unlike traditional systems with fixed cycles, modern algorithms allow traffic signal timings to be adjusted according to demand at any given moment. This type of traffic signal control is based on variables such as vehicle density, number of pedestrians, the presence of priority vehicles or the status of adjacent intersections. In addition, integration with traffic counters and cameras that analyse traffic flow or detect anomalies is common.

Public transit priority is one of the most advanced strategic lines of urban planning. It consists of giving priority to buses or trams at key intersections, reducing their waiting times and making their use more competitive with private vehicles. Modern urban management also incorporates dynamic origin-destination estimation systems, which allow us to understand where flows move to according to time slots. This data, derived, for example, from mobile networks, cameras with automated video analysis, or public transport ticketing systems, is used to anticipate conflicts and plan detours. Effective urban traffic control depends not only on technology but also on careful planning and public space management. Its effectiveness is not only measured by traffic speed, but also by accessibility, modal equity, and the sustainability of the system as a whole.

Traffic management plans (TMP)

TMPs are strategic frameworks aimed at minimizing the disruptive impact of both planned and unplanned events on mobility. Their primary objectives include ensuring efficient and safe traffic flow, reducing travel times, and enhancing coordination among traffic management agencies. These plans rely heavily on advanced technologies for continuous monitoring and real-time adaptive responses. Implementation often necessitates coordinated efforts among various public authorities and sometimes private entities, promoting sustainable transport modes where feasible.

TMPs encompass a broad spectrum of scenarios, such as rapid response protocols for traffic accidents to swiftly mitigate mobility impacts, strategies for managing traffic diversions and rerouting during road works and maintenance to prevent congestion, controlled traffic flows during major events to ensure safe movement in high-traffic areas, adjustments in speed limits and road closures in response to adverse weather conditions, and adaptive measures like signal timing adjustments and temporary access restrictions during peak traffic hours.

Each situation demands a tailored approach and the utilization of sophisticated management tools. While typically temporary, these interventions may extend to long-term solutions when integrated with infrastructure development or maintenance operations.

Traffic management tools

Traffic management strategies cannot be understood as a closed set of tools, but as an articulated system of tactical and operational decisions that respond to local realities and instead of a single recipe, a flexible repertoire of interventions combining physical (infrastructure), normative (regulation) and technological (control and monitoring) management is proposed.

For instance, the implementation of reversible lanes as shown in Figure 3, has become a widely adopted solution in cities with pronounced directional flow differences between morning and afternoon hours. This measure not only optimizes the use of existing roadway space but also avoids the need for physical infrastructure expansion. Its success depends fundamentally on clear signage, scheduling that aligns with mobility patterns, and continuous operational monitoring.

Figure 3 Reversible lanes (Driveris, 2023)

Similarly, BUS-HOV lanes (Figure 4) are designed to prioritise the most sustainable and efficient modes of transport. By limiting access to high-occupancy vehicles and public transport services, these lanes help reduce the overall volume of traffic, thereby easing the burden on the road network.

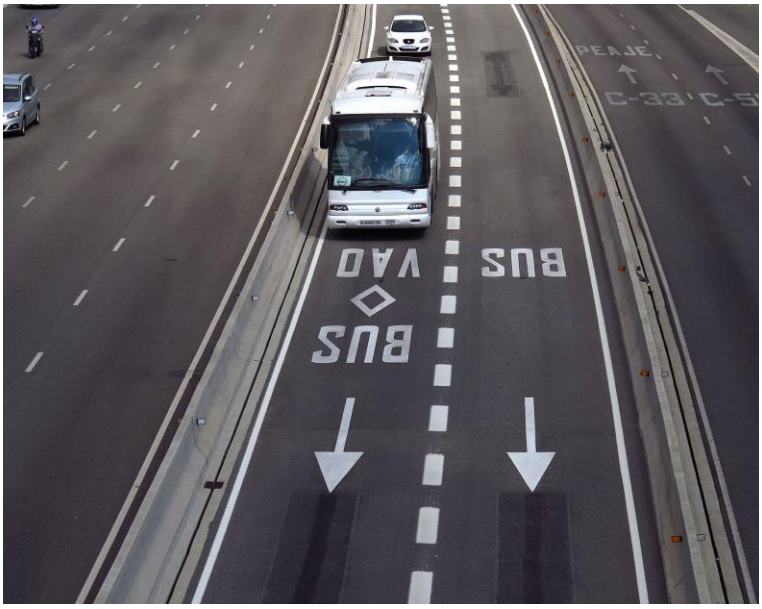

Figure 4 BUS-HOV lanes (Gabriel González, 2023)

Other strategies, such as dynamic signage, allow traffic circulation to adapt to unforeseen conditions. These systems not only inform drivers about congested areas but also influence their behaviour by guiding them toward alternative routes. Real-time automated information and rerouting have proven critical to flow across congested networks.

Smart intersections like the Figure 5 are designed to ensure safety without compromising efficiency. They are equipped with sensors that examine vehicle flow and, to adjust signal timings based on demand, enable the selective prioritisation of vulnerable or strategic modes, such as pedestrians, public transport, or emergency vehicles. This reduces the number of conflicts and enhances equity in the use of infrastructure.

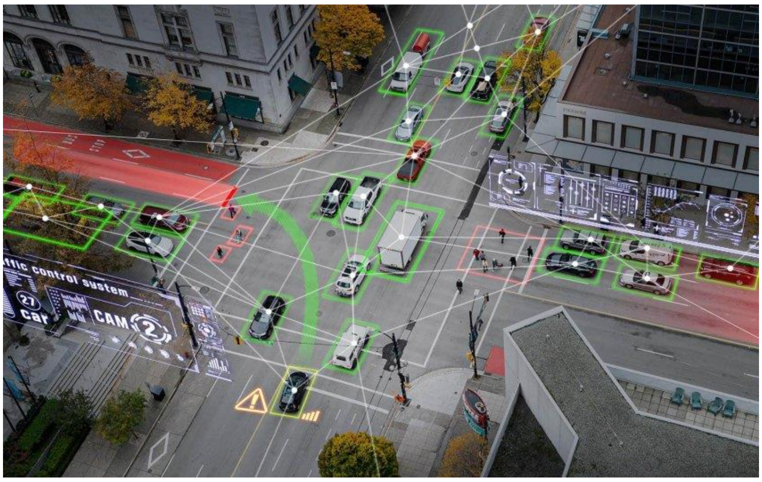

Figure 5 Smart intersections (EMESA, 2023)

Another function is AID. Through computer vision technologies or pattern analysis, these systems can rapidly identify the presence of accidents, stationary vehicles, or hazardous situations. This enables an immediate response, which may include activating detours, rescheduling signal timings, or dispatching emergency services.

A well-defined and coordinated institutional framework is essential. Cities that demonstrate more effective adaptive traffic management are not necessarily those with the most advanced technologies, but those that have managed to integrate the actors involved, define protocols jointly and establish continuous evaluation mechanisms, making use of the best technological tools.

Demand management

Traffic management based on demand management has emerged as one of the most effective and sustainable strategies for improving urban and metropolitan mobility. It is a method that seeks to balance and redistribute the use of the existing transport system, assessing the structural conditions that generate imbalances in the network and act on user behaviour.

This approach is based on the understanding that congestion cannot always be solved by building new infrastructure. In many cases, saturation is concentrated in certain timetables, routes or modes of transport, while there are underutilised alternatives.

These are some of the most effective structural measures:

- Promotion of public transport and active mobility: Enhancing the coverage, frequency, and quality of public transport, together with the provision of safe infrastructure for walking and cycling, creates credible alternatives to private car use. These improvements are supported by fare integration, signal priority, transit corridors, and planning focused on public transport.
- Teleworking and staggered schedules: Flexible work policies help reduce demand during peak hours. Teleworking, enabled by digital technologies, has proven to be an effective tool for relieving congestion in central areas and avoiding unnecessary trips.
- Dynamic road pricing: Applied in areas with high congestion or at metropolitan access points, this measure introduces tolls that vary according to time of day or traffic conditions. Its purpose is to discourage car use during peak periods by internalising the external costs of motorised travel; and
- Access restrictions: Low-emission zones, residential priority streets, and urban toll areas limit access for polluting or unauthorized vehicles. These measures also support the redesign of public space to favour pedestrians and sustainable modes of transport. The design of such areas must be integrated into the wider urban environment, including surrounding areas that may be affected by the access restrictions they impose.

Overall, traffic management based on demand management should be conceived as a long-term policy. It must include educational campaigns, public-private agreements to encourage modal shift, and evolve within the broader goals of urban sustainability and ecological transition.

2.2. Automatic Incident Detection (AID) and Management Systems

When an incident occurs on the road network, the risks of congestion, secondary collisions, and loss of functionality increase significantly. In such situations, access to reliable data and the ability to implement predefined response plans are essential. However, these actions must be supported by prior planning, well-defined protocols, and technologies capable of enabling an effective operational response (ElSahly and Abdelfatah, 2022).

Incident response should no longer rely solely on human intervention. Transport networks can be designed to react automatically and adjust the response based on real-time conditions, examples of which are given in Table 3.

Table 3 Detectable Event Types and Corresponding Operational Responses

Event type	Detection Method	Initial Action	Criticality Level
Stopped vehicle	Occupancy sensor or camera	Confirmation and alert	Medium–High
Wrong-way driving	ANPR + thermal camera	Immobilization and urgent signage	Very High
Collective hard braking	Speed variation algorithm	Assessment and preventive warning	Medium
Collision	Image + alerts from other sensors	Dispatch of an emergency team	Very High
Widespread speed reduction	Flow analysis	Activation of adaptive control measures	Medium

Automatic Number Plate Recognition (ANPR)

For minor incidents (e.g., vehicle breakdowns, slight congestion), warning messages and isolated signal timing adjustments can be activated to redirect traffic. For moderate situations (e.g., non-injury collisions, blocked lanes), access points and/or urban gates can be closed remotely, traffic can be diverted, and technical intervention coordinated. In severe cases (e.g., accidents involving injuries, a breakdown in traffic flow, or adverse weather conditions), mobile alert systems linked to navigation platforms should be complemented by a coordinated response among key actors, such as emergency services, police forces, road maintenance teams, public transport operators, and civil protection agencies.

Each response must be pre-programmed into the system to ensure real-time action and reduce dependence on operator discretion. The value of these tools lies in their integration: a properly managed incident simultaneously triggers information dissemination, traffic control measures, and resource deployment on the ground.

The effectiveness of incident management is assessed using key performance indicators that reflect both the speed and quality of the operational response. Among the most relevant are average detection time, time to initial intervention, total incident resolution time, the percentage of cases resolved without causing secondary congestion, and the estimated impact on the network, measured by the number of affected vehicles or the extent of disruption (Mumtarin *et al.*, 2023).

Continuous analysis of these indicators supports the improvement of protocols, resource allocation, and the optimisation of future responses. Also, the automatic detection and planned response mechanisms are essential components of any contemporary smart urban mobility model.

2.3. Current State of the Art About Information Systems

Effective traffic management requires access to a wide range of data from multiple sources. These include real-time information on traffic conditions, accidents, and isolated events, as well as weather data and characteristics of the road network and infrastructure. It may also be necessary to incorporate data on regulated or restricted-access zones, ongoing construction works, mobility patterns, or user behaviour, among others. Ultimately, the data required for traffic management depends on the specific characteristics of the area and typically defines a complex mobility scenario, in which source data must be standardised.

Sources of data

Institutional and policy sources:

Both national agencies and certain international organisations collect and publish data on mobility, traffic, and related statistics, in addition to establishing regulatory frameworks. The ITS Directive 2010/40/EU (European Union, 2010)establishes the need to develop interoperable traffic and transport information services in Europe. From this directive, National Access Points (NAPs) are created, official digital platforms of each state that facilitate access and exchange of mobility-related data among others. Table 4 shows some of the European NAPs.

Table 4 Europeans NAP

COUNTRY	NAP	WEB
Austria	Mobilitätsdaten.gv.at	https://www.austriatech.at/en/mobility-data
Greece	National Access Point	https://nap.imet.gr/
Hungary	NAP Portal	https://napportal.kozut.hu/
Italy	CCISS	http://www.cciss.it/
Latvia	Transport Data	https://www.transportdata.gov.lv
Lithuania	Eismo Info	https://maps.eismoinfo.lt
Luxemburg	data.public.lu	https://data.public.lu/en/
Holand	NDW (National Data Warehouse)	https://www.ndw.nu/
Sween	Trafficdata.se	https://trafficdata.se/pages/about
Germany	Mobilithek	https://mobilithek.info/
France	Transport.data.gov	https://transport.data.gouv.fr/
Spain	Centro Nacional de Acceso a Datos NAP-ESP	https://nap.dgt.es/

In Spain, traffic management is shared between the Ministry of Transport and Sustainable Mobility (MITMA) and the DGT, which reports to the Ministry of the Interior. The Spanish

National Meteorological Agency (AEMET), attached to the Ministry for Ecological Transition and the Demographic Challenge (MITECO), collaborates with them, providing real-time weather data, warnings on adverse phenomena and regional weather characteristics derived from its record of historical series.

Empirical and observed data

These are obtained through direct traffic observations, the use of sensors, fixed cameras, drones, vehicle counts, and others. Recent publication by Lautanala (Janne Lautanala, 2025) explains the importance of field tests conducted in different locations to validate traffic models and provide real-time information about vehicle density and travel times.

Data generated by ITS and intelligent infrastructure

Positioning systems such as Galileo, Glonass or GPS, together with information from road infrastructure sensors and telemetry systems, provide real-time information on vehicle flow and road conditions. This is explained in the PIARC document (Wallace, Speier and Miles, 2016), where the implementation of advanced sensors to collect data on congestion and traffic behaviour is discussed.

In order to structure a complete system for decision-making, it is certain that before being interpreted and able to provide useful information on the state of the road network, the data, which comes from different types of sensors and sources, must be combined and integrated. This process of "data integration and consolidation" can be followed in the PIARC (PIARC, 2016) monitoring documentation.

Integration systems and interoperability standards

The integration of data into common platforms based on established standards is crucial for ensuring interoperability and enabling the exchange of information required for effective traffic management. In Europe, the *European Committee for Standardization* (CEN) (European Committee for Standardization CEN, 2025) plays a key role in this process, overseeing the standardisation of data exchange models, including the DATEX II (NAPCORE, 2021)framework.

Other recognised standards related to transport and intelligent transport technologies are General Transit Feed Specification (GTFS)(Google & TriMet, 2006) ITS Architecture.

Table 5 Interoperability standards

STANDARD	DEVELOPMENT
GTFS (Google and TriMet, 2006)	An open standard originally developed by Google, designed to exchange transportation information, it can include data on routes, schedules, stops, fares, and public transport calendars.
DATEX II (NAPCORE, 2021)	European standard for the electronic exchange of information related to traffic management.

	It highlights Real-Time Traffic Information (RTTI), including data on traffic volume, speed, location and length of traffic queues, travel times, waiting times at border crossings, and fuel/charging prices. In addition, DATEX II defines SRTI categories related to road safety, has developed the UVAR regulation to standardize access restrictions, permits, and/or exemptions in urban areas, and provides information on infrastructure and truck parking occupancy, as well as electric vehicle charging infrastructure.
National ITS Architecture	Regulatory framework and standards for transportation management, created by the United States Department of Transportation (USDOT).

(GTFS) General Transit Feed Specification; (ITS) Intelligent Transportation Systems

In terms of platforms, the main European open data portal is European Data (European Union, 2025) which collects information on both freight and passenger transport modes, as well as many other datasets.

The strategic role of information in traffic management

Currently, the challenge for managers is no longer data acquisition, but its processing, reliability (which highlights the importance of sources), and operational usefulness, which must also be shared with users in a clear, accessible, and useful manner.

This progress has transformed traffic management into a highly technical process, where information systems have become the core of the daily operational functioning of many urban and interurban networks.

Real-Time information delivery and distribution systems

One of the most significant advancements in the field of mobility information systems has been the ability to provide real-time data to both traffic managers and users. Real-time information and dissemination platforms allow operators to monitor the road network with precision and maintain effective communication with citizens.

Real-time information systems enable operators to use analytical visualisation tools that facilitate understanding of the network's status. These dashboards include congestion, heat maps, levels of service by section, alerts at critical nodes, and temporal evolution of key parameters.

These visual environments allow technicians to assess the impact of their decisions, plan interventions and optimise resources.

Modern traffic management relies heavily on real-time information systems that prioritize data, interoperability, and user-centric approaches. Key components include advanced data analysis techniques such as big data processing, machine learning algorithms, and dynamic dashboards with key performance indicators. These tools transform raw data into actionable insights, enabling traffic managers to anticipate trends, detect anomalies, and make informed decisions swiftly. Additionally, forecasting tools like urban traffic simulators and congestion prediction models play a crucial role in preemptively assessing network behaviour under various conditions, allowing for proactive mitigation of potential disruptions such as large events or adverse weather.

Furthermore, effective traffic management systems integrate seamlessly with external platforms such as public transport systems for prioritization, emergency services for swift response coordination, and shared mobility platforms. This connectivity enhances overall operational efficiency, improves road safety, and enhances user perception of system reliability and quality. By leveraging these interconnected capabilities, traffic managers can minimize congestion impacts, optimize resource allocation, and ensure a smoother, safer experience for all road users.

2.4. Integrated Traveller Information Platforms (TIS)

One of the most visible and highly valued components for citizens in relation to traffic management is the TIS. Its objective is clear: to provide users with relevant, reliable, and understandable data about the state of mobility, both before and during their journey.

From a management perspective, TIS serves as a bridge between the system's internal operation and users' external perceptions. When the information transmitted is useful, the overall efficiency of the system is improved: users make better decisions, avoid congested areas, choose more sustainable modes of transport, and anticipate unexpected incidents.

Types of TIS in the current context are:

- VMS on roads: These are illuminated panels located on highways, tunnels, and urban access points that display real-time messages about congestion, accidents, speed limits, roadworks, or weather conditions.
- Mobile applications: These are a set of tools or software installed on personal mobile devices that allow users to plan routes, check traffic status, receive incident alerts, consult public transport schedules, or get personalized notifications based on their travel habits. When users report incidents, it enriches the operator´s databases and improves the system's response capacity. In this sense, TIS are not only dissemination tools but also active listening instruments for user behaviour.
- Onboard vehicle systems: One example are GPS devices with internet connectivity installed in vehicles, which receive real-time traffic data from control centres or open platforms. This allows for route recalculation, arrival time adjustments, or reporting road obstacles.

- Traffic management websites and social media: Institutional channels such as the DGT(Dirección General de Tráfico (DGT), 2025) in Spain, metropolitan consortia, or local governments stand out. These channels provide information on road network events, activate protocols in response to incidents, and maintain direct communication with users; and
- Physical multimodal information points: Screens at bus stations, metro stations, interchanges, or park-and-ride facilities that offer combined information across various transport modes.

Travel services can be divided into four distinct types:

- Pre-trip information: Refers to gathering information about the available options, whether regarding the route or mode of transport, and understanding the conditions of the transport networks in advance.
- On-trip information: Real-time information allows travellers to modify their route or mode of transport at a given moment. Knowing about delays or road conditions is a significant benefit for the traveller.
- Location-based services: These make use of GPS receivers in mobile phones, which have become an increasingly important component of traveller services. For example, real-time public transport information apps, such as "Moovit" (Moovit App Global LTD, 2025), tourist information, points of interest, etc; and
- Social media / social data functions: A platform is provided to disseminate information about delays and disruptions in the transport network, enabling users to communicate with each other and with the transport company.

2.5. Communication (V2X, IoT, 5G)

The evolution of traffic management in urban environments has undergone a significant transformation thanks to the integration of advanced technologies such as V2X communication, the IoT, and 5G networks. These innovations have enabled the development of more efficient and safer systems, capable of adapting in real-time to changing traffic conditions and improving urban mobility.

Introduction to Communication Technologies in Traffic Management

Modern traffic management hinges on the seamless collection, processing, and utilization of real-time data facilitated by various advanced techniques. These include ANPR, enabling vehicle identification and monitoring traffic flow for enforcement purposes. Test vehicle data utilizes sensors within vehicles to analyse traffic patterns and assess road conditions accurately. Intelligent video measurement employs sophisticated cameras and computer vision algorithms to detect incidents, count vehicles, and evaluate traffic density swiftly and accurately. Additionally, virtual loops, sensors integrated into road infrastructure, detect vehicle presence and speed without physical devices embedded in the road, providing crucial real-time data for optimizing traffic management strategies effectively.

Figure 6 Vehicle counting software

Control algorithms use this information to automatically adapt to vehicle flow conditions, analysing in real-time variables such as queue lengths at junctions, point-to-point travel times, acceleration or braking rates, occupancy levels per section, and cumulative delays.

Technologies such as V2X, IoT, and 5G networks are becoming essential in advanced traffic management, playing a central role in connecting, controlling, and dynamically adapting the system.

Vehicle-to-Everything communication (V2X)

V2X communication is a technology that allows vehicles to exchange information with their environment, including other vehicles (V2V), infrastructure (V2I), pedestrians (V2P), and the network (V2N). This two-way communication capability is fundamental to the development of intelligent transport systems and autonomous driving.

V2X, comprising V2V, V2I, V2P, and V2N components, revolutionizes modern transportation by enabling seamless communication across vehicles, infrastructure, pedestrians, and networks. V2V facilitates direct vehicle-to-vehicle communication, enhancing road safety through collision avoidance and real-time hazard alerts. V2I connects vehicles with road infrastructure like traffic lights and toll plazas, optimizing traffic flow by adjusting signals and managing routes to minimize congestion. V2P improves pedestrian safety by alerting drivers to crossing pedestrians, while V2N integrates vehicles with cloud services and traffic control centers, facilitating updates and enhancing overall system connectivity.

Implementing V2X technology brings numerous benefits, including enhanced road safety through early warnings and improved traffic management. By providing real-time traffic information, V2X enables optimized signal timing and route planning, reducing travel times and enhancing energy efficiency by minimizing fuel consumption and emissions. For instance, vehicles receiving updates on traffic light statuses can adjust speeds to optimize arrival times at intersections, demonstrating V2X's potential to enhance traffic efficiency and environmental sustainability.

IoT in traffic management

The IoT refers to the connection of physical objects through digital networks, thus facilitating the collection and transmission of information in real-time. In traffic management, it uses this technology with sensors and smart devices in both infrastructure and vehicles.

<u>IoT applications in traffic</u>

- Intelligent traffic sensors: Devices installed on roads and traffic lights that collect data on vehicle flow, detect congestion, and adjust signal timings to optimise traffic.
- Environmental monitoring: Sensors that measure air quality and noise levels in urban areas, providing valuable information to implement pollution reduction policies.
- Intelligent parking systems: Use sensors to detect available parking spaces and guide drivers to them, reducing search time and congestion in urban areas.
- Fleet management: Transport companies use IoT devices to monitor the real-time location, performance, and maintenance of their vehicles, improving operational efficiency.

The implementation of IoT in traffic management enables more informed decision-making and faster response to incidents, contributing to smarter and more sustainable cities.

Integration between systems: mobility as a service (MaaS)

One of the biggest advances in traffic management is the ability to interconnect heterogeneous systems. It is no longer a matter of managing vehicles, public transport, bicycles, or pedestrians as separate elements, but of integrating all modes on common platforms. The MaaS philosophy is based on offering users seamless, multimodal and personalised mobility through applications that combine schedules, routes, payments and smart recommendations.

Communication between V2X systems, urban sensors, transport operators, emergency services, and open data platforms is what makes it possible to move from a traffic network to a network of intelligent services.

This integration is made possible by open standards, such as those defined by (Mkinsi and Lueje, 1992), interoperability of APIs, and the use of data orchestration technologies (Edge AI, data federation, distributed storage). The existence of smart connected infrastructure, such as sensor-equipped streetlights, interactive bus stops, or predictive crossings, enables such integration without generating friction in the system.

3. Infrastructure And Technologies for Intelligent Transportation Systems

The architecture of ITS constitutes the structural framework that defines the functional organisation of these systems, their components, the relationships between them, and the information flows necessary for their operation. From a systemic perspective, this architecture integrates both technological elements and organisational processes, considering technical, legal, and operational aspects, as well as the interactions between users, operators, infrastructure, and services.

An effective ITS architecture enables interoperability between heterogeneous platforms, secure real-time data exchange, and automated or assisted decision-making. This includes communication between traffic control centres, traveller information systems, road sensors, connected vehicles, and external services such as emergency or weather services. This requires compliance with standards such as DATEX II(NAPCORE, 2021) or GTFS(Google and TriMet, 2006), as well as regulatory frameworks such as the General Data Protection Regulation (GDPR) or Directive 2010/40/EU (European Union, 2010). There are various approaches to representing the architecture of an ITS: the logical model (which describes functions and information flows), the physical model (which defines the specific components and their interfaces), the communications model (which specifies the protocols and technologies used), and the organisational model (which assigns responsibilities among the actors). This modular structure allows for the scalable planning of the deployment of ITS solutions adapted to different territorial contexts, technological capabilities, or levels of automation.

ITS architecture also considers the requirements associated with the deployment of these systems, including cost-benefit analysis, risk assessment, maintenance management, and technological update mechanisms. These elements are essential to ensure the resilience, security, and sustainability of systems throughout their life cycle.

From a functional point of view, ITS architecture facilitates the transition to connected, cooperative, and automated mobility models. This involves not only the integration of autonomous vehicles or shared mobility platforms, but also the ability to adapt to emerging challenges such as the management of exceptional events (natural disasters, multiple accidents, massive congestion) or the need to mitigate environmental impact through low-carbon solutions.

In this sense, ITS not only extends the operational capabilities of traditional transport systems but also enables more flexible and personalised planning of urban and interurban mobility.

3.1. Physical And Technological Infrastructure

ITS are the result of the digital revolution driven by information and telecommunications technologies. Today, ITS plays an important role in the management and operation of transport networks, ranging from roads and railways to waterways, ports, and airports. These systems also contribute to the control of vehicles travelling on these networks and to the efficient planning of transport operations.

ITS encompasses a wide variety of user support functions, ranging from simple alerts on mobile phones to attractive traffic control systems. To fulfil their functions, ITS employs a variety of technologies. Table 6 shows different ITS technologies.

Table 6 Technologies used in ITS

Category	Description / Examples
Data processing, management, and storage technologies	Infrastructures and systems for the collection, integration, and analysis of large volumes of data in real-time. These include servers, databases, and cloud platforms.
Detection technologies	They enable information about the environment and traffic to be captured.
Communication technologies	Infrastructures and protocols that enable data exchange between ITS systems and users: V2X, IoT, 5G, mobile networks, specific wireless networks (DSRC, ITS-G5).
Technologies for information dissemination	Systems for informing users and operators: VMS, mobile applications, on-board systems, web platforms.
Positioning and location technologies	Technologies such as GPS enable the precise geolocation of vehicles and mobile elements in the transport network.
Vehicle and traffic control technologies	These are classified as: • Infrastructure-based: adaptive signal control, ramp control. • Vehicle-based: ADAS, Adaptive Cruise Control (ACC).
Electronic payment technologies	Systems for automated payment at tolls, low-emission zones, public transport, etc. For example: contactless cards, TAG systems, mobile apps.
Taxation and supervision technologies	Devices that support regulatory compliance and surveillance: ANPR cameras, speed detectors, traffic signal control, automated image analysis.

V2X: Vehicle-to-Everything; IoT: Internet of Things;DSRC: Dedicated Short-Range Communications; ITS-G5: Intelligent Transport Systems at 5 GHz; VMS: Variable Message Signs ; GPS: Global Positioning System; ADAS: Advanced Driver Assistance Systems ; ACC: Adaptive Cruise Control; ANPR: Automatic Number Plate Recognition.

Overall, ITS technologies optimize mobility, enhance safety, and improve efficiency in managing transportation systems across various domains. At the core of ITS are control technologies and information technologies. Control technologies encompass infrastructure-based systems like adaptive traffic signals and ramp meters, as well as vehicle-based systems such as ADAS and ACC. Information technologies play a crucial role in data collection, processing, integration, analysis, and dissemination to users. Real-time data from ITS technologies informs decision-making processes that enhance network performance. Detection technologies include infrastructure-based sensors like inductive loops and Closed-Circuit Television (CCTV), along with vehicle-based methods such as probe vehicles and citizen reports, ensuring timely, accurate, and reliable information availability.

3.2. Current Implementation of ITS Technologies

Telecommunications are an important part of ITS and road network management. Over the last 40 years, these technologies have evolved, connecting control centres with different devices on the road, like phones, CCTV cameras, variable message signs, and traffic signals. Today, digital communications dominate the field of voice, video, and data signal transmission, replacing previous technologies.

Digital technology offers significant advantages, becoming increasingly reliable, flexible, and easy to manage compared to previous generations. Thanks to these digital communications, advanced technologies for traffic management and the most modern ITS applications have been developed and are now in operation, including connected vehicles in Active Traffic Management systems. In addition, the use of CCTV has grown significantly, enabling the digital transmission of video images over long distances without compromising image quality, which significantly improves real-time traffic monitoring and control.

Some ITS have been successfully implemented on roads for several decades and have proven to be instrumental in improving road safety (Janušová and Čičmancová, 2016; Garg and Kaur, 2023). These systems, which include technologies such as real-time traffic monitoring, traffic signal management systems, and driver alert devices, have helped to reduce accidents and improve route efficiency. However, the main driver behind the installation of ITS in-road infrastructure is often more related to improving transport network capacity and optimising mobility than to road safety itself.

Despite their benefits, the useful life of ITS is considerably shorter than that of other road infrastructure measures. This is due to the rapid technological advances that characterise this sector. Each new generation of devices and systems improves on the capabilities of its predecessors, leading to faster technological obsolescence. This cycle of constant innovation means that ITS generally have an estimated useful life of between 10 and 15 years before being replaced by more advanced, efficient versions that are better suited to the changing needs of modern transport.

3.3. Road Safety

Information and Communication Technologies enhance road safety by preventing accidents, reducing severity, and improving survival rates. Onboard systems and route information protect drivers, maintenance workers, cyclists, pedestrians, and vulnerable groups like children and people with reduced mobility. Additionally, advanced weather alerts help drivers avoid hazards and assist operators in preventive actions and emergency route planning.

.

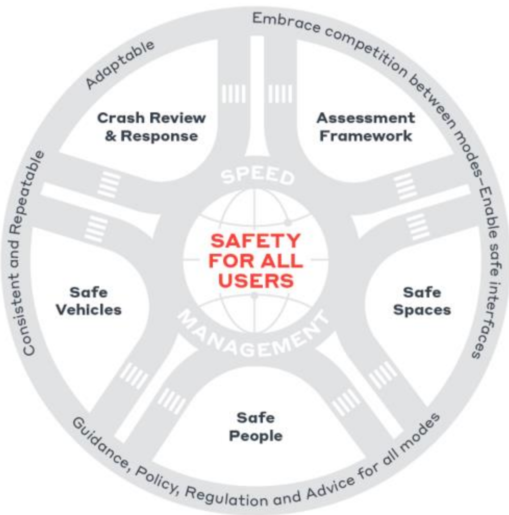

Figure 7 Integrated framework for road safety management (WSP, 2020)

The mechanisms through which ITS (Figure 7) impact road safety are diverse. Firstly, ITS directly enhance user safety by modifying driver behavior in real time through information provided either within the vehicle (e.g., collision alerts, distance or visibility warnings, windshield displays) or on road infrastructure (e.g., variable message signs, V2I systems). However, it is important to recognize that, in some cases, these technologies may induce cognitive overload, potentially impairing driver attention and reducing safety.

Secondly, ITS contribute to indirect and long-term behavioral adaptations among drivers. These systems not only affect immediate users but also influence the overall driving environment, leading to changes in following distances, speed management, and attentional focus. Additionally, ITS modify users' exposure to road risk by impacting travel patterns, mode choices, and route selection. Through recommendations, restrictions, and real-time guidance (e.g., parking management, access controls, dynamic route information), ITS can steer users toward safer travel times, transport modes, and routes.

Finally, ITS play an important role in mitigating accident consequences. Intelligent in-vehicle systems reduce the severity of crashes and enable rapid emergency response through immediate collision notifications. Numerous ITS technologies are specifically designed to improve safety by assisting drivers in critical situations, issuing hazard warnings, and even autonomously intervening to prevent dangerous maneuvers. These systems actively monitor the driving environment to support and enhance driver decisions, ultimately reducing accident risks and improving survival rates

Driver assistance systems can function in various modes (autonomous, connected, and coordinated). Autonomous systems are fully integrated into the vehicle and operate independently, while connected systems receive information from external sources. Coordinated systems interact with other vehicles and infrastructure, particularly within traffic control environments, to enhance overall safety and efficiency.

In addition to technological innovations, the DGT (DGT, 2022a; Dirección General de Tráfico (DGT), 2025) has developed several road safety plans aimed particularly at rural and conventional roads, intersections, and areas with vulnerable users. These include automated deviations during adverse weather or incidents, intelligent traffic guidance systems, intelligent crossings, automatic animal detection on roads, and systems for detecting vulnerable users on the shoulder. Other measures involve pedestrian push-button activated traffic lights at high-risk crossings.

Several ITS applications have already been widely implemented to improve road safety. Examples include speed control systems through imminent danger alerts and variable speed limits, intelligent speed adaptation technologies, automatic enforcement mechanisms (such as traffic signal cameras, speed control in tunnels, and alcohol testing), automated incident detection, the use of variable message signs for dynamic speed control, and on-board warning systems like the e-call system that provides immediate alerts in case of emergencies.

Reducing accidents, especially those causing injury or death, is one of the main objectives of the use and deployment of ITS technology. This makes it possible to analyse the current traffic situation and include driver behaviour, vehicle dynamics, and road conditions, with an emphasis on safety. It is important to note that ITS systems are not specifically focused on road safety, although they can improve it indirectly as a side effect.

Road safety: an operational priority:

From a management perspective, road safety cannot be relegated to information campaigns or sporadic checks. It needs to be addressed as a systemic function, integrated into all layers of traffic control. Early detection of dangerous events (stopped vehicles, wrong-way traffic, pedestrians on the road, signal violations) can significantly reduce risks.

Active management also includes direct intervention in unsafe behaviour using tools such as:

- Red light enforcement systems (Figure 8a).
- Non-stop sensors at STOP (Figure 8b).
- Personalised warning signs displaying licence plates in the event of speeding (Figure 8c).
- Cameras that warn of insufficient safety distance (Figure 8d).

These technologies enable the creation of safer urban environments, reinforce regulatory compliance, and reduce accidents associated with human error.

a. Traffic signal - Photo-red (Sergio Rodriguez, 2023).

b. Enforcement – video stop

c. Warning signboard (IMPLY, n.d.)

DAS system (Qué Es El Sistema de Seguridad ADAS y Cómo Utilizarlo - Red Itevelesa, 2020)

Figure 8 Example of direct intervention tools for unsafe behaviour

Network optimisation: operational efficiency

At the same time, the overall efficiency of the traffic system depends on the ability to anticipate disruptions and restore traffic flow as quickly as possible. When an incident is detected, the key is not only to respond quickly, but also to minimise the impact on the entire network.

This is achieved by:

- Redistributing traffic to parallel roads.
- Prioritising public transport.

- Reducing signal times to relieve congestion in critical areas.
- Deactivating routes that feed congested areas.

The positive impact is manifold: less time lost by users, lower fuel consumption, reduced pollutant emissions, and greater predictability in journey times.

Evaluation and continuous improvement

Traffic management requires a data-driven approach. To this end, indicators such as the following are analysed:

- Reduction in the number of incidents with victims.
- Average event resolution time.
- Variation in congestion levels by day and time.
- Increase in driver compliance with regulations.

This analysis allows critical patterns to be identified, operational strategies to be reformulated, and more effective interventions to be developed, such as the reconfiguration of intersections, the installation of new sensors or the redesign of school routes and shared zones.

Safety and sustainability: converging objectives

Detecting incidents enhances safety, reduces environmental impact, and strengthens the resilience of road infrastructure by enabling quick adaptation and recovery to any event. Road safety must therefore be understood as an investment in sustainability, urban productivity, and equity in the use of public space. Traffic management not only moves vehicles but also protects lives and improves the quality of the environment for all users, including pedestrians, cyclists, public transport, and people with reduced mobility.

From a management perspective, early detection is an efficiency multiplier: it prevents chaos, reduces exposure to risk, and promotes a more robust network. At the systemic level, it allows resources to be mobilised more rationally, avoiding prolonged congestion, excessive emissions, and public discomfort.

Furthermore, by better controlling passive safety (such as red lights, illegal stopping, driving in prohibited areas), a deterrent effect is generated that reduces offences, accidents, and the misuse of road space. All of this strengthens the institutional credibility of the traffic management system.

The connection with environmental objectives is also clear: detecting and managing events avoids unnecessary emissions, downtime with the engine running, and promotes more orderly mobility. This alignment between operational efficiency, safety, and sustainability is what makes these systems strategic tools beyond the technological sphere.

3.4. Current Techniques and Devices for Road Network Monitoring

In recent years, the DGT has been implementing ITS using traffic counters, cameras, radars, and other devices located on the roads. This infrastructure allows real-time traffic monitoring and informs users about incidents. This improves both safety and sustainability on our roads (DGT, 2022b).

The recent introduction of V16 devices, which enable the geolocation of vehicles stopped on the road, along with new regulations requiring tow truck operators to transmit the location of broken-down vehicles electronically, complements this infrastructure and forms what is known as DGT 3.0 (DGT, 2021) .

In addition, any entity, administration, or operator of ITS applications and services can and must register in the DGT's register of intelligent applications and services. This expands the information and services available to citizens, such as electronic toll collection or congestion charges, video cameras, and digital character recognition technology. Automatic enforcement of traffic offences and in-vehicle emergency notification systems are other examples of these advanced intelligent transport systems.

Information can also be obtained from other data sources such as the AEMET, national, regional, or local networks, and the Civil Guard Traffic Group.

These systems can be classified into different categories, but the main ones are as follows:

- ITS focused on road safety.
- ITS focused on traffic management.
- ITS focused on surveillance and control.

These three groups of plans improve road safety, make traffic management more efficient, and ensure that drivers comply with traffic regulations. They thus serve to provide users with information that improves mobility and safety on the road. Below are some proposals designed by the DGT within each group.

1. ITS Focused on Road Safety: Road safety oriented ITS include systems that automatically redirect traffic during bad weather or accidents and guide vehicles in adverse conditions. Technologies like intelligent pedestrian crossings, animal detection on roads, and identification of vulnerable users on the shoulder improve overall safety. Smart traffic lights and push-button systems also enhance pedestrian protection at crossings.

2. ITS Focused on Traffic Management: These ITS tools aim to optimize flow and reduce congestion. Examples include reversible lanes, Bus-HOV lanes, smart routing based on real-time data, dynamic speed limit adaptation, and access control systems to manage vehicle entry in specific areas.n3. ITS Focused on Surveillance and Control: This category includes enforcement technologies such as point and section speed control, dynamic speed limits linked to radars, red light and stop sign enforcement systems, and seat belt

detection. These systems help ensure compliance with traffic laws automatically and efficiently.

These are the guidelines or plans proposed by the DGT to improve the current situation. A wide range of different sensors installed inside, outside, or on the network are necessary to achieve the required geographical and critical time coverage. With the development of these new ITS, this problem is being solved and improved through the following instruments:

- Magnetic loops
- Virtual loops
- Magnetometer
- Anemometers and visibility meters
- Piezoelectric sensors
- Infrared laser sensors
- CCTV cameras
- Photo-red sensors
- Arrow-shaped panels
- Lane closure barriers
- Beacons
- E-CALL
- Odour barrier
- Cynegetic closing
- APNR systems
- Thermal cameras
- Instant and sectional radar
- Artificial vision cameras
- Podotactile systems
- Weigh-in-motion
- Hybrid DMS signs
- Toll TAGS devices

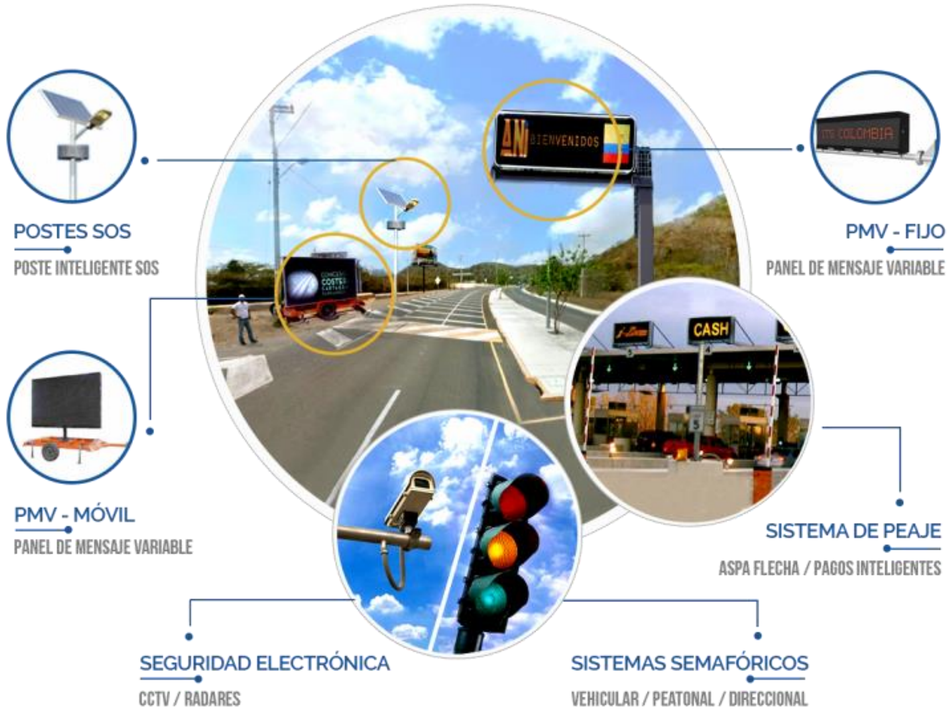

Figure 9 Some examples of ITS (Daniel Urieles López, 2023)

Various infrastructure-based ITS systems have proven highly effective in reducing road casualties and fatalities. Specifically, according to the report by the PIARC Technical Committee on Road Safety (PIARC, 2016), the following systems have been identified as ready for implementation by road authorities:

- **Speed control systems:** These include technologies such as localised hazard warning systems and variable speed limit signs, which allow the speed limit to be adjusted according to specific road conditions.
- **Intelligent speed adaptation and speed alerts:** These systems automatically adjust vehicle speed according to traffic conditions and send alerts to drivers when they exceed established speed limits, using updated digital databases.
- **Automated enforcement of traffic regulations:** This includes the use of infrared cameras, automatic enforcement cameras, and systems to monitor compliance with safety distances in tunnels. It also incorporates devices such as alcohol ignition interlocks to prevent drink-driving.
- **Incident management:** This system covers AID, variable message signs and panels that provide real-time traffic information, and warning systems in both infrastructure and vehicles. It also includes the eCall system, which automatically calls emergency services in the event of an accident, optimising response times.

4. Real-World Applications and Case Studies

A comprehensive understanding of real-time traffic management requires the examination of both research and pilot projects, as well as real-world implementations.

Research and development studies that have contributed to innovation in this field are often accompanied by pilot initiatives that test new technologies and methods. These include traffic optimisation algorithms and systems for incident detection and response, allowing for an assessment of their potential to improve mobility. Each case provides an opportunity to analyse the technologies applied, the challenges faced, and the lessons learned.

In parallel, reference is made to real-world implementations of real-time traffic management systems integrated into urban and regional mobility and logistics strategies. These cases offer insights into outcomes related to congestion reduction, improved road safety, shorter travel times, and lower pollutant emissions.

4.1. Projects

Autonomous Ready Spain (2018-2020)

Autonomous Ready Spain (2018–2020)(Mobileye and Dirección General de Tráfico, 2020) is an example of a project that incorporated features of Cooperative Intelligent Transport Systems (C-ITS) without requiring changes to existing infrastructure. Led by DGT and involving the company Mobileye, the project included a pilot trial in Barcelona in which a device (Mobileye 8 Connect) was installed on vehicle dashboards.

This ADAS (Advanced Driver Assistance System) device enables the detection of vulnerable road users and issues alerts for forward collisions, lane departures, pedestrian or cyclist collisions, and speed limit violations. The information is transmitted to a central server, where detection maps of vulnerable elements are generated. It can also be sent back to vehicles to provide additional information to users.

This aligns with CIRCUIT's objectives of integrating smart, resilient transport infrastructures and preparing them for emerging autonomous mobility trends, especially through CIRCUIT's commitment to including updated traffic simulations and future autonomous vehicle scenarios into transport design

Transforming Transport coordinated by Indra (2017-2019)

At a more advanced level, the Transforming Transport project coordinated by Indra (2017-2019)(Indra, 2019) proposes the use of various data sources, Big Data, and Machine Learning techniques in multiple areas of transport and logistics. This directly supports CIRCUIT's ambition to foster digitalization within transport infrastructure, particularly by developing open-source platforms interoperable with traffic simulation tools to support greener, smarter, and more sustainable infrastructure solutions

Within the field of Smart Highways, a pilot project has been carried out in a 96-kilometer section of the Ausol toll highway belonging to the AP-7 Motorway. This initiative integrated data from 16 different sources, including inductive loop detectors, ANPR cameras, queue length measurements at toll stations, toll payment records, real-time data provided by TOMTOM, incident information from the DGT, and weather data from the Spanish State Meteorological Agency. These sources were consolidated into a unified dashboard, and short-term predictions (15, 60, and 120 minutes) were generated using machine learning techniques. Based on these forecasts, infrastructure managers could act on various operational elements, such as:

- Toll station configuration: enabling an increase in the number of operational toll booths when short-term forecasts indicate rising demand.
- Scheduling of maintenance tasks: including lane closures, shoulder cleaning, and road marking.

Midlands Future Mobility (MFM)

The Midlands Future Mobility (MFM) (Midlands Future Mobility, 2021)project, led by the UK government (2020–2022), seeked to implement a practical deployment of connected road technologies for the benefit of both road users and infrastructure managers within a defined area of the country. It aligns with CIRCUIT's pillars of digitalization and smart infrastructure by contributing to the development of safe and sustainable transport systems capable of dynamically adapting to autonomous and connected technologies, reinforcing CIRCUIT's goal of rapid infrastructure adaptation. The project covered approximately 300 km of roads, linking conventional and autonomous vehicles while integrating both existing and newly installed sensors. The main objective is to collect and provide information to users. Ultimately, the project aims to establish the conditions required for the operation of Level 4 autonomous vehicles under appropriate circumstances. The actions include:

- Integration of electromagnetic loops
- Interpretation of CCTV data using computer vision
- Digitalisation of infrastructure through LIDAR
- Integration of weather and road condition data
- Collection of data from connected vehicles
- Use of high-precision GPS
- 4G, LTE, and 5G communication technologies

C-Roads-Spain

In Spain, the C-Roads Spain (C-Roads Spain Consortium, 2023) project was developed within the framework of the European C-Roads platform. The initiative focuses on the deployment of Cooperative Intelligent Transport Systems (C-ITS) in a coordinated and interoperable manner across EU member states. C-Roads Spain, which involved the Government of Spain and the Provincial Council of Bizkaia (2017–2020), carried out a series of pilot deployments using both Wi-Fi-based (ITS-G5) and cellular (LTE) communication protocols. Through the installation of sensors and antennas, real-time information on traffic conditions and emergency incidents can be captured and transmitted to road users. This supports improved service provision and contributes to greater safety for both vehicles and passengers. This is highly synergistic with CIRCUIT's mission to create sustainable, circular, and digitally integrated infrastructures, as both initiatives focus on smarter, connected transport networks that can better handle future multimodal traffic demands

The project has been divided into four major pilots developed in Madrid, the Mediterranean, the Cantabrian, and Siscoga (Vigo). There is also an additional pilot project called DGT 3.0 (DGT, 2021), which covers the entire Spanish road network using 3G/4G and LTE technology.

In the case of Madrid, a fleet of 120 vehicles was mobilized, one of them autonomous, to also evaluate the new functionalities of cooperative transport. The pilot was developed on the M-30 by means of hybrid ITS-G5 and mobile communication, simulating slow or stopped vehicles, construction site warnings, different weather conditions, emergency vehicle approach warnings, and vehicle speed limits.

For the pilot developed in the Mediterranean, information from refuelling and charging stations for electric vehicles or alternative fuels was also integrated. Another objective was to control, through the Smart Slip Road service, incidents related to unforeseen circumstances when entering or leaving the highway.

In the case of the Cantábrico, in addition to using the Smart Routing application for vehicle routing, tests were carried out on the risk of collision on mountain roads, which is why this most rugged area of the Spanish geography was chosen. Specifically, the test was carried out on 75 km of roads in the regions of Galicia, Asturias, and the Basque Country, all of them connected by the A-8 at various kilometre points. The number of vehicles assigned to this test was 145, and hybrid communication was used.

The case of Siscoga (Figure 10), limited to the city of Vigo and with an extension to the Portuguese city of Tuy, consisted of testing the use of ITS-5G technology in most of the route, complemented with LTE. The motivation of this pilot was to improve road safety and facilitate traffic flow in the case of an infrastructure that crosses a border between two EU member states. Specifically, this test aimed to know in real-time the existence of slow or stopped vehicles, road works, and specific weather situations. Four autonomous vehicles were used to drive along sections of the road between the A-55 in Spain and the A-27 in Portugal. This covered a distance of 150km.

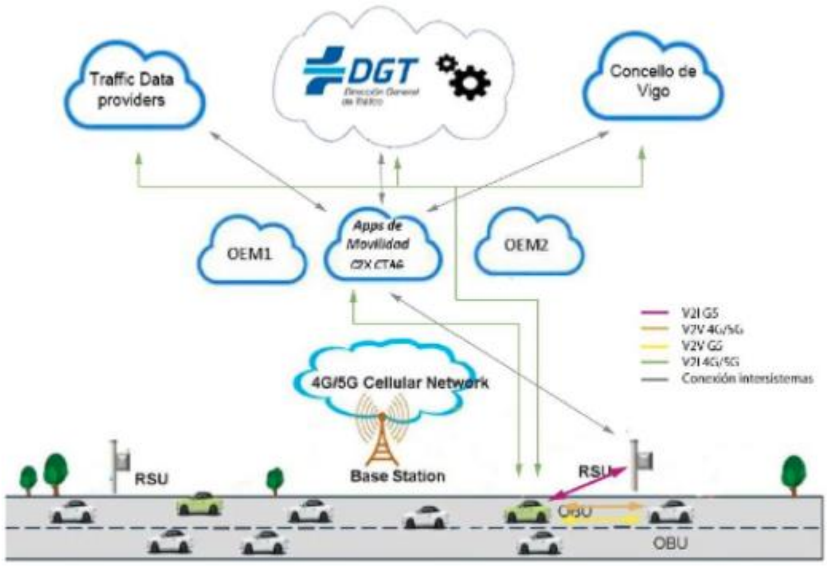

Figure 10 Operational diagram of the Siscoga pilot (C-Roads Spain Consortium, 2023)

The DGT 3.0 project (Figure 11) provides coverage across 12,270 kilometres of the Spanish road network through the implementation of "Day 1" and "Day 1.5" services.

"Day 1" services include: information on slow or stationary vehicles, roadworks warnings, weather condition updates, alerts regarding approaching emergency vehicles, speed restrictions, and notifications of other road hazards.

"Day 1.5" services build on this by incorporating information on refuelling stations, protection of vulnerable road users, on-street and off-street parking availability (including Park & Ride), and more detailed traffic condition data.

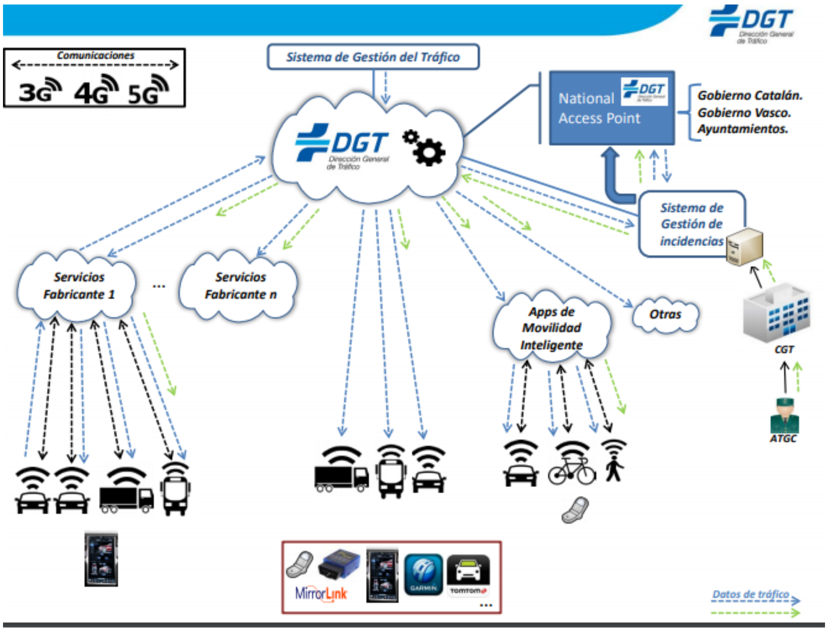

Figure 11 Connected vehicle platform of the DGT 3.0 project (C-Roads Spain Consortium, 2023)

DGT 3.0. combines aspects related to the connected vehicle as well as the IoT: In Europe, information from emergency vehicles is already accessible, and emergency fleets are geolocated.

The project involves the development and assessment of approximately twenty operational services which, through alerts displayed on navigation systems, mobile phones, or in-vehicle interfaces, will inform drivers about traffic conditions, weather, roadworks, and stationary vehicles.

CORDIS

CORDIS (Community Research and Development Information Service) (European Commission, 2021) is the European Commission's primary platform for disseminating the results of EU-funded research projects. In the field of transport, it provides access to a wide range of initiatives related to intelligent mobility, sustainable logistics, infrastructure digitalisation and the deployment of new technologies in traffic management. It serves as a key reference point for tracking ongoing developments and identifying transferable innovations across Europe.

CORDIS also develops advanced simulation models (Table 7). These models include, among others traffic management (e.g. cooperative traffic management system (CTMS) and real-time traffic information for multi-purpose CCAM services), fleet management (e.g. pick-up and delivery problem with cross-docking for perishable goods and real-time FMS with incident management), multimodality (e.g. a demand forecasting method using a novel probabilistic traffic assignment model and a multimodal trip planning solution), multimodality (e.g. a probabilistic traffic assignment model and a multimodal trip planning solution), a demand forecasting method using a novel probabilistic traffic assignment model and a multimodal journey planning solution), interoperability (e.g. agent-based interoperability framework) and multi-resolution simulation (e.g. simplified mesoscopic simulation model, Aimsun-FleetPy bridge for co-simulation and a calibrated traffic simulation model using real-world data to allow testing of coordinated traffic signal controls).

Table 7 Pilot Studies from the CORDIS Project

Location	Project	Technology implemented	Impact
Madrid (Spain)	CORDIS	GoOpti	Model designed to improve the management of unexpected events in transport and ensure effective post-disruption network recovery. Cooperative routing (identifying transport patterns to maximise fleet resources) for moving passengers to and from airports. Reducing traffic caused by the growing demand for last-mile deliveries by transporting passengers and freight in the same vehicles.
Athens (Greece)		FleetPy	Bus, metro and tram timetables synchronised to maximise passenger choice.
Almelo (Netherlands)		Aimsun.next	Logistics corridor implementing traffic prioritisation systems at selected junctions.

Other projects

The European Union has promoted numerous research and innovation projects in the field of Intelligent Transport Systems through its framework programmes, particularly Horizon 2020 and its successor, Horizon Europe. These projects explore various dimensions of smart and sustainable mobility.

Horizon 2020-funded projects such as DIT4TRAM (Agreement 953783)(DIT4TraM Consortium, 2024), ORCHESTRA (Agreement 953618)(ORCHESTRA Consortium, 2024), TANGENT (Agreement 955273)(TANGENT Consortium, 2024), and FRONTIER (Agreement

955317)(FRONTIER Consortium, 2024) focused on multimodal optimisation and digitisation of traffic management. DIT4TRAM developed advanced digital solutions to improve the efficiency and safety of urban traffic, using optimisation algorithms and real-time information systems. ORCHESTRA focused on the synchronisation of different transport modes, implementing predictive models to optimise coordination between buses, trams, and other vehicles. TANGENT employed state-of-the-art data processing techniques to manage multimodal traffic dynamically, using sensors and cameras to collect real-time information and adapt management strategies accordingly. FRONTIER worked on the integration of different transport modes into a unified system, using simulation models to assess the impact of different management strategies on the efficiency and sustainability of the transport system.

Horizon Europe projects (Table 8), on the other hand, are characterised more by a focus on sustainable urban mobility and the development of technologies for automated driving. The ACUMEN (101103808 Agreement)(ACUMEN Consortium, 2026) and AUGMENTED CCAM (101077049 Agreement) projects represented a significant investment in the creation of a carbon-neutral mobility ecosystem and the assessment of the infrastructure necessary for the deployment of Connected, Cooperative and Automated Driving (CCAM) systems. ACUMEN focused on developing simulation models to assess the impact of different sustainable mobility strategies on reducing emissions and improving air quality. AUGMENTED CCAM assessed the physical and digital infrastructure needed to ensure the safety and efficiency of automated driving systems, including the implementation of advanced sensors and communication systems.

The DELPHI (101104263 Agreement) and SYNCHROMODE (101104171 Agreement) projects are focused on traffic prediction and advanced multimodal synchronisation. DELPHI develops predictive solutions to anticipate and better manage traffic flows, using machine learning algorithms to analyse historical data and predict future traffic patterns. SYNCHROMODE aims to optimise the synchronisation of different transport modes by implementing optimisation models to coordinate the schedules of buses, trams, and other vehicles, thereby improving the efficiency and sustainability of the transport system. These projects (Table 8) are essential to improve real-time traffic planning and management.

Table 8 Summary of European Projects

Project	Period	Programme	Agreement	Research Focus
DIT4TRAM https://dit4tram.eu/(DIT4TraM Consortium, 2024)	2021-2024	Horizonte 2020	953783	Digital solutions for traffic management
ORCHESTRA https://orchestra2020.eu/(ORCHESTRA Consortium, 2024)	2021-2024	Horizonte 2020	953618	Multimodal transport optimisation
TANGENT https://tangent-h2020.eu/(TANGENT Consortium, 2024)	2021-2024	Horizonte 2020	955273	Data processing for multimodal traffic
FRONTIER https://www.frontier-project.eu/mtm-cluster(FRONTIER Consortium, 2024)	2021-2024	Horizonte 2020	955317	Multimodal transport management
ACUMEN https://acumen-project.eu/(ACUMEN Consortium, 2026)	2022-2025	Horizon Europe	101103808	Carbon-neutral urban mobility
AUGMENTED CCAM https://augmentedccam.com/(AUGMENTED CCAM, 2025)	2022-2025	Horizon Europe	101077049	Infrastructure for automated driving
DELPHI https://delphi-project.eu/(DELPHI, 2026)	2023-2026	Horizon Europe	101104263	Predictive traffic solutions
SYNCHROMODE https://synchromode.eu/(SYNCHROMODE, 2024)	2023-2026	Horizon Europe	101104171	Synchronisation of transport modes

Multimodal Traffic Management Cluster (MTMC) brings together seven of these projects under a shared vision to advance sustainable and efficient transport. Integration of passenger and freight transport into a single system, working towards integration of sectors and harmonisation of data.

Pilot studies are associated with some of the projects mentioned in table 9.

Table 9 Pilot studies of European projects

Location	Project	Implemented Technology	Impact
Athens, Greece	ACUMEN(ACUMEN Consortium, 2026)	Integrated mobility platform, multimodal data from different sources, calibration with real data (vehicle trajectories and drone data)	Simulations for predicting traffic changes in Athens
Helsinki, Finland		Integration with multimodal traffic management, analytics, and AI tools. Traffic simulation calibrated with last-mile and drone data	Dynamic Traffic Restriction Zones (ZRE) in the West Harbour area of Helsinki
Amsterdam, Netherlands		Virtual pilot. User distribution across transport modes	Bottleneck management at the IJ tunnel
Luxembourg		Shuttle use for goods delivery to and from the local train station. Demonstration of air vehicle readiness for rescheduling and fleet versatility during low passenger demand	Demonstration of technical readiness for airborne freight delivery and multi-use fleet scheduling
Amsterdam, Netherlands	DIT4TraM(DIT4TraM Consortium, 2024)	Massive multiplayer simulation game: human decisions combined with dynamic simulation to determine effects on multimodal networks	Resilient mobility management through cooperation
Athens, Greece		Perimeter control algorithm. Signal learning for coordinated traffic lights at protected network entries	Maximising throughput while minimising queue lengths at network entry points
Glyfada, Greece		Flexible, demand-responsive mobility services	Passenger flow management, fleet management, and optimal vehicle assignment
Barcelona, Spain		Precise modelling and extension for infrastructure-to-vehicle communication	Replacing the current toll collection system with a distributed traffic and mobility management approach

Utrecht, Netherlands		At least eight traffic control facilities and three ramp metering points will coordinate local traffic management	Large-scale, multi-objective, regional multimodal traffic management
Bordeaux, France		Intersections with intelligent signal control where road users negotiate priority	Real-time auction-based prioritisation at intersections

5. Strategies and Emerging Trends

Adaptive traffic control is in a phase of structural redefinition. It is no longer simply about managing traffic flow but about integrating mobility into a systemic logic where efficiency, environmental sustainability, safety and social justice coexist as simultaneous objectives. Smart cities of the 21st century must reinvent ways of understanding and managing mobility through digital platforms, predictive technologies and public-private collaborative networks.

5.1. From Detection to Prediction

Traffic management systems of the future must move from being reactive to proactive. The key to this lies in the ability to capture, process and interpret large volumes of data in real-time. The following tools are highlighted as neccesary for future traffic management systems: ANPR, Intelligent video queue detection, Virtual loops, and data from connected vehicles or test fleets. These tools feed algorithms that measure travel times, leg delays, cumulative congestion, and levels of service. Moving forward, the integration of this data into predictive systems capable of anticipating incidents or changes in demand patterns. These systems feed algorithms that measure travel times, leg delays, cumulative congestion and levels of service. What will be relevant in the coming years will be the integration of this data into predictive systems capable of anticipating incidents or changes in demand patterns.

5.2. Adaptive Decision and Self-Learning Algorithms

Advances in artificial intelligence have made it possible to develop algorithms that not only execute commands but also learn from the system's behaviour. These algorithms, trained on millions of historical data, continuously optimise traffic light management, lane assignment, activation of special measures, and dynamic signalling. Generative AI even makes it possible to automatically draw up contingency plans, prioritise intervention zones, or redesign the management of an entire network following exceptional events.

5.3. Smart Sensors and Edge Computing

The deployment of distributed sensors with edge computing capabilities enables immediate response at critical points without the need to consult a central server. These local nodes process events such as sudden braking, pedestrian presence or weather changes and make immediate adjustments to the environment: change a signal, activate a traffic light, redirect a flow. This increases the resilience of the system and reduces the reaction time to unforeseen situations.

5.4. Digital Twins and Urban Performance Simulation

The digital twin concept allows the real state of the mobility system to be replicated in a virtual environment. By connecting sensors, weather stations, cameras, vehicle GPS, and mobile platform data, it is possible to generate a live simulation of what is happening in the city. This tool facilitates strategic decisions such as reconfigure transport routes, adjust temporary cycling networks, schedule construction works, or simulate weather emergency scenarios.

Digital twins that enable real-time modelling, simulation, testing, and validation. Various analytical, simulation, and AI tools to generate measurable traffic predictions and forecasts.

5.5. Multimodal Integrated Control Platforms

Vehicle traffic can no longer be managed in isolation. MaaS (Mobility as a Service) platforms allow traffic to be controlled in coordination with public transport, logistics, last-mile delivery, and micro-mobility. These platforms use occupancy data, schedules, demand forecasting, and service levels to make coordinated decisions that maximise the efficiency of the overall system.

5.6. Environmental Parameters

The integration of meteorological systems and air quality sensors enables dynamic decision-making to improve road safety and environmental conditions. Actions such as activating temporary restrictions, reducing speed limits, modifying access routes, and prioritising non-motorised transport modes in sensitive areas will become increasingly common.

Traffic management will progressively rely on real-time parameters, including emission levels, ambient temperature, and the risk of extreme events such as storms, fires, or fog. This shift will enhance the ability to respond to hazardous conditions and optimise the flow of traffic in a sustainable manner.

Moreover, regulatory frameworks have accelerated transport decarbonisation by establishing emissions standards, promoting low-carbon technologies, and encouraging behavioural changes among users. These initiatives are fundamental to achieving cleaner, safer, and more resilient mobility systems.

5.7. Collective Intelligence

Citizen participation and transparency are indispensable for automated mobility decisions to be accepted. It is necessary that the population that will be affected accepts and is aware of the decision system(s) in order to prevent bias in prioritisation and ensure equal access.

5.8. Cybersecurity and Operational Reliability

The deployment of communication networks in critical environments such as urban mobility requires special attention to cyber security, operational flexibility and data privacy. Every connected vehicle, every sensor and every cloud platform is a potential attack vector. That is why security policies must include:

- Digital certificates and mutual authentication between devices.
- Encrypted communication protocols
- Segmentation of critical networks
- Real-time monitoring of network traffic
- Threat simulation and contingency planning

In Europe, initiatives such as CCAM Cybersecure and ENISA (European Union Cybersecurity Agency)(Enisa, 2025) standards are developing specific frameworks to ensure that mobility ecosystems are not only efficient, but also reliable.

<u>Implementation challenges</u>

Despite their potential benefits, the implementation of V2X, IoT and 5G solutions faces numerous challenges, including:

- Infrastructure costs: sensors, cameras, 5G network nodes, data platforms and maintenance.
- Institutional coordination: between municipalities, transport operators, telecoms and emergency services.
- Disparate technical standards: hindering interoperability between cities or countries.
- Social reticence: due to concerns about privacy, surveillance or algorithmic control.
- Technology gap: between large cities and rural environments, or between countries with different levels of digitisation.

These challenges require a coordinated strategy, adequate public funding and clear regulatory frameworks. Digital inclusion policies are also needed to ensure that no one is excluded from the benefits of connected mobility.

Over the next decade, these technologies are expected to converge towards some of the following trends:

- Increased integration between V2X and autonomous vehicles
- Reduced private car use in favour of on-demand mobility services
- Increased personalisation of mobility thanks to artificial intelligence
- Participatory algorithmic governance, with transparency and ethics in automation
- Expansion of the use of digital urban twins and traffic simulation at scale

The future of traffic management lies not in sensors and algorithms, but in the ability to build a coordinated, adaptive and people-centred ecosystem.

6. Case Study: Wrong-Way Vehicle Detection System On Motorway A-8 Islares (Cantabria, Spain)

As discussed in sections 3 to 5 of this document, road safety is one of the most important strategic pillars in the design, management, and operation of high-capacity transport infrastructure. The complexity of these networks, their high traffic density, and the coexistence of different types of vehicles (light, heavy, motorcycles, etc.) make it essential to deploy systems capable of anticipating risky situations that could compromise user safety.

Among the most critical scenarios are wrong-way entries onto expressways, a manoeuvre that, although infrequent, has an extremely high potential for harm. This type of event is characterised by a significant speed differential between vehicles travelling in opposite directions, combined with extremely short reaction times for the drivers involved and for system operators. The consequences of such incidents are often fatal, especially when they occur on sections with complex geometry, limited visibility, or proximity to restrictive elements such as tunnels, where manoeuvrability is critically compromised.

In this context, this use case is designed as a proactive risk mitigation measure, designed to automatically, early, and robustly detect the presence of vehicles entering the wrong direction. This is a highly technological intervention that combines advanced artificial vision (edge AI), and immediate action capabilities on the infrastructure, as part of an architecture based on Cooperative Intelligent Transport Systems (C-ITS).

The proposed solution not only responds to a preventive approach but also aligns with European guidelines for the deployment of resilient, sustainable digital infrastructures capable of operating under changing environmental conditions. The system integrates detection, decision-making, and action in an autonomous and energy self-sufficient flow, directly contributing to risk reduction at a particularly conflictive point in the road network.

6.1. Geographical Description of the Study Area

The location selected for the implementation of the system is at kilometre 156 of the Cantabrian Motorway (A-8), one of the main transport arteries in northern Spain (Figure 12). This road carries a significant volume of traffic, with a total average daily traffic (ADT) of 35,145 vehicles, of which 30,542 are light vehicles and 4,603 are heavy vehicles. These statistics reflect the high operational demands on the infrastructure and highlight the need for monitoring systems to enhance safety at critical points in the network.

The section under study is situated near the town of Islares, within the municipality of Castro Urdiales, in Cantabria region, specifically on the access ramp in the ascending direction (towards Bilbao), from the road coming from Santander. This is a junction where multiple risk factors converge (merging traffic, changes in gradient, high-speed approaches, and risk of wrong-way entries), justifying the installation of an intelligent system for detecting and preventing unauthorised access.

Figure 12 Intersection location

From a topographical and geometric point of view, the environment has a complex configuration, characterised by curved transitions with reduced radius, longitudinal slopes, and dense vegetation on the sides, which limits direct visibility. In addition, there is a tunnel in the vicinity of the entry point, which acts as a restrictive element in terms of both visual field and manoeuvrability. This type of geometric layout increases the likelihood of incorrect manoeuvres by disoriented drivers or those with poor visibility (Figure 13).

Figure 13 Study area intersection 156 A8 direction Bilbao

In terms of climate, this area is frequently affected by adverse weather conditions typical of the Cantabrian coast, such as heavy rain, dense fog, and low night-time visibility. These conditions act as aggravating factors in road operations and reduce the effectiveness of passive signalling measures. All of this makes it necessary to deploy ITS solutions capable of operating reliably in a wide range of environmental conditions and allowing the automatic activation of reactive measures in real-time.

Based on previous road risk assessment studies and analysis of black spots on the network, this link has been identified as a strategic location for the installation of automated detection systems for oncoming vehicles. The critical nature of this section is not only due to its geometry or traffic volume, but also to the potential impact of an improper manoeuvre in an environment with access to a high-capacity road. In this sense, the implementation of an intelligent system based on Edge Computing and artificial vision represents a proactive measure of great value for improving road safety.

FUNCTIONAL AND TECHNOLOGICAL ARCHITECTURE OF THE SYSTEM

The system is designed under a distributed vehicle IoT edge paradigm, aimed at ensuring detection latency of less than 500 ms, local operational redundancy, and energy autonomy. It consists of the following functional elements:

- Intelligent visual perception node:
  - 4K resolution camera with back-illuminated CMOS sensor, extended dynamic range (WDR), and HDR backlight compensation system.

  - Embedded processing module based on multi-core ARM architecture with GPU acceleration (Jetson Xavier NX or equivalent).
  - Anti-vibration assembly and IP68 housing.
- Set of inference models by scenario type: YOLO v11 Multi-Backbone Ensemble trained on a mixed synthetic-real dataset (combination of COCO, BDD100K, and own labelled dataset). Specialised models for:
  - Heavy vehicles with different entry angles and projected shadows.
  - Passenger cars in low visibility conditions (<30 lux).
  - Severe weather conditions (fog, heavy rain, night refraction).
- Perimeter computing infrastructure (Edge AI):
  - Ubuntu Core operating system with Docker container environment for model orchestration.
  - Local storage on NVMe SSD with event retention, 48-hour buffer, and incremental retraining capability.
  - Redundant local logging system and time synchronisation via NTP over a secure channel.
- Vehicle-to-infrastructure (V2I) communication platform:
  - Dual-SIM LTE/5G mobile connectivity module with fallback to LoRaWAN for critical notifications.
  - Persistent VPN with AES-256 encryption and embedded intrusion detection system (IDS).
  - MQTT with QoS 2 for guaranteed event delivery, and RESTful API with OpenAPI 3.1 schema for interoperability with existing ITS platforms.
- Remote actuation subsystem:
  - Activation of variable signalling elements: existing high-visibility LED panels with NTCIP protocol.
  - Active beaconing devices with 360° LED modules and automatic light adaptation photocells.
  - Integration with the central traffic control system via SCADA interface.
- Solar power supply system:
  - 550W monocrystalline panels with redundant DC-DC inverters.
  - LiFePO4 battery bank with BMS (Battery Management System) and real-time telemetry.
  - 96-hour autonomy guaranteed with 30% depth of discharge.

Figures 14 and 15 show the operating architecture of the system:

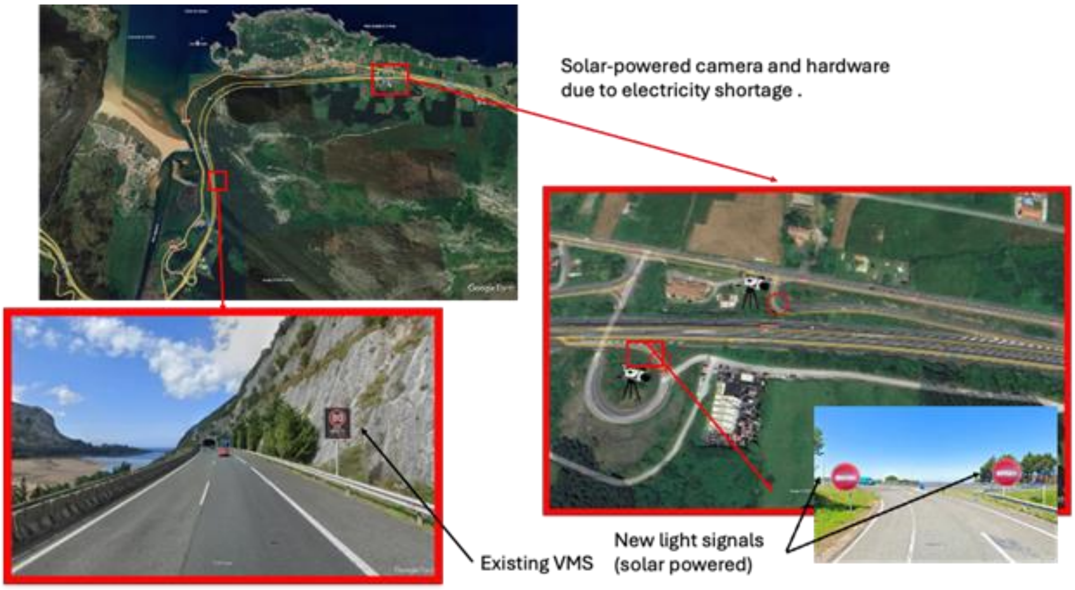

Figure 14 Visual diagram of the solution in situ

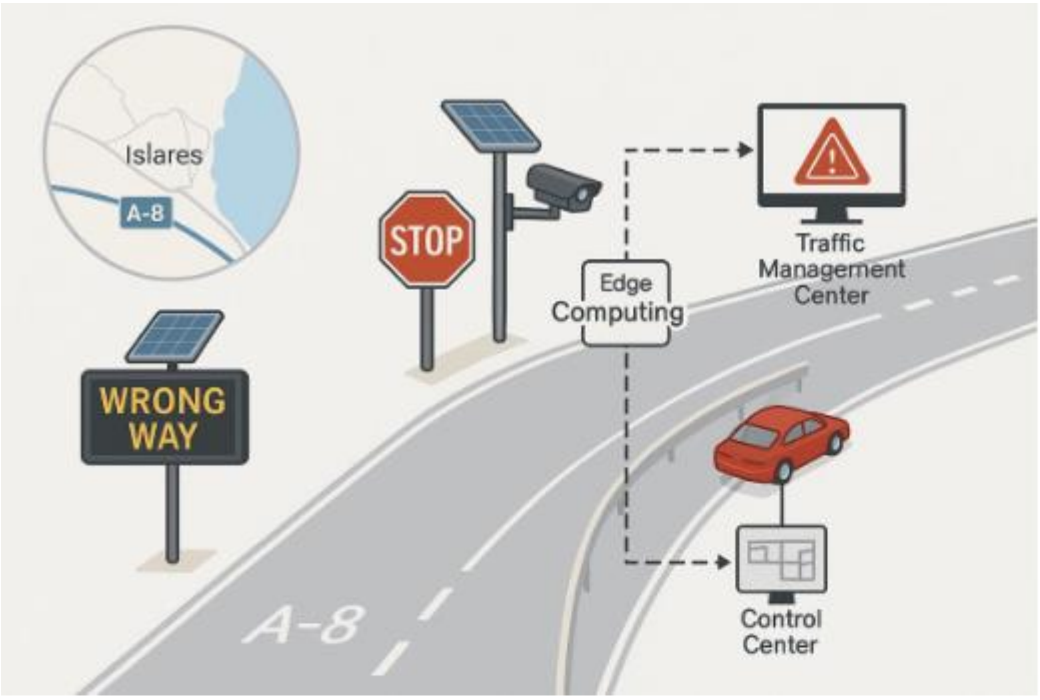

Figure 15 Conceptualisation of the solution

6.2. Operational Flow and Control Logic

The system operates based on a detection-reactivation-control scheme (see Figure 16), with the following logical steps:

1. Continuous perception: The camera detects all vehicles accessing the ramp and extracts movement trajectories using flow optics estimation and neural networks with YOLOv11 models.
2. Classification and validation: Inference is performed on parallel models, and validation is carried out by consensus (ensemble weighting) to minimise false positives.
3. Response activation: In the event of a positive detection, warning signals are activated simultaneously, the event is recorded, and a critical alert is sent via a secure channel.
4. Notification and traceability: Operators receive the alert with metadata, images, vehicle type, and model confidence, and can initiate action protocols.
5. Retrospective analysis: All events are stored for auditing, model retraining, and system KPI evaluation (accuracy, response time, availability, false alarms).

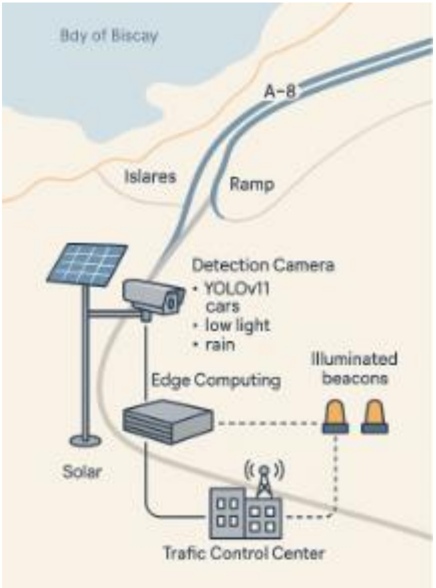

Figure 16 Operational flow

6.3. TRAFFIC SIMULATION AND VALIDATION OF OPERATIONAL STRATEGIES

To support the design and validation of the intelligent wrong-way vehicle detection system, a high-resolution traffic micro-simulation model was developed and specifically calibrated for the operating environment at kilometre 156 of the A-8 motorway. This model has been implemented using Aimsun Next microsimulation software, incorporating real traffic parameters, geometric characteristics of the junction, and conditions representative of the location (Figure 17).

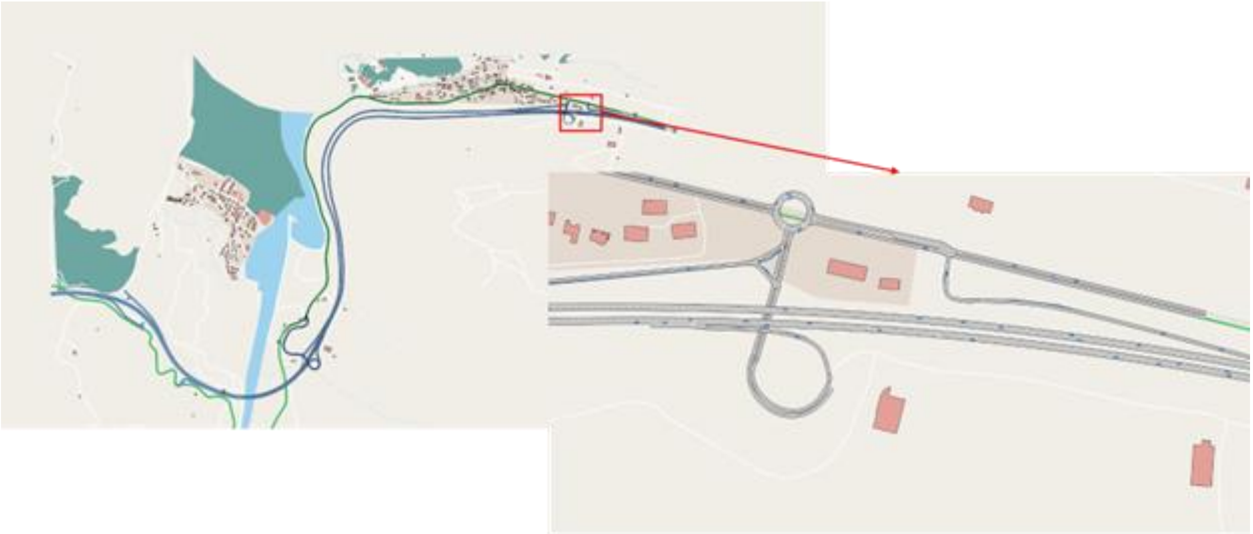

Figure 17 Traffic micro-simulation of the current situation in the study area

Micro-simulation allows the individual behaviour of each vehicle to be accurately represented, including acceleration, deceleration, perception of traffic signals, and reaction times, as well as its interaction with other vehicles under normal and emergency conditions.

6.3.1 Specific objectives of the model

The simulation model has been used with the following technical objectives:

- **Evaluation of the effectiveness of the response times of the system**: determining the critical interval between the entry of the vehicle in the opposite direction and the activation of the warning lights.
- **Simulation of abnormal trajectories**: modelling erroneous traffic patterns, such as wrong-way entries, improper turns on the ramp, or aggressive lane changes, in order to calibrate detection models for extreme scenarios.
- **Optimisation of sensor and actuator locations**: comparing different locations for the camera, Edge node, and STOP signs to maximise the effective detection rate and minimise visual interference or activation latencies.
- **Calculation of optimal advance times**: By analysing vehicle dynamics, the minimum time required for a vehicle to stop safely after receiving a warning has been calculated, which determines the system's action threshold.
- **Estimation of unwarning vehicles:** those that were already in the section between the unauthorised access and the PMV location at the time of detection, performing an analysis for different traffic intensity values. These vehicles will be those with the highest potential risk. Figure 18 shows examples of simulations with a vehicle entering in the opposite direction and the message displayed on the PMV.

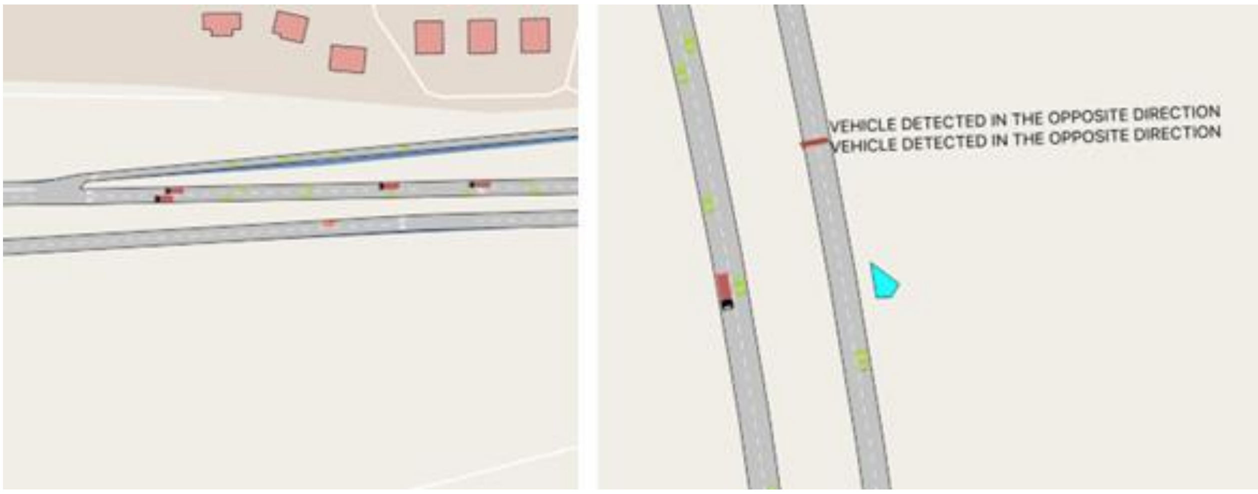

Figure 18 Traffic micro-simulation of the oncoming vehicle detection scenario

6.3.2 Simulated parameters and boundary conditions

The model includes:

- IMD data segmented by time of day and vehicle type.
- Behaviour of light vehicles, heavy vehicles, and motorcycles.
- Driving profiles in low visibility conditions.
- Latency of electronic elements (camera, processing, network, VMS) using the microsimulation software API.
- Assessment of the effective visibility of LED panels according to position and environment.

In addition, different weather scenarios (fog scenarios with reduced speed and visibility, heavy rain, and night-time conditions without artificial lighting) have been simulated to test the detection system's robustness under adverse real-life conditions.

6.4. REAL-SCALE CONTROLLED TESTING OF THE DETECTION SYSTEM

In accordance with the objectives established in Work Package 5 of the CIRCUIT project, a real-scale, controlled test campaign will be carried out to validate the technological solution under multiple operational conditions. This phase constitutes a critical milestone in the system’s development pathway, ensuring that the proposed wrong-way vehicle detection mechanism not only performs correctly in simulation environments but also demonstrates reliability, robustness, and responsiveness when deployed in real-world conditions.

The testing protocol has been designed to replicate a diverse set of traffic and environmental scenarios representative of the operational context at kilometre 156 of the A-8 motorway, including but not limited to:

- Different vehicle classes (light, heavy, and two-wheeled vehicles).
- Variable entry angles and speeds simulating erroneous access manoeuvres.
- Low visibility and adverse weather conditions (dense fog, night-time operation, etc).
- Edge-case scenarios with high latency and sensor occlusion.

These tests will be conducted within a secure and controlled environment, where vehicle movements, detection activations, and system reactions will be monitored with high temporal and spatial resolution. Each scenario will be repeated across multiple runs to statistically validate detection accuracy, false positive/negative rates, actuation latencies, and system resilience.

Objectives of the real-scale testing include:

- Verification of the end-to-end detection-actuation pipeline under operational constraints.
- Validation of interoperability with existing traffic control and signalling systems via SCADA interfaces and VMS protocols.
- Measurement of real-time response latencies, including perception, processing, communication, and warning actuation delays.
- Assessment of environmental adaptability, ensuring functionality across a range of lighting and weather conditions.
- Identification of possible failure modes and mitigation strategies contributed to the refinement of the operational logic and system redundancy measures.

These tests will provide evidence-based confirmation of the system's ability to meet the performance benchmarks defined under WP5, particularly regarding **safety assurance, fail-safe design, and operational continuity** in a heterogeneous traffic context. The insights derived from this campaign will inform the final optimisation loop and pave the way for large-scale deployment and regulatory compliance certification.

7. CONCLUSIONS

This document provides an analysis of real-time traffic management, framed within the evolution towards smarter, more sustainable and resilient mobility systems. Throughout the document, it is shown how new technologies (such as V2X communication, IoT, artificial intelligence, smart sensors and edge computing) are transforming the traditional traffic management paradigm. It is no longer just a matter of responding to incidents or congestion, but of anticipating them using predictive tools that enable dynamic optimisation of road resources, improved road safety and reduced environmental impacts. This transformation also involves designing systems adapted to different territorial levels (urban, interurban, interregional and cross-border), recognising that each has different problems, resources and actors, and requires specific, yet interoperable, technological and organisational solutions. The document emphasises the need to address traffic management, combining smart physical infrastructure with digital platforms capable of integrating multiple data sources (sensors, cameras, connected vehicles, public transport platforms) under common standards such as DATEX II (NAPCORE, 2021)or GTFS (Google and TriMet, 2006). It highlights the growing importance of interoperability between systems, the integration of transport modes (private vehicles, public transport, active mobility, shared vehicles) and citizen participation through traveller information platforms.

In addition, a case study aligned with KER 8 of the project has been developed based on a system for detecting oncoming vehicles on the A-8 motorway near Islares (Cantabria, Spain). This development demonstrates that it is possible to implement solutions based on Edge AI and autonomous systems, capable of operating even in adverse visual conditions, with a solid and energy-self-sufficient technological architecture. These implementations, validated through traffic simulations with microsimulation software and real-world testing, provide evidence of the technical feasibility and impact of these innovations on road safety and network operability.

Finally, the report does not ignore the challenges associated with this digital transition of transport systems. Aspects such as implementation costs, the need for effective institutional coordination between public administrations and private operators, the existence of disparate regulatory frameworks between countries, as well as social concerns related to privacy, cybersecurity and digital equity, must be taken into account. The analysis of the issues in the document leads to the proposal of a strategy based on technical standardisation, European financial support (through programmes such as Horizon Europe or CEF), the design of inclusive mobility policies, and transparent and participatory governance. Thus, real-time traffic management is not only presented as a technological tool, but also as an essential component for achieving the objectives of the European Green Deal and the European Commission's Sustainable and Smart Mobility Strategy, contributing to the development of more liveable, safe and sustainable cities.

8. REFERENCES

ACUMEN Consortium (2026) 'Ai-aided deCision tool for seamless mUltiModal nEtwork and traffic managemeNt (ACUMEN)'. Available at: https://cordis.europa.eu/project/id/101103808.

AUGMENTED CCAM, C. (2025) *Augment and evaluate the physical and digital , 2025*.

C-Roads Spain Consortium (2023) 'C-Roads Spain: Deployment of C-ITS services on Spanish road networks'. Available at: https://www.c-roads.eu/platform.html.

Daniel Urieles López (2023) *Tendencias y soluciones en sistemas de gestión de tráfico inteligente a nivel mundial: una revisión basada en PRISMA*. Universidad cooperativa de Colombia.

DELPHI, C. (2026) *Development of platforms for passenger and freight intermodality*.

DGT (2021) 'DGT 3.0'.

DGT (2022a) *Plan ITS de la DGT*.

DGT (2022b) *Plan ITS de la DGT*.

El Diario Montañés (2024) *El cerebro que dirige el tráfico de Santander*. Available at: https://www.eldiariomontanes.es/santander/cerebro-dirige-trafico-santander-20240317073605-nt.html (Accessed: 29 April 2025).

Dirección General de Tráfico (DGT) (2025) *DGT - Inicio*. Available at: https://www.dgt.es/inicio/ (Accessed: 29 April 2025).

DIT4TraM Consortium (2024) 'Distributed Intelligence and Technology for Traffic and Mobility Management (DIT4TraM)'. Available at: https://cordis.europa.eu/project/id/953783.

Driveris (2023) *¿Qué es un carril reversible, cómo funciona y cómo circular por él? | Driveris*. Available at: https://www.driveris.es/blog/carril-reversible-que-es-como-funciona (Accessed: 29 April 2025).

ElSahly, O. and Abdelfatah, A. (2022) 'A Systematic Review of Traffic Incident Detection Algorithms', *Sustainability (Switzerland)*. MDPI. Available at: https://doi.org/10.3390/su142214859.

EMESA (2023) *¿Cómo Funcionan los Cruces Inteligentes? - Emesa M-30*. Available at: https://www.emesa-m30.es/como-funcionan-los-cruces-inteligentes/ (Accessed: 29 April 2025).

Enisa (2025) *European Union Cybersecurity Agency*.

European Broadcasting Union (1992) 'Eureka 147: Digital Audio Broadcasting (DAB) Standard'. Available at: https://www.ebu.ch/.

European Commission (2021) 'Community Research and Development Information Service (CORDIS)'. Available at: https://cordis.europa.eu/.

European Committee for Standardization CEN (2025) 'CEN/TC 278 - Road Transport and Traffic Telematics'. Available at: https://standards.iteh.ai/catalog/tc/cen/aa876bfe-1d4c-4f9a-8e50-2fcca8393dea/cen-tc-278.

European Union (2010) 'Directive 2010/40/EU on the Deployment of Intelligent Transport Systems in the Field of Road Transport'. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32010L0040.

European Union (2025) *data.europa.eu – the official portal for European data*. Available at: https://data.europa.eu/.

FRONTIER Consortium (2024) 'Next generation traffic management for empowering CAVs integration, cross-stakeholders collaboration and proactive multi-modal network optimization (FRONTIER)'. Available at: https://cordis.europa.eu/project/id/955317.

Gabriel González (2023) *Trànsit propone que las motos puedan ir por el carril bus-VAO*. Available at: https://www.totbarcelona.cat/es/movilidad/transit-motos-entrar-barcelona-carril-buzo-vao-433205/ (Accessed: 29 April 2025).

Garg, T. and Kaur, G. (2023) 'A Systematic Review on Intelligent Transport Systems', *Journal of Computational and Cognitive Engineering*, 2(3), pp. 175–188. Available at: https://doi.org/10.47852/BONVIEWJCCE2202245.

Google and TriMet (2006) 'General Transit Feed Specification (GTFS)'. Available at: https://gtfs.org/.

IMPLY (2025) *Panel de Mensajería Variable Fijo*. Available at: https://imply.com/es/paneles/panel-mensajeria-variable-pmv-fijo/ (Accessed: 29 April 2025).

Indra (2019) 'Transforming Transport: Big Data solutions for mobility and logistics'. Available at: https://transformingtransport.eu/.

Itevelesa (2020) *Qué es el Sistema de Seguridad ADAS y cómo utilizarlo - Red Itevelesa*. Available at: https://www.itevelesa.com/es/blog/que-es-el-sistema-de-seguridad-adas-y-como-utilizarlo (Accessed: 29 April 2025).

Janne Lautanala (2025) 'Traffic and TransportationTechnology Trends'.

Janušová, L. and Čičmancová, S. (2016) 'Improving Safety of Transportation by Using Intelligent Transport Systems', *Procedia Engineering*, 134, pp. 14–22. Available at: https://doi.org/10.1016/J.PROENG.2016.01.031.

Midlands Future Mobility (2021) 'Midlands Future Mobility: Enabling connected and autonomous vehicle trials in real-world environments'. Available at: https://midlandsfuturemobility.co.uk/.

Mkinsi, H. and Lueje, C. (1992) 'ISO/TC 204 . Sistemas de transporte inteligentes'.

Mobileye and Dirección General de Tráfico (2020) 'Autonomous Ready Spain: Piloting advanced driver-assistance systems (ADAS) in urban mobility'. Available at: https://www.dgt.es/.

Moovit App Global LTD (2025) 'Moovit: Urban Mobility App'. Available at: https://moovitapp.com/.

Mumtarin, M. *et al.* (2023) 'Traffic Incident Management Performance Measures: Ranking Agencies on Roadway Clearance Time', *Journal of Transportation Technologies*, 13(03), pp. 353–368. Available at: https://doi.org/10.4236/jtts.2023.133017.

NAPCORE (2021) *DATEX II (European standard for traffic and travel information)*. Available at: https://datex2.eu/ (Accessed: 29 April 2025).

Nuria Herraiz (2024) 'Tecnología para una movilidad inteligente'.

ORCHESTRA Consortium (2024) 'Coordinating and synchronising multimodal transport improving road, rail, water and air transport through increased automation and user involvement (ORCHESTRA)'. Available at: https://cordis.europa.eu/project/id/953618.

Paniagua, E. (2019) 'El complejo puzzle de la movilidad urbana', *El País* [Preprint].

PIARC (2016) *Aplicaciones nuevas y emergentes*.

Sergio Rodriguez (2023) *Autopista*, *Autopista*. Available at: https://www.autopista.es/noticias-motor/funcionan-exactamente-radares-foto-rojo-semaforos-multas-ponen_287174_102.html (Accessed: 29 April 2025).

SYNCHROMODE, C. (2024) *Advanced traffic management solutions for multimodal transportation services, 2024*.

TANGENT Consortium (2024) 'Enhanced Data Processing Techniques for Dynamic Management of Multimodal Traffic (TANGENT)'. Available at: https://cordis.europa.eu/project/id/955273.

Toh, C.K. *et al.* (2020) 'Advances in smart roads for future smart cities', *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 476(2233), p. 20190439. Available at: https://doi.org/10.1098/rspa.2019.0439.

TPEG | EBU Technology & Innovation (no date). Available at: https://tech.ebu.ch/tpeg (Accessed: 29 April 2025).

Wallace, C., Speier, G. and Miles, J. (2016) 'Gestión del Tránsito'.

World Health Organization and Global Road Safety Partnership (2023) 'Speed Management: A Road Safety Manual for Decision-Makers and Practitioners, 2nd Edition'. Geneva: World Health Organization. Available at: https://www.who.int/publications/m/item/speed-management–a-road-safety-manual-for-decision-makers-and-practitioners.-2nd-edition.

WSP (2020) *Creating Safe Road Ecosystems* | *WSP*. Available at: https://www.wsp.com/en-gl/insights/creating-safe-road-ecosystems (Accessed: 29 April 2025).