Deliverable D3.1
Analysis of Technological Advances

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Executive summary

The document presents the results of technological innovation analysis under WP3 "Future scenarios: New technologies, demographics, and patterns of demand" of the project MORE (Multi-modal Optimisation for Road-space in Europe). The main objective of this deliverable is to analyse the trends and challenges of new technologies that impact digital transport infrastructure, and the applications for improving the sustainability of the transport network from an economic, environmental, and social perspective. It addresses innovations in transport modes and operations, sensor and communication technologies, traffic signal control and dynamic traffic management at a network level, innovations in construction and maintenance, and new solutions for parking and loading goods. The technologies and further development and deployment will enhance the digital and physical infrastructure of the MORE corridors.

Besides the main technologies that play a role in the transport system, components of transport planning and policy, traffic management, road users and the interactions between these are reviewed and analysed. The impact of the technological innovations on the VRUs (Venerable Road Users), and the alternative transport modes emerging with the innovations are discussed. Mobility as a Service (MaaS), micro-mobility, and shared mobility are also addressed.

Future mobility applications (based on technical development trends and future mobility scenarios) are addressed. Road (re)designing and (efficient and flexible) usage will consider the dynamic change and uncertainty of progress in the development of advanced technologies. These future scenarios of mobility include a new pattern of services due to the advancement of technology and operation of (C-)ITS ((Cooperative) Intelligent Transport Systems, flexible space management, and data-driven dynamic traffic management at a network level.

In addition, an example of recent research on big traffic data analysis that aimed to compare the reliability of mobility services provided by different control technologies is presented. From the SPaT (Signal Phase and Timing) data analytics, it can be concluded that significant variation in the predictability of a signal plan is observed, both between signal groups of a road intersection as well as between different types of traffic signal control methods. This indicates, that identifying the differences regarding the stability of the control plan would lead to recommending C-ITS applications, such as GLOSA (Green Light Optimal Speed Advisory) and in-vehicle information at signalised intersections.

Technical innovation has stimulated rapid improvements in transport systems. Specifically automated road transport, mobility services, and new modes of travel pledge transform how people and goods move. Moreover, together with the advancement of technologies, the trends in demographics and human behaviour are driving new business models in mobility. However, fundamental solutions for sustainable mobility depend on human behaviour. Furthermore, data privacy and systems security are the main challenges along the evolution path. Therefore, implementation of advanced technologies and new intelligent transport systems needs a proper road space design (both physical and digital infrastructure) and consider the impact of human behavior on the application of technology; and needs to take contextual factors into account – opportunities and risks of new technologies.

Acronyms

Acronyms	Meaning
ADAS	Advanced Driver Assistance System
AI	Artificial Intelligence
AID	Automatic Incident Detection
AV	Automated Vehicle
CAM	Cooperative Awareness Message
CAV	Connected and Automated Vehicle
CCTV	Closed-circuit television
C-ITS	Cooperative Intelligent Transport Systems
COVID-19	Corona Virus Disease 2019
EV	Electric Vehicle
EPAC	Electrically Pedal Assisted Cycle
FCD	Floating Car Data
GDPR	General Data Protection Regulations
GPS	Global Positioning System
GLOSA	Green Light Optimal Speed Advisory
ICT	Information and Communication Technology
IoT	Internet of Things
ITS	Intelligent Transport Systems
KPI	Key Performance Indicator
LED	Light-emitting diode
MaaS	Mobility as a Service
MORE	Multimodal Optimisation of Road-space in Europe
OBU	On-board unit
RSU	Road-side unit
SAE	Society of Automotive Engineers
SPaT	Signal Phase and Timing
TEN-T	Trans-European Transport Network
TMS	Traffic Management System

TSC	Traffic Signal Control
TTC	Time-to-change
TTG	Time-to-green
TTR	Time-to-red
UAV	Unmanned aerial vehicle
UTC	Urban Traffic Control
UTMS	Urban Traffic Management Systems
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VRUs	Vulnerable Road Users

Terms and definitions

Term	Definition
Electric Vehicle	A vehicle that uses one or more electric motors or traction motors for propulsion. It may be powered through a collector system by electricity from off-vehicle sources or may be self-contained with a battery, solar panels, or an electric generator to convert fuel to electricity.
Electrically pedal assisted cycle	A bicycle that adds a small electric boost to the pedal movement. EPACs include pedelecs (speed up to 25 km/h and power up to 250 W) and speed-pedelecs (up to 45 km/h)”
Kerb management	Policies, enforcement, and design strategies relating to methods of regulating, managing or pricing the use of the kerb for activities such as parking, pickup/drop-off or loading goods.
Mobility as a Service	A term describing a move away from the private ownership model of transportation towards platforms that allow mobility to be consumed as a service. It can take the form of a single platform through which users can book multiple different modes, including bike-share, ride-hailing and public transport.
Micro-mobility	A term used to indicate transportation devices that allow for personalised mobility, as opposed to transport services on a schedule or a fixed route. Often used in reference to technologies such as dockless bike-share, e-bikes, and e-scooters.
Ride-hailing	Ride-hailing services are app-based platforms that allow customers to connect to drivers using their personal vehicles to offer taxi-style transportation. Drivers are not technically employed by the ride-hailing company but are classified as self-employed drivers accessing work via the platform. Examples include Uber and Lyft.
Ride share	Often as a part of a ride-hailing service, users may decide to share their ride with other users who are traveling a similar route to receive a reduced fare or other incentives.
Shared mobility	Concept indicating the move away from the private ownership of mobility assets, like cars, towards accessing transportation through shared assets services such as car share and bike share.
Time-to-Change	The time required to change the traffic signal state, in traffic signal planning often called remaining time. TTC (Time-to-Change) can be TTG (Time-to-Green) or TTR Time-to-Red).

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1. Introduction

1.1. Role of technologies in the transport sector

The transport sector is in a period of significant disruption, with new technologies, products, and services fundamentally shifting customer expectations and opportunities. New technological development is essential to achieve the required improvements in connectivity, performance, productivity, and efficiency of the overall transport system [1]. It is now possible to integrate journey planning across modes and to provide live, accurate information that customers can rely on. It is also providing new opportunities that are lowering the barriers for businesses and innovators to enter the transport sector. Digital technologies such as Big Data, IoT, and AI provide great capabilities for developing innovative automated driving functions and mobility solutions for the future [1].

Mobility is undergoing one of the most transformational social, technological and economic shifts of a generation, shaped by three key disruptive forces: connected and automated vehicles, electrification of transport systems, and MaaS. Indicative for that are the requirements of the *Moblity4EU Action Plan; Moblity4EU* is Horizon 2020 project[1]. Low/zero-emission mobility, connected and automated driving, safety and security in transport, mobility planning, and cross-

This document presents new technologies for enhancing digital and physical transport infrastructures of the MORE corridors. It categorises and analyses technical development and deployment of ITS and the applications for improving the sustainability of the transport network, from economic, environmental, and social perspectives. The opportunities and threats arising from the new transport and non-transport technologies and digital eco-systems are also analysed.

1.3. The goal of this deliverable

Deliverable D3.1 mainly provides a comprehensive review and analysis of the following areas: 1) new transport and non-transport technologies; 2) components of traffic systems; 3) mobility services; 4) components of future mobility for optimal use of road-space and its capacity; and 5) examples of the application of some traffic-related technologies.

1.4. Target audience

The target audience of this report comprises MORE partners, transport planners and policymakers, transport companies, and MORE cities. This comprehensive overview of both transport and non-transport technologies will help the cities' policymakers, transport and traffic experts, urban planners and road designers to make road space design and use it more efficiently. Audiences from other sectors and researchers can use the document for the future improvement of transportation.

1.5. Organisation of the document

The document is structured into different chapters; the main relevant technologies and methods are presented in the second chapter; traffic systems and transport planning in the third chapter; mobility services in the fourth chapter; components of future mobility in the fifth chapter; an example of the application of advanced technologies in the sixth chapter; and discussion and conclusions in the seventh chapter.

2. Main relevant technologies and methods

Smart mobility is contained in the domain of ITS, this domain integrates information and communication technology with transport infrastructure, vehicles, and road users. ITS technologies are aimed at improving road network performance and enhancing safety and environmental quality through the application of advanced computing, electronics, and communication systems [2]. ITS technologies are aiming to mitigate or even prevent problems with congestions, pollution, transport efficiency, safety and security of passengers and goods [3]. Smart mobility allows people to get more from their transport network in greater safety and with less impact on the environment [4].

The communication technologies enhance the exchange of data among traffic system components, enabling C-ITS, which promise to reduce traffic congestion, lessen the environmental impact of transport, and significantly reduce the number of traffic accidents. IT enables and transforms elements in transport systems such as vehicles, roads, traffic lights, and message signs, to become intelligent by embedding them with microchips and sensors and empowering them to communicate with each other through wireless technologies [5].

The positioning and control systems are also playing a major role in transport operations and traffic management. Many advanced aspects of ITS are not possible without positioning systems. In the context of ITS, positioning systems measure the location of cars, trucks, buses, and trains. However, positioning systems are never stand-alone, they are always part of a larger system, feeding positioning information into a control system together with other sensor information enabling it to make more accurate and therefore more efficient decisions [2]. Communication technology enables the output of more sensors and their applications in different areas including safety, traffic management, and the environment to be leveraged to achieve smart, sustainable, and intelligent transport systems as well [6].

These technologies are likely to profoundly influence the development of smart mobility. To develop safer, sustainable, cleaner, and efficient intelligent transport systems for both consumers and industry, there will need to be an understanding of the evolution in basic technologies. Considering this, it is increasingly relevant to understand the implication of the development of technology for transport systems. This gives a general picture to develop a comprehensive approach to the planning, design, management, and operation of road-space on MORE corridors. Analysing the status and the future directions in the development of transport and non-transport technology enables the MORE project to provide concepts and tools that are sustainable and flexible. Thus, in this chapter, we present the overview and categorization of the existing and new technologies that play a crucial role in improving the ITS. The current and prospective outlook of technology applications in the transport system is documented.

2.1. Information technology

Information Technology plays a vital role in most of our lives. It offers a range of advantages, it increases efficiency and productivity, sharing and storing of information, dissemination, and communication of data. In particular, ICT has considerable importance for transport systems, as they provide access to travel information, transport control systems, planning tools, opportunities to share transport modes, work at-a-distance, compare transport mode costs, make payments, improve safety, and communicate travel patterns [7].

The role of IT in ITS applications ranges from the basic data management infrastructure to more advanced application systems– including wireless communication and computational technologies. Advances in IT areas such as hardware, software, and communications have created new opportunities for developing a sustainable, intelligent transport system. The advances in IT improve the possibility to detect hazards and provide real-time warning and traffic control actions for motorists to negotiate roadway natural hazards. These warnings include road hazards, like accidents, bad road conditions, and congestion but also roadworks/closures. The improved application of IT in the transport systems will enable a better, safer travelling experience and focus on the main objectives of the ITS, so it is essential to have an insight into the enhancements of IT and its practice.

2.1.1. Data Infrastructure

Traffic Data and information are collected, stored, and processed for traffic flow management and users' information purpose in databases. Faced with the challenge of rising volumes of traffic and transport data - including geographic information and a need for real-time data, traditional databases (e.g., SQL- Structural Query Language, and NoSQL- non-SQL) are shifting their operation to cloud-based data storage and management. Moreover, the integration and management of data from disparate data sources in the context of real-time and historical data analysis require ITS databases that can accommodate the volume, variety, speed, and purpose of data acquisition and processing, which is named Big Data. Consequently, database solutions are shifting from simple infrastructure solutions to developing cloud strategies that provide services such as Software-as-a-Service (SaaS), Infrastructure-as-a-Service (IaaS), and Platform-as-a-service (PaaS) in combination with adaptive security. For example, Microsoft Azure and Amazon web services provide big data and related services.

Using the highly scalable cloud computing technologies providing intelligent real-time data management help to develop advanced and sustainable ICT-based ITS infrastructure to control and manage transport. It also provides condensed and relevant information for transport policymakers and traffic managers in a short time with less effort. For example, MaaS combines transport services from public and private providers, creating a huge amount of data from the users and service providers and therefore requires cloud-based data acquisition and management when the service expands and gets more complex. This data is key to unlocking the users’ needs and the value of the service providers. The impact that IT has had on e-commerce is now trickling down to ITS, leading to additional transport journeys in the urban areas (last-mile transport) which has enormous potential for sustainable urban logistics.

2.1.2. Artificial Intelligence

The advantages of advances in big data and the digital ecosystem would allow the road authorities to make the best use of available road space in time and space. Data analytics uses data mining, machine learning, and AI methods to generate insights that help to improve logistics, predictive maintenance, and inventory management. In the transport system, AI has brought a vast amount of progress in areas such as road transport, railway transport, aviation, shipping, navigation, ports, and logistics. It is expected to perform functions for automation, monitoring, and the workplace include risk management and cybersecurity. AI can help to automate, adapt, and enhance vehicle systems for safety and better driving by reducing the potential for human error. Predictive maintenance of the road and control systems can be based on machine learning outcomes based on real-time data from the systems.

With a rise in big data and computational power, AI has been changing the way of decision-making and giving services. For example, in logistics, the use of AI will lead to a more effective distribution of resources in freight transport. Information on traffic flow would potentially be useful for traffic management and assess the performance of signal controlling systems. In this respect, the use of AI and data mining techniques would be expected to provide relevant information to make decisions and improvements. According to [8], cities with good database infrastructure can use AI applications, particularly machine learning for predicting where and when transport infrastructure can be built, determining effective mobility corridors, and recommending infrastructure projects.

Other AI components such as computer vision and robotics have been used widely in smart mobility. Computer vision in transport and traffic can be used for road infrastructure management and road safety inspection and assessment, and automatic traffic control. Robotic devices for road construction and maintenance have evolved along with the automation of driving. Robotics and intelligence-based functions of goods would appear on the road and streets and change the logistics in the assembly of goods, which can minimize parking and loading time along kerbsides[3].

These days, road transportation sector has evolved to the level where, for instance, vehicles can navigate and move without any human assistance, delivery drones/robots operate in the cities, and traffic management and predictions are based on Big data analytics. AI has been one of the most astounding technological innovations in most areas of road transportation [9]. In several applications, Machine Learning is used for traffic detection and classification, traffic monitoring and management, road authority decision process, traffic patterns prediction [10], and logistic operation. These show that although various components of AI are widely being used for automation, AI is also applicable for traffic data collection and data analytics. AI applications in road transportation have enormous benefits, for example, it decreases labour costs through automation, safety and traffic accidents through automated

[3] https://aethon.com/robotics-future-logistics/ (Accessed on 14 May 2019)

vehicles, and improves the reliability and efficiency of traffic management through predictive analytics. Despite the wide range of benefits of AI in road transportation, the applications need to be validated before the AI-based products are to be deployed on a large scale. Furthermore, the associated reliability and safety issues of the application of AI in transportation are still under question. Generally, AI cannot be used for every challenge and solve all the problems in road transportation, but it can be used for specific purposes. In this regard, there have been developments of several Reinforced Learning (RL) based traffic signal control systems; however, the systems are not deployed on roads because of safety issues.

2.1.3. Internet of Things

Internet of Things refers to the networking of physical objects using embedded sensors, actuators, and other devices that can collect and transmit information about real-time activity in the network. In ITS, these vast connected networks could potentially influence many aspects of our daily driving such as route planning, accident prevention, and safety. It has the potential to transform by profoundly altering how the transport system gathers data and information by bringing together the major technical and business trends of mobility, automation, and data analytics. The data gathered from these devices can then be analysed to provide greater safety, more efficient travel, improved vehicle maintenance, and more strategic traffic management [11].

IoT brings more efficient and less costly transit, that employs networks of sensors, digital cameras, and communication systems to increase system capacity and enhance passenger safety. It also displays real-time road status, lane closures and travel times automatically relayed from sensors and cameras. Moreover, it allows automated vehicles to sense their environment, predict behaviour, communicate with other vehicles and their surroundings, and react instantaneously to traffic and environmental situations.

The IoT is gradually connecting everyone to everything, and new datasets are emerging which would be fused with existing data and be analysed. These data have the potential to solve mobility challenges facing urban areas – including congestion, public safety, climate change, and social equity. To answer questions related to these topics of challenge, cities need to deploy IoT to monitor infrastructure and understand how data can improve mobility. Integrated Big Data analytics encompassing data from IoT sensors, transport infrastructure, and smart assets are a promising way to understand and improve the holistic view of mobility. For instance, Big Data analytics frameworks integrating data from various sources create a single platform that gives a whole new level of insight.

Nevertheless, the growth of IoT in transport also brings an explosion of cybersecurity threats, as the proliferation of sensors and connected devices greatly expands the network attack surface. IoT is presenting challenges for network and data management along with increased security risks. The threats can be addressed by adapting traditional network designs to provide new levels of network intelligence, automation, and security [11]. In this case, AI can help to detect anomalies in real-time and fraud in sensor networks.

2.1.4. Digitalisation

Digital infrastructures are driving forces for the digital economy, the economy that is based on digital technologies including digital communication networks (e.g., Internet, intranets), computer software, and other related information technologies. IT is the driver of digital technology platforms including ITS systems, IoT platforms, and data management platforms, API management platforms such as mobile applications, interfaces, and analytics. These, in turn, affect the business model, payment service, and digital economy as a whole.

When we come to mobility, there is a different definition of digital infrastructure, particularly digital road infrastructure – the digital representation of road environment required by automated driving systems, C-ITS, and advanced road/traffic management systems. To enable increasing autonomy in mobility, a transformation needs to be made from visual perception to digital perception. All the signs and road configurations need to be digitised so that autonomous mobility can use it. This applies to both static and dynamic infrastructure.

Information technology is essential for digital innovation in the transport systems, improving local economic, environmental and social wellbeing, and reducing public expenditure. Digital innovation has the potential to revolutionise the highways system, improving roads, and network management and user experience. For example, digitally enabled highways systems of the future should operate very differently, and its realisation is fundamental [12].

Furthermore, innovative digital-based transport services such as vehicle hailing apps, and electronic ticketing and payments have been improved by the developments in ICT. Transport information systems have seen major advances in recent years, and travellers have profited from a wide range of apps developed to facilitate travel and to make public transport systems more accessible. One of the most important innovations is the integration of different transport modes (e.g., tram, train, subway, bus), with apps informing about the closest departure location, departure time, arrival time, and cost [7]. The review of ICT and transport interrelationships shows that Internet sites, smartphone and tablet applications, as well as social media have gained considerable importance for transport systems, by changing transport behaviour [7].

In recent years, emerging technologies and digitalisation have also been impacting health care services[4] and education, which in turn affect transportation. Remote diagnosis and operations in the health care services, known as telemedicine service, will reduce future transportation[5]. The development in remote diagnosis of patients and data analytics-based health care services will have a positive impact on the demand for transportation. Doctors and medical staff contact the patients via cell phone devices to monitor a patient's condition and control check-ups outside medical facilities. Transportation will also be affected by

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[4] https://theconversation.com/how-drones-can-improve-healthcare-delivery-in-developing-countries-49917 (Accessed on 29 August 2019)
[5] https://mhealthintelligence.com/news/telehealth-companies-team-up-to-deliver-remote-patient-monitoring-to-go (Accessed on 29 August 2019)

digitalisation and web-based education. Many education institutions have started to use web-based distance learning systems to provide flexible education that is independent of time and place. In online learning frameworks, educators and students are separated in distance and communicate with technology (e.g., video, audio, data, simulation, and written text). In this regard, there is a remarkable change in traveling to schools and universities, which would impose a positive impact on the demand for transportation services and parking[6,7].

2.2. Vehicular communication

Wireless technologies have been widely developed in the last years and now are ready to meet the increasing demand for communication services of smart transport systems like high-speed railways, buses, and any other transport systems. Other important technologies are wireless sensors and ad hoc networks for security and monitoring of vehicles and infrastructure. The main application of communications in the transport systems is communications between traffic participants, creating a digital situational awareness to increase safety, reliability but the communication can also be used for improving efficiency and providing passenger services [13].

In modern mobility, intelligent driver assistance, information services, multiple vehicle information sharing, and cooperation require communication technologies that are advanced, secure, and reliable. Communication between entities in the traffic can be a crucial feature to protect life and reduce the number of road accidents. Vehicular communication can be a feature to reduce road traffic fatalities, decrease the level of traffic congestions, enhance traffic efficiency, and save energy. In C-ITS (V2V and V2I systems), the operators, infrastructure, vehicles, drivers and other road users will cooperate and communicate to deliver the most efficient, safe, secure, and comfortable transport [14][[15]. However, the primary challenge is to develop scalable, robust, low-latency and high-throughput communication technologies for safety applications that will significantly enhance the safety and efficiency of the transport. Moreover, there are technological challenges in integrating VRUs into V2X systems. For example, an effective V2P system needs to consider the varying characteristics of different VRUs [16].

Road users send and receive different messages via C-ITS application systems – including RSU and OBU. For example, CAM to create and maintain awareness of each road user, Decentralised Event Notification Message (DENM) to notify road users about a specific events on the roads, SPaT message to describe the current state of signal systems and its phase, *MapData* (MAP) message to relate intersection geometry to movements on roads, In-Vehicle Information (IVI) to inform the road users or the vehicles about current and relevant

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[6] https://www.triplepundit.com/story/2015/4-unsung-environmental-benefits-online-education/35151 (Accessed on 29 August 2019)
[7] https://www.westga.edu/~distance/ojdla/winter144/campbell_campell144.html (Accessed on 29 August 2019)

travel information and road signs, and other messages such as FCD, Road Tolling Message (RTM) and Personal Safety Message (PSM) [14].

2.2.1. Cellular networks

There has been a vast improvement in mobile wireless communication in the last few decades. This improvement consists of several generations, ranging from the first generation (1G) to the fifth generation (5G). The 5G is going to be a new revolution with high speed, high capacity and providing broadcasting of large volumes of data [17] due to lower data rate provided by Global Systems for Mobile communications (GSM), 2G and General Packet Radio Services (GPRS), 2.5G. The evolution of mobile communication systems gains high attention in C-ITS, considering that Universal Mobile Telecommunication System (UMTS) 3G, Long-Term Evolution (LTE) 4G, and 5G technologies offer increasingly improved communication coverage, data rates and bandwidth [14] [15]. Among the cellular network technologies in C-ITS, next to ITS-G5 the two standard protocols under the 3rd Generation Partnership Project (3GPP) are 4G LTE (LTE-V2X) and 5G New Radio (5G-V2X).

The new standard addressing C-V2X communication intends to support V2X applications such as V2V, V2I, and V2P, and Vehicle to network (V2N) if important constraints like coverage and low latency are met as is currently done by ITS-G5. In general, these applications are essential in providing real-time and highly reliable information flows to enable safe, efficient and environmentally healthy transport services and pave the way to connected and automated driving. Cellular technologies can use the standardized V2X message set (e.g., CAM) to improve road safety while making more efficient use of transport networks and infrastructure. Other messages from the set could support platooning, cooperative driving, queue warning, avoiding collisions, hazard ahead warning, speed management, and automated driving [14].

Furthermore, 3GGP provides the concept of advanced V2X service in its Release 16, the evolution of C-V2X towards 5G. In this release, new advanced safety applications for automated driving, such as Ultra-reliable, low latency, high throughput, and communication with Broadcast and Unicast/Multicast are included. The new 5G-V2X technology tested, validated, and is expected to be commercially available in vehicles in a few year-8(X)15( )-4(se)-8(r)7(vi)5(ce

automated

2.2.2. WLAN-VANET

Vehicular network communications are a key enabling technology for ITS services. V2V communication is attracting significant attention because cooperative mobility systems improve mobility and enable a high level of vehicle automation. Wireless vehicular networks operating on the standard Dedicated Short-Range Communications (DSRC), named IEEE802.11p is a key enabling technology for the emerging market of the ITS [14]. The technology of choice for V2X has been IEEE802.11p, which has been standardized, implemented, and thoroughly tested [18], [19].

Wireless Local Area Network Vehicular ad-hoc network (WLAN-VANET) technology with different standards such as IEEE 802.11p, IEEE 1609, and WAVE under Institute of Electrical and Electronics (IEEE); GeoNetworking (GN), and ITS-G5 under European Telecommunications Standards Institute (ETSI) in Europe; and SAE J2735 and WAVE Short-Message Protocol (WSMP) under SAE in North America. These are the standards in vehicular network communication currently in use [14] [19].

WSMP is to support a high priority and time-sensitive communication between entities. This protocol enables ITS applications to control or modify lower-layer parameters (e.g., transmit power). Compared to the WSMP in the WAVE protocol stack, GN is optimized for multi-hop communication with geo-addressing, which provides more technical features in application support, but comes with an increased protocol complexity and overhead. The Wireless Access in Vehicular Environments (WAVE) protocol is the only wireless technology that can potentially meet the extremely short latency requirement for road safety messaging and control. The WAVE system has two devices: OBU enables V2V and RSU enables V2I communications [18].

2.2.3. Broadcasting technologies

Dynamic travel information can be supplied to motorised vehicle drivers through multiple technologies – including roadside units and in-vehicle information systems. In the alternative, Radio Data System-Traffic Message Channel (RDS-TMC) and mobile data radio are among the others. RDS-TMC provides dynamic traffic information to in-vehicle satellite navigation systems. RDS is used for transferring data over Frequency Modulation (FM). TMC is a technology for delivering traffic travel information to motor vehicle drivers, which can be transmitted on Digital Audio Broadcasting or satellite radio in users' languages. DAB is a digital radio standard for broadcasting digital audio radio services in European countries. DAB is generally more efficient in its use of spectrum than FM radio and thus can offer more radio services for the same given bandwidth.

Transport Protocol Experts Group (TPEG) manages a data protocol suite for traffic and travel-related information such as information on road conditions, weather, parking, and delay of public transport. TPEG can be carried over different transmission media such as digital broadcasting or cellular networks.

2.3. Sensor technology

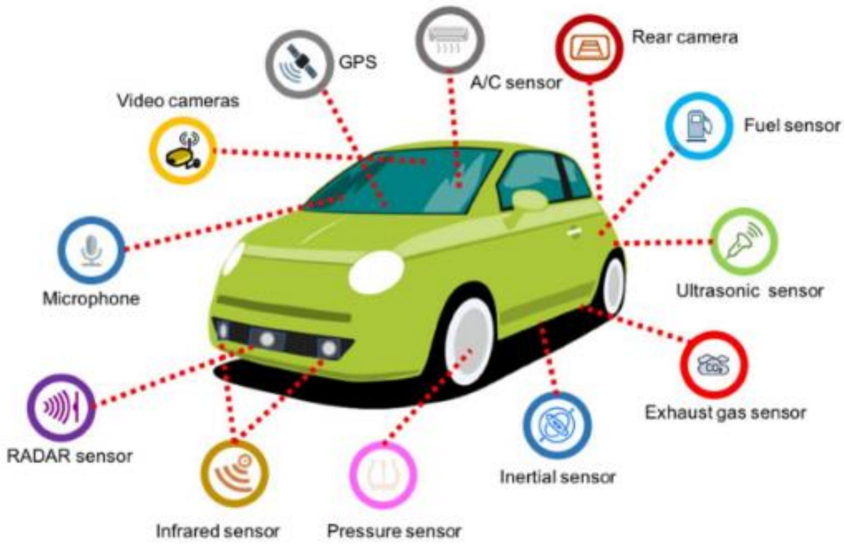
The rise in ICT, development of new in-vehicle sensors, implementation of improved roadside detection like intelligent cameras and new sensors for environmental and traffic conditions provide opportunities to solve serious problems of the modern transport systems including but not limited to traffic congestion, air pollution, and safety. The increased application of sensors in ITS can expedite the enabling of automated vehicles and smart parking. Sensor technology is a vital component used for data collection to support advanced driver assistance systems using V2V and V2I communications [20].

Increased integration of these sensor technologies improves the calibration of the analysis result and integration of multiple sensor sources will result in more stable data collection for the development and evolution of ITS. Integrating sensing technologies such as radar, imaging, and video processing ITS applications results in a cost for procurement and maintenance, but it will help reduce the hierarchical nature of data flow in ICT-based ITS systems by introducing intelligent cooperative sensing for improved traffic efficiency based on fused data from different sources. This would help reduce the traditional data flow from the bottom (e.g., vehicles, sensors, roadside units) to top (central management system), processing and back to the bottom layer (VMS, emergency services). The traditional structure limits the inclusion of new devices and exhibits latency and security issues [21].

2.3.1. In-vehicle systems

There are a few in-vehicle sensors categories; safety, traffic, assistance, environmental, and users' sensors, as portrayed in *Figure 1*. Traffic sensors such as cameras, radars and ultrasonic monitor the traffic conditions in specific zones and gather data that can also be used to improve traffic management if communicated to the traffic management systems [20], [6].

Figure 1: Different types of in-vehicle sensors



Source: Sensor Technologies for intelligent transport systems (source: [6])

2.3.2. Traffic status detection

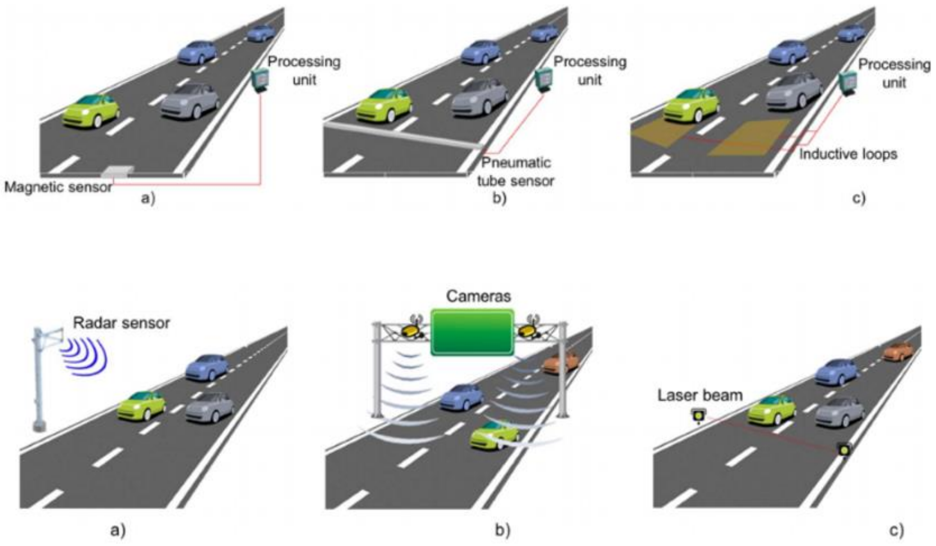
Even though the automotive industry has invested a lot of money to increase vehicle safety, performance and comfort using sensors, traffic data collection using roadside sensors has become one of the main challenges for ITS. The deployment of roadside sensors within the transport network enables new services such as smart parking and environment monitoring, both providing benefits to transportation.

Road-side sensors can be intrusive or non-intrusive sensors; Intrusive sensors are installed in or below pavement surfaces, for example, pneumatic road tube, Inductive Loop Detector (ILD), magnetic and piezoelectric sensors. Non-intrusive sensors are installed at different places on the roads, for example, video cameras, radar, infrared, ultrasonic, acoustic array sensors, road surface condition sensors, and RFID Radio-frequency identification (RFID). One of the most common road network monitoring technologies is CCTV, which has been developed to support Traffic Control Centre (TCC) operations [6] [20].

The piezoelectric sensor is used to detect, count and/or classify vehicles and measure the vehicle's weight and speed. Inductive Loop Detectors (ILD) are used for the detection of vehicle presence, count, speed, and classification. The data generated are recorded in a device at the roadside that can calculate the occupancy of the road, this is the RSU. Radar sensors transmit low-energy microwave radiation that is reflected by all objects within the detection zone. From the reflections, speed and classification can be derived. Radar sensors are very accurate and easy to install.

The video camera can detect vehicles across several lanes and can report vehicle presence and speed. It can classify vehicles by their length. Based on this data flow rate and occupancy can be calculated. In [22], a survey of vision-based traffic monitoring of road intersections presents vehicle detection and tracking scenarios. The review distinguishes and compares roadside and in-vehicle visual systems. The stereo camera provides great accuracy in determining traffic volumes by collecting entry and exit counts in real-time.

Figure 2: In-road sensors



Source: Sensor Technologies for intelligent transport systems [6]

The new development in in-vehicle systems brought a certain level of safety for vehicles and VRUs. For example, the ADAS is a collision warning system with auto brake when detecting pedestrians and cyclists[8]. On the infrastructure side, Pedestrian detectors can signal a traffic light controller which in turn can extend the crossing time for pedestrians already on the crosswalk and shorten the crossing time if pedestrians have already cleared the crosswalk. Detectors can be pressure mats, infrared or microwave detectors mounted on the signal pole, or video cameras using remote sensing software at the waiting and crosswalk areas[9]. More traditional are multiple pedestrian push-button signals control provided by *Ocean state signal*[10].

More recently, the emergence and development of deep-learning provide a new method for visual-based pedestrian recognition technology [23], deep-learning is also used to estimate the intention of pedestrians or cyclists [24]. Significant progress has been achieved over the past decade on vision-based pedestrian detection; however, comparatively little effort has been spent on vision-based cyclist detection. The development in new object detection

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[8] https://www.volvocars.com/au/support/manuals/v60/2018/driver-support/collision-warning-system/collision-warning-system---detection-of-cyclists (Accessed on 28 November 2019)
[9] https://americawalks.org/pedestrian-detecting-traffic-signals/ (Accessed on 22 December 2019)
[10] http://oceanstatesignal.com/products/ (Accessed on 22 December 2019)

methods will make pedestrian and cyclist detection more accurate at greater distances, although most of the deep learning methods-based detection needs a huge number of images data.

2.3.3. Air quality monitoring

Urban air pollution has caused public concern worldwide because it seriously affects human life, including our health, living environment, and economy. In the urban areas due to an increase in the number of industries and vehicles, emission of toxic gases such as Carbon monoxide (CO), Nitrogen Oxide (NO_x), Carbon dioxide (CO_2), and Sulphur dioxide (SO_2), and Particulate matters ($PM_{2.5}$ and PM_{10}) is requiring attention. Due to these adverse effects of air pollution on the population, the development of air quality monitoring systems has been in high demand for both indoor and outdoor applications [25].

Recent developments in sensors and communication technologies have made the deployment of small, portable, and relatively low-cost Monitoring Sensor Units (MSUs) possible. They offer air pollution monitoring at a lower cost than conventional methods, in theory making air pollution monitoring possible in many more locations. Air pollution data captured by the sensor nodes, after obtaining the authorization for the data dissemination, can be made available to the public through various devices/platforms like internet pages, mobile and Web Apps, etc. Air quality measuring sensors provide quality data enhancing the quality and accuracy of the information disseminated to the public. However, the low-cost sensors (micro-sensors) do not provide sufficient resolution yet so there is still room for improvement to develop ultimately real-time and continuous air pollution monitoring at low cost and high energy efficiency.

There are several categories of sensors currently available: electrochemical sensors (used to measure NO_2, SO_2, O_3, NO, CO), metal oxide sensors (used to measure NO_2, O_3, CO), Photoionization detector (used to measure VOC), Optical particulate counter (used measure PM), and optical sensors (used to measure CO, CO_2). The signals from sensors not only depend on the air pollutant of interest but are also affected by a combination of several aspects, such as other interfering compounds, temperature, humidity, pressure, and signal drift (instability of signal). The quality of sensor results, therefore, depends on the resilience of the technology towards influences of all these aspects [26].

A UK firm, *Pollution Solution* has launched a new method of tackling toxic pollution from road vehicles, using pods submerged in the centre of the road. The technology helps authorities to achieve clean, safe and legal air quality during the transition to 100% electric motorised vehicles. The firm said the air that leaves the roadside unit is ‘cleaned to a rate of 99%’, removing particulate matter (PM1 - PM10) along with a range of harmful gases including nitrogen oxides and carbon monoxide. The technology involves a series of partially submerged pods installed in the centre of the carriageway where there can be slow-moving, and/or stationary traffic, creating pollution hotspots. The pods are connected under the surface to pipework which extracts the polluted air into a roadside cleaning unit. In the MORE project, this kind of technology is expected to improve the detection of pollution hotspots across the cities.

2.3.4. Noise measurements

Public authorities are concerned about environmental and human risks related to air pollution, but another part of the environment is noise excessive; noise is also considered to be pollution. It is increasing in the urban areas mainly caused by transport, civil work, manufacturing industries, and other activities. As a result, noise measurement sensors have been emerging. Noise sensors are not only used to record noise levels but to use noise profiles to estimate vehicle types and to detect vehicle speed. For example, a wireless Noise Sensors Network (WNSN) can be used for this purpose. Applications based on WNSN can be integrated into ITS [27].

Although street-level noise is hard to avoid, noise measurement is essential to measure and monitor noise in the public space – including a residential area, hospitals, and green public areas in the neighbourhoods. This helps to characterize the urban soundscape and the role of street-level noise on overall personal noise exposure in an urban setting.

2.3.5. Incident detection and management

Road incidents like congestion and accidents apart from human hardship cause financial losses due to lost travel time and healthcare costs. To prevent this automatic detection, called AID is required. AID computers continuously monitor traffic conditions and detect incidents of risks and occurrence. Most of the existing AID systems use fixed detectors to detect traffic parameters like occupancy, speed, and lane change information. Road networks equipped with a variety of detectors and CCTV cameras provide the basis for improved automated continuous monitoring. The AID system uses this data to anticipate increased incident risk and enables it to deploy mitigation measures.

Traditional ITS systems use automatic incident detection systems with a limited geographical scope. There is a need to extend this scope to be able to have better prediction and mitigation. By adding additional sources, the system becomes prone to delay, inaccuracy, and false alarms during data collection due to short-range communication, weather conditions, road repairing, and driver's driving pattern. Thus, an effective and robust approach for automatic incident detection will be needed [28].

In summary, sensors will play a vital role in ITS in the future. Incident management involves the implementation of a systematic, planned and coordinated set of response actions and deployment of resources to prevent accidents in potentially dangerous situations and to handle incidents safely and quickly. Their usage enables the development of a wide variety of applications for traffic safety, traffic management, and driver assistance. Sensors provide the mechanism for data acquisition related to the vehicular context (such as road conditions, traffic conditions, vehicle conditions) that can be integrated with the current transport systems to mitigate some of the problems that have been faced currently and in the past. The use of analytical and statistical techniques demonstrates the real potential of intensified integration of sensors in ITS [20].

2.4. Positioning systems

In the context of ITS, positioning systems measure the location of cars, trucks, buses, and trains. Examples of positioning systems include Loran, Omega, the GPS, radar, sonar, terrestrial vehicle tracking system and dead reckoning (DR) systems. Satellite-based systems include GPS, Differential GPS, European Geostationary Navigation Overlay System (EGNOS), Russian Global Navigation Satellite Systems (GLONASS), and the Europe GALILEO. Positioning integrated into an application always needs communication, options for terrestrial-based systems are described in IMT-2000. Properties for each application are based on accuracy, cost (infrastructure and in-vehicle cost), and coverage (global-based) [2]. Positioning and communication are the key supporting technologies of traffic safety applications such as collision avoidance and lane-keeping. These technologies are also essential for other ADAS functions – including speed assistance, navigations, and intersection support [29].

2.4.1. Absolute positioning systems

Absolute positioning uses satellite positioning in combination with sensors and map data to provide both absolute position and velocity. Among absolute positioning systems, today's GPS navigation devices are becoming increasingly versatile. Not only do they fulfil the basic functionality of planning a trip, but they can adjust for extreme weather, traffic conditions or even your preferred route.

The widespread availability of GPS devices in recent years has fundamentally altered the way spatial data are collected in transport. The most fundamental application focuses on the efficient movement of people and goods through space and time. This is achieved through in-vehicle navigation systems and fleet tracking and management systems. Furthermore, location information provided by GPS can be used for vehicle travel analysis (e.g., used as an input for estimation of the arrival time of vehicles and electronic payment and charging systems) and traffic monitoring based on probe vehicle data [30].

Today's automated vehicles use a variety of sensors, starting from the global GPS coverage called Global Navigation Satellite Systems (GNSS) but also cameras, laser scanners, ultrasonic, and radar. The connected and automated vehicle applications that are currently being developed depend on these systems to be able to determine the vehicle's absolute position relative to any obstacles. No single technology can provide the required absolute positioning in all situations, and when we combine different technologies, it becomes vital that we understand the integrity of the available information. In this regard, the EU-funded Horizon 2020 *PRoPART* project is developing a software solution for automated vehicles and advanced driver assistance systems, which aims to combine some of Galileo's distinguishing features with other positioning and sensor technologies.

Due to multipath propagation in absolute positions the accuracy of the relative position degrades, which has resulted in a new development in the relative positioning systems. In-car positioning and navigation have supplemented GPS receivers' application. Positioning technologies based on stand-alone GPS receivers are vulnerable and, thus, must be supported by additional information sources to obtain the desired accuracy, integrity, availability, and continuity of service. Safety is another aspect of absolute positioning systems; in this regard, electric transportation firm Bird has announced new ‘smart sidewalk protection’ technology which aims to prevent e-scooters and other micro-mobility devices from being used on footways and footpaths[11]. The technology is a sensor fusion solution that trucks location with centimetres level precession.

Figure 3: Application of absolute positioning systems

2.4.2. Relative positioning systems

Relative positioning determines the position and velocity (speed and direction) of the vehicles relative to the road infrastructure and other objects, by using image sensors and image processing. Active sensors, radar, and lidar measure the reflection of signals, whereas optical and infrared sensors are generally used in an automotive application in a passive sense by measuring the radiation that is naturally transmitted by objects.

In the ITS, preventing collisions requires maintaining a safe distance between vehicles, which is usually derived from radar signals or computed from position information. The change from the physical map to a digital map of any neighbourhood or city in the world was a huge step forward, drivers could better plan routes, pickups, and deliveries, saving valuable time and money.

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[11] https://www.transport-network.co.uk/E-scooter-tech-prevents-footway-riding-in-real-time/ (Accessed on 10 January 2022)

An increasing number of ITS applications rely on the availability of accurate digital maps describing the road network geometry, topology, and traffic-related map attributes such as traffic regulations. An accurate public road, traffic, and travel data are key elements of ITS deployment specially to guarantee the safe operation of vehicles with a certain degree of automation. The availability of intelligent digital maps allows operation with a good knowledge of the environment and relative position. Digital map shows things like kerbs, sidewalks, lane markings, traffic signs, speed limits, buildings, trees, and other features.

The development of a digital map will bring more benefits to the future of digital mapping technology. The future changes in digital map technologies are location pins, in which tracking apps will generate real-time streaming traffic data with concise details that will feed automated vehicles with information such as fairs, festivals, and events[12]. A connection between the physical world and the virtual world such as augmented reality might change the future virtual billboard advertising that relies on new digital mapping technology, and in the near future, we expect developments in ridesharing and parking space information that is based on a real-time context map.

On the other hand, the application of the remote relative positioning sensors to detect road traffic hazards in complex traffic situations is more problematic in terms of response time, accuracy and reliability compared to measuring general traffic flow conditions [29]. More importantly, cooperative relative positioning for ITS has been emerging to solve challenges related precision of relative positions. It improves the relative positioning by sharing the GNSS measurements between vehicles.

2.5. Control technology

Control systems apply automatic control to target control environments without human input. They manage, command, direct or regulate the behaviour of other systems or devices using

Lane-keeping support and adaptive cruise control are the most recently developed applications for in-vehicle control systems. These systems are expected to integrate with information systems and communication technology to cooperate with the surrounding traffic to improve driving comfort as well as safety [31]. The potential benefits of connected vehicles are likely to be realised as part of a C-ITS, where real-time communication data is exchanged between connected vehicles, control centres, infrastructure, personal devices, and cloud-based storage. Such data sharing could lead to increased safety, more efficient transport, and better inter-modal transport links.

With the development of vehicle control systems and communication technologies that can process information and control vehicles safely, networked real-time vehicle control is one of the applications for the transition to fully automated vehicles. Vehicular automation ranges from level zero without automation to level 5 where the vehicle can complete travel autonomously in any environmental conditions. According to the *EC intelligent Car Flagship Initiative*, the automation level includes plenty of uses such as adaptive cruise control, lane departure warning system, automatic parking, automatic night vision, and advanced automatic collision notification.

2.5.2. Traffic signal control

Broadly, traffic control systems comprise UTC systems and motorway control systems. There have been significant advances in vehicle detection and communications technologies that have enabled the capabilities of UTC systems. Consequently, there have been a series of changes, from early (fixed time) signal plans to modern policy-based and demand response systems. However, fixed time control systems are still in operation in many cities where modern traffic infrastructure is limited.

There are many different UTC systems in operation around the world that use different traffic control methods. Based on control methods, UTC systems are defined into different generations[13]. The first-generation systems were the fixed time systems, which consisted mainly of timing plans that were developed from off-line analysis programs and stored in computer memory, for example, Traffic Network Study Tool (TRANSYT). The first-and-a-half generation is a hybrid, which automated the timing plan development process and detects when pre-calculated timing plans should be modified. Plan selection systems, plan generation systems and local adaptation are included in this generation. The second-generation systems involved real-time production and implementation of plans through online techniques based on detectors data, for example, Split, Cycle, and Offset optimisation Technique (SCOOT). The third generation implements and evaluates a fully traffic responsive, online control system. In this case, signal control systems must be changed continuously in response to real-time measures of traffic variables. Examples from this generation are Urban Traffic Optimisation by Integrated Automation (UTOPIA) and

[13] http://www.its.leeds.ac.uk/projects/konsult/private/level2/instruments/instrument014/l2_014a.htm (Accessed on 4 December 2019)

Optimisation Policies for Adaptive Control (OPAC). The detail of each traffic control system is discussed in *Section 3.5.2*.

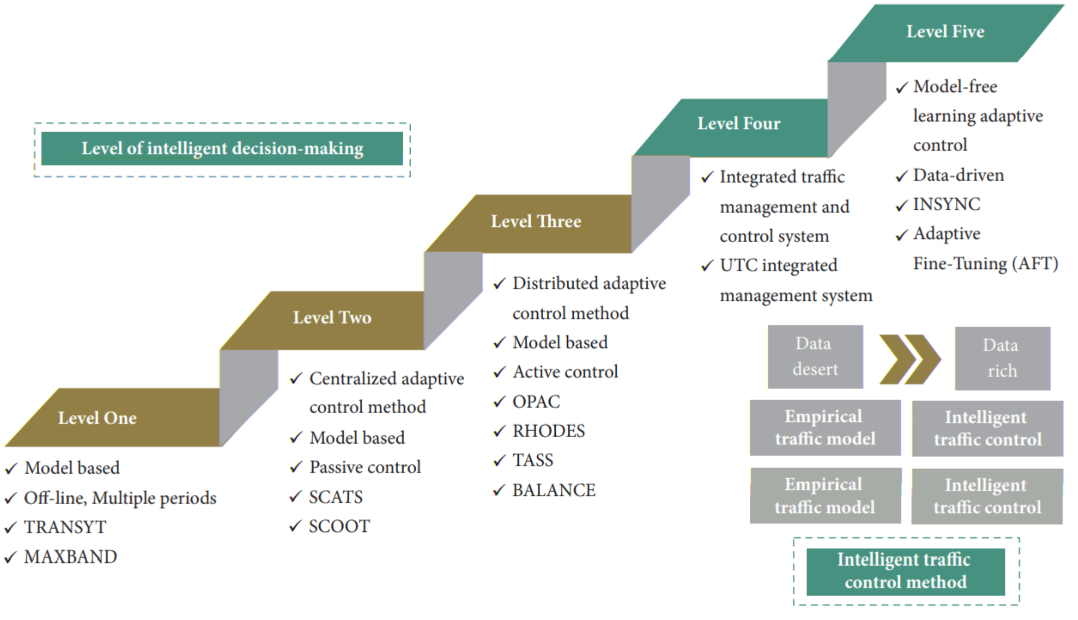
Similarly, [32] categorised the development of urban traffic self-adaptive control systems into five levels, as presented in *Figure 4*. More commonly, traffic signal control methods can be categorised as follows [33]:

- Fixed time control method – this is often used to minimise network vehicle delay. The signal plans are calculated based on average flow and include a margin to cope with cycle-by-cycle demand fluctuations, to prevent queues from forming. When average demand fluctuates by the time of the day, multiple fixed-time plans can be selected at different times of the day.
- Semi-fixed time control method – based on fixed time control plans, but the switching moment can occur between the configured minimum and maximum time.
- Actuated control method – based on sensors detecting whether traffic is present or not. Stop-line detection is used to check the demand at a signal group and gap detection for extension of green time beyond the minimum duration. Apart from the costs of sensors maintenance, optimisation of signal plans requires much less updating.
- Adaptive control method – based on the approach of traffics towards the intersection. Most of the modern traffic control and management systems are using adaptive signal control algorithms where signal timing is adjusted in real-time to accommodate detected changes in traffic patterns.
- Enhanced adaptive control method – is an adaptive control method that extends a configurable cost, adding an element that prevents the optimiser to change the planning frequently or by large deviation.

Traditional signal control optimization problems rely on some basic assumptions about the traffic model to make optimization problems tractable. One of the assumptions is traffic flow is uniform during a certain period and at a constant rate. Nonetheless, as traffic condition is affected by many factors, traffic models cannot fully describe the reality. Learning-based traffic control algorithms have recently been explored as an alternative to existing traffic control logic. In the past few years, research about the application of AI, particularly deep Reinforcement learning (RL) for traffic signal control has appeared widely. RL methods can directly learn from the trial-and-error of the observed data without making unrealistic assumptions about the traffic model. Reinforcement learning is a type of machine learning for solving sequential decision-making problems. It explores and exploits different state-action pairs so that the highest possible rewards are achieved and accumulated over time for system performance enhancement.

Traffic control on arterial roads works based on a timing cycle that is broken into “phases”: North/South and East/West. Examples of modern controllers are Advanced Traffic Controller (ATC), and Microprocessor Optimised Vehicle Actuation (MOVA). Motorway control systems, include Ramp metering (to control the rate of traffic entering a motorway), Variable Speed Limits (VSL) to optimize traffic flow, Dynamic Route Guidance (DRG), Variable Message Sign (VMS), Dynamic Lane control, and hard-shoulder running [34].

Figure 4: Urban Traffic self-adaptive control system development process



Source: A Review of the Self-Adaptive Traffic Signal Control System Based on Future Traffic Environment: Review Article [32]

2.6. Civil engineering and material technology

With rising globalisation, roads have become a very vital infrastructure in enabling the transfer of freight as well as people, making a better and sustainable development of roads very important. Without modern technologies in construction, the number of infrastructures caused by traffic jams would have been much higher than the current level. Moreover, there is high government spending on road construction and maintenance, so there is also a need for the use of innovation to find methods that will be cost-effective. Innovation can be used for better materials for road construction, for example, solar roads, eco-friendly roads, recycled materials, foamed bitumen, etc[14] [35].

Sustainable Drainage Systems (SUDS) are a collection of water management practices that aim to align modern drainage systems with natural water processes. The primary goal of SUDS is to switch from a pipe-engineered system to practices and systems that use and enhance natural processes, i.e., infiltration, evapotranspiration, filtration, and re-use. It improves the sustainability of the effect human development has had or may have on the natural water cycle particularly on surface runoff and water pollution trends.

The fusion of construction technology with other technologies such as IT and automation has led to a new construction system based on prefabricated, automated, and computer

[14] https://highways.today/2018/12/15/road-innovations-future/ (Accessed on 20 January 2020)

integrated development that is key in modern road construction. Innovation concerning road construction technology including noise-reducing asphalt (fine-graded surfaces, open-graded friction courses, rubberized asphalt, and stone-matrix asphalt), computer modelling in road construction, Computer-Aided Design Software, dust suppression, porous pavement with more rock and less oil, plastic roads, dynamic paint, anti-icing roads, wind-powered lights for roads, solar roads, piezoelectric roads, and intelligent network highways[14] [35].

Moreover, innovative construction techniques are being developed and used across the manufacturing and building environmental sectors. Self-healing materials for road surfaces, for example, are currently being trialled which can repair cracks in the pavement. 3D metal printing facilities, producing on-demand replacement components, are now in use by infrastructure operators to reduce asset interruption [36]. The other development is the use and application of nanotechnology in transportation. Nano-engineered materials in automotive products include high-power rechargeable battery systems; thermoelectric materials for temperature control; tires with lower rolling resistance; high-efficiency/low-cost sensors and electronics; thin-film smart solar panels; and fuel additives for cleaner exhaust and extended range are among the main applications. Nanotechnology offers the promise of developing multifunctional materials that will contribute to building and maintaining lighter, safer, smarter, and more efficient vehicles.

The impact of 3D printing is also promising in the automotive industry as well as in construction. In the automotive industry, 3D printing plays the role of manufacturing components of a car. In road construction, we see 3D-printed concrete bridges. The application of 3D printing to fabricate construction components and architectural design is also in development.

2.6.1. Materials science

Materials science has underpinned many of the technological leaps in the last 50 years and this shows no sign of abating. Smart materials, which are reactive to external stimuli and provide enhanced resilience and new capabilities, and lightweight composite materials which exhibit improved strength to weight ratio and are likely to be commonplace across a range of industries. Energy-generating pavements, using solar or kinetic energy, are also being investigated. Self-healing concrete or asphalt, for example, could have mass relevance in reducing the expenditure on the renewal and maintenance of our assets [36].

Although there has been advanced progress in road construction, maintenance of the existing roads impacts the traffic flows. The road of the future is expected to use new surface materials, dynamic paints, anti-icing surfaces, and solar energy production. Material science would improve the construction and maintenance of the roads. Most of the current roads are made from asphalt concrete and a composition of bitumen and mineral aggregate. The road of the future will be based on environmentally-friendly organic materials including piezoelectric capabilities to generate energy from the vibrations that vehicles generate and they will be equipped with electric road systems that charge electric vehicles while they drive.

Figure 5: Materials for road construction a) Plastic-road, b) porous paving materials

a. b.

Source: a) www.plasticroad.eu[15], b) www.urbangreenbluegrids.com (Accessed on 20 August 2019)

Recently plastic-road and porous pavement are also becoming a sustainable alternative to traditional paved and asphalt roads. For example, the Netherlands builds the first plastic-road, which will bring plastic waste back into the chain, reducing the environmental impacts of building and maintaining a road. Plastic-road is expected to be 70% faster to install than traditional road surfaces, last 3 times longer than traditional paved roads, and will take only half the construction cost[15]. This sort of road construction is not a far-future scenario. The long-lasting road surface has been in development with new surfacing materials, for example, self-healing roads. Self-healing roads come with built-in crack healing, which is less thick than normal pavements. The benefits of smart asphalt – including self-repairing asphalt are to minimise repair (or replacement) costs, improve durability, and therefore less traffic hindrance[16]. In the Netherlands, self-healing asphalt has been tested on different roads, and studies from this pavement suggest that the life of the asphalt can be doubled[17].

2.6.2. Road maintenance

Our network has become smart, with maintenance driven by data-rich detection of emerging issues before they would normally have been identified. This is achieved through a mixture of advanced analytics, based on better asset data, and smart infrastructure which can even make decisions for itself. A due exponential increase in the amount of sensor data and IoT, predictive maintenance is a promising application in asset management and road maintenance. The major technologies enabling predictive maintenance are machine learning and predictive analytics. Data from other sensors - including temperature, humidity, and wind speed are integrated with data from the road to predict the future failure/crack of the road surface or its component. This could help road managers to make a convenient schedule for

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[15] www.plasticroad.eu (Accessed on 26 August 2019)
[16] https://www.buildsoft.com.au/blog/self-healing-asphalt-and-the-future-of-smart-roadways (Accessed on 26 June 2019)
[17] https://interestingengineering.com/self-healing-roads-last-80-years (Accessed on 26 June 2019)

road maintenance based on data than the traditional preventive maintenance. Several innovations have emerged for road maintenance. For example, the UK government put millions of Pounds for pothole repair and road maintenance in 2018 to 2019 financial year to make technological trails on a real-world test of new road surface and technologies including plastic roads that could stop potholes from forming [37].

Weigh-in motion technology is aimed at overweight vehicle reduction, innovative use of truck weighing technology is growing as strategies aimed at reducing numbers of overweight vehicles gather momentum. For example, Transport Scotland has updated its site selection criteria for safety cameras and introduced advanced weigh-in-motion systems to detect overloaded Lorries. Overloaded Lorries have an exponential contribution to road wear and are causing increased road maintenance costs. Overload also raises the centre of gravity of a lorry that making it more susceptible to tipping over in curves, and the brakes are also more strained in an overloaded situation with the risk of failing and causing road accidents.

There has been also a huge investment in the way of maintenance of underground water pipes which usually cause disruption and congestions on the roads in case of failure. Scientists from British universities are to develop 1cm-long robotic devices that use sensors and navigation systems to find and mend cracks in the pipes network to help cut roadworks [38].

Moreover, the advances in trenchless technologies enable underground construction and repair of utilities like water, gas pipes, electric or telecommunication cables without disruption at the surface. Trenchless technology is a type of subsurface construction work that requires few trenches or no continuous trenches. It is capable of being used for a new installation, replacement, or rehabilitation of existing underground infrastructure within a minimal disruption to surface traffic, business, and other activities. The most popular trenchless technology methods are Horizontal Direction Drilling (HDD), Microtunneling (MT), Horizontal Auger Boring (HAB), Pipe Ramming (PR), and Pipe Jacking (PJ)[18].

2.7. Other technologies

2.7.1. Blockchain

A blockchain is secure and enables more efficient and cost-saving business operations for transport and logistics companies. The idea is to keep track of the load but linking that to ITS allows you to manage the arrival of container trucks at a terminal for example. In transportation, blockchain addresses for instance the efficiency of administration and tracking issues, improve security, trust in data, logistic management, and financial management; however, it is not needed for most use cases. More broadly, it has been researched that blockchain can be used to address the issues of privacy, security, and data ownership that

[18] https://ideas.stantec.com/blog/trenchless-technologies-five-methods-for-non-disruptive-utility-installation (Accessed on 26 August 2019)

come to the application of CAVs [39], [40]. Integration of blockchain technology to the CAVs would play a substantial role to promote public trust in CAVs [41]. CAVs systems may not adequately protect against malicious user interference, leading to numerous accidents that may result in the loss of life. Blockchains technology aimed to alleviate those problems, though CAVs are still not fully utilised in practice. For example, blockchains can be used for transactions between drivers willing to share data with the city management for better traffic management. The introduction of incentives to drivers who are willing to share travel data would be possible with a Blockchain that would allow keeping a complete track of all transactions and interactions [42].

2.7.2. 3D printing

3D printing is an additive technology used for making three-dimensional solid objects up in layers from a digital file without the need for a mould or cutting tool. 3D printing can be applied to all sorts of fields such as education, medicine, manufacturing, construction, and design. The effect of 3D printing on smart mobility is likely to improve logistics and reduce transport demands. The key opportunities of 3D printing, reducing transport costs and time by creating products closer to the point of use and providing new business models like on-demand spare parts printing and delivery. In the future, 3D printing is expected to end-of-runways services, creates more decentralise and on-demand manufacturing, and 3D printing shops for businesses and consumers [43]. However, the delay in the adaptation of this technology and regulatory certification and liability aspects of using 3D printed parts will be a key challenge.

3. Traffic systems and transport planning

3.1. Road infrastructure

The major activities for automated vehicles are focused on in-vehicle with less attention for the need for advances on the road infrastructure side. This will impact the coexistence of automated and conventional vehicles. New and existing infrastructure elements need to be designed and adapted to allow the current infrastructure to address future traffic scenarios in a flexible, fast and cost-effective way. Investigation of deployment, operation, and maintenance of the physical and digital infrastructures for connected and automated driving, and transport will add value to the design and development of a comprehensive solution for transport problems [44].

The introduction of automated driving systems on the road requires new arrangements and modes of operation of infrastructure. Building new roads is a costly procedure, so there is a need for intelligent and adaptable interventions in the road infrastructure that considers innovative vehicle developments and unforeseeable human needs. This should be able to cope efficiently with the new safety challenges emerging from the introduction of automated vehicles and the diverse needs of all traffic participants.

In the long run, road infrastructure can support and guide automated vehicles by using physical-digital elements. It is necessary to invest in physical infrastructure to support quality and capacity, but at the same time investing in the digital equivalent of the existing infrastructure is also necessary to be able to support automated driving. New developments should be hybrid, a combination of both. An example of that is the EC funded H2020 *INFRAMIX* project. It is aimed at designing, upgrading, adapting and testing both physical and digital elements of the road infrastructure, ensuring uninterrupted, predictable, safe and efficient traffic. The project focuses on high-value traffic scenarios: dynamic lane assignment to automated driving, roadwork zones, and bottlenecks (on-ramps, off-ramps, lane drops, tunnels, sags).

In general, smart infrastructure, increases efficiency, capacity, and resilience for existing and new assets enhance service provision and a better understanding of asset performance, allowing new investments to be optimized and delivered for the best value [36]. There are open issues however related to the deployment, operation, and maintenance of the physical and digital infrastructures for connected and automated driving and transport. Among others, infrastructure maintenance, security, economic feasibility, business models in different operating environments. In the future, the adaptation of physical infrastructure and its link with the digital infrastructure is becoming a key issue for the deployment of connected and automated vehicles [45]. Furthermore, the role and responsibility of multiple stakeholders in deployment scenarios and time plans need to be agreed upon by the stakeholders from the supply and demand sides of infrastructure.

3.1.1. Physical road infrastructure

The physical road infrastructures include both roads and roadside facilitate, junctions, bridges, traffic signals, and lamp posts. The physical road-side elements like communication units, sensors, traffic controls, CCTV, parking areas (e.g., bicycle racks) and VMS are included in physical infrastructure. The design and visual display of this infrastructure are expected to encompass the capabilities supporting conventional and automated vehicles and the cognitive abilities of human drivers and road users. The alternatives of the physical infrastructure such as extensive use of smartphones for in-vehicle visual and electronic signalling and guidance are investigated. There have been ideas to increase road capacity without changing the physical infrastructure through making adjustments on parking, dynamic road tolling and reallocating road lanes to occupancy, vehicle size, and vehicles capable of platooning.

Redesign and improvement of road infrastructure are expected to increase safety and road efficiency. It reduces road traffic injuries and fatalities and lowers emissions. Road design that is based on safety and focuses on promoting walking and cycling is needed. Regarding the structural design of flexible pavement, bitumen has been widely used in the construction of flexible pavements for a long time. It is the most convenient and simple type of construction. However, due to weather conditions, the performance of conventional bituminous pavement may not be considered satisfactory. Recently, many investigations have demonstrated that bitumen properties (e.g., viscoelasticity and temperature susceptibility) can be improved using an additive or a chemical reaction modification. For example, polymer-modified bitumens (PMBs), which have improved functional properties include permanent deformation, fatigue, and low-temperature cracking. Other pavements that are common for the structural construction of roads are rigid pavement (concrete), and semi-rigid pavements.

Physical infrastructure design and construction in terms of accessibility has focused on the street space that can be used continuously without any difficulty and the assistance of another person. The design process of roads and intersections must take into consideration the needs of elderly and handicapped people. An excellent example is the preferred height difference between the kerb and the street. People with wheelchairs and pedestrians prefer dropped kerbs to cross the road safely and comfortably [46].

One of the components to be considered during the design and construction of infrastructure is a dynamic bus lane road marking. Dedicated bus lanes and bus streets have, in recent years, become common measures for prioritisation of public transport. By ensuring free paths along routes, they increase the average speed and travel time reliability of buses. However, a major drawback is that the total traffic capacity of the road decreases. Hence, dynamic bus lanes can be utilised. Dynamic bus lanes are only dedicated to buses when and where the buses need them, and otherwise are open for all vehicles to use. A bus lane instead of a regular lane on an intersection reduces capacity. Therefore, cities have many short patches of bus lanes that end slightly upstream of intersections for the bus to overtake part of a queue while not reducing capacity. The outer lane could also be allocated as a loading bay. Depending on the cycle time and green phase length, the length of loading bays and bus lanes could be made dynamic. Besides, the electrification of road infrastructure will meet the challenges of electric vehicles. Infrastructure could be electrified to facilitate fast/ultra-fasting charging in public places.

On the other hand, there have been many experiments undertaken in the pursuit of the vision of “streets for people” instead of “streets for traffic”. In [47], extensive literature reviews on city streets in terms of re-marking of streets, the re-purposing of car parking, and the repurposing of sections or entire streets have been highlighted. The literature details significant positive impacts on physical activity, a shift of mobility away from the car and towards walking and cycling, public transport, increased safety, enhanced social interactions and social capital, and at least the absence of negative impacts on local business.

3.1.2. Digital road infrastructure

Digital road infrastructure can be both a visual and an electronic signal; a static and dynamic digital representation of the physical world with which vehicles will interact to operate. The role of the digital infrastructure includes providing accurate map data, enabling high relative position accuracy, and providing dynamic information around the vehicle. Two of the basic aspects in this area are: (1) the High Definition (HD) digital maps and the accurate localisation (lane-level accuracy), (2) the traffic infrastructure positioning (e.g., satellite position of lane markings, traffic signs, speed limits, info from roadside through VMS signs. HD digital maps are particularly for AVs, which have extremely high precision at a centimetre level. Even though digital maps are widely available today, there are legal issues to be detailed when coming to HD digital maps, for example, where someone is allowed or not.

Sensors and detectors embedded in infrastructure can send a signal or digital data to vehicles. For cooperative ITS applications digital map and traffic information need to be communicated with low latency, that is, cooperative awareness (objects not visible to a driver) and dynamic map data in less than one second, and semi-dynamic information related to congestion, weather, and accident in less than a minute. Communication networks such as DSRC, WAVE, Bluetooth, and emerging 5G networks are enhancing the transition of digital information for V2X in C-ITS, these transmit data from and to road-side units or in vehicle-ITS applications. Vehicles and infrastructure equipped with C-ITS can, for example, communicate a warning to each other in a digital form.

In the future, the digital infrastructure that integrates aspects of low latency communication and cloud computing will fundamentally change the ICT-based road infrastructures [44]. Digital infrastructure by C-ITS - including mobile and nomadic devices will impact next-generation ITS. For automated driving, digital road infrastructure can be understood as the integration of multiple geo-located information layers containing static information (e.g. topological data, road facilities), semi-static information (e.g. traffic regulations, road works, and weather forecast), semi-dynamic information (e.g. surrounding vehicles, pedestrians, timing of traffic signals), and dynamic driving recommendation information (e.g. lane change, distance gap) [45].

For the fast deployment of digital infrastructure, especially in combination with automation in the road, accurate data/position, data integration, reliability and support levels of automated driving, liability, roles of static and dynamic data, privacy, roles for national governments, standards (e.g. interface standard), and map updates need to be identified [44]. On the other hand, the digital infrastructure must be reliable and clear governance must be in place for data sourcing, processing, and maintenance. The digital infrastructure will need to be maintained which requires close cooperation between the public authorities and road operators managing physical infrastructure.

In-vehicle route guidance systems have seen great development in recent years. They have become an important tool in alleviating congestion in the urban transportation network. As a result of the advantages associated with navigation techniques and popularized digital maps, in-vehicle guidance systems are both economical and useful. In the future, not all vehicles will be automated and can be reached with special messages. When human drivers are still present on the road they must be properly informed about zones as well to ensure safety. While this is a solution that is already widespread in navigation systems, the TM2.0 framework can still offer improvements by proving extra information to navigation system providers to enhance their route advice. For example, they cannot predict future traffic management measures that may change road capacity. TM2.0 also envisions a coordinating role for the road authorities in exceptional situations where the user-centred functionality of personal navigation devices may conflict with societal objectives.

3.1.3. Advances in variable message signs

Figure 6: Some of the feature VMS products

Source: Messagemaker[19]

Variable message signs are a proven tool in traffic management, but the role is increasingly replaced by personal navigation systems with real-time traffic info. Still, there are challenges high potential for managing route choice, especially for vehicles without a navigation system. It also provides information related to incident detection across the network.

LED-based high-resolution signs have much greater visibility and possibilities than traditional traffic signs and can be applied for parking guidance, route guidance, and roadworks warnings. For example, Lane Control Sign of the Cross Arrow types are variable message signs which switch to a red cross to indicate a closed lane and show a green arrow to indicate the open lane (s); Mobile Variable Message Sign (VMS) is a flexible way to communicate messages, alerts, and warnings such as temporary road works, travel time information, and events control; LED Message Displays; Vehicle Activated Speed (VAS) advice is highly visible sign suitable for both road and parking applications [48].

3.1.4. Advances in street/corridor furniture application

The complexities of transportation infrastructure mean that varying types of lighting are needed to ensure smooth traffic flow so that people are feeling safe and cities save on costs. Street furniture applications have been developed to suit this purpose. Street furniture should be available in proportion to the intensity of activity in a particular area. Furnishings include benches, waste receptacles, signs, outdoor fountains of light, and other elements to make people feel comfortable and enjoy outdoor space. Besides its functional aspects, well-designed street furniture enables cities to continually update outdoor space sustainably while being environmentally conscious at the same time [49].

Smart lighting is the umbrella that encompasses different solid-state technologies such as LEDs and organic light-emitting diodes (OLEDs) to illuminate indoor and outdoor environments related to demand. For that purpose, smart lighting systems include digital sensors, actuators drivers and communications interfaces, preventing energy to be wasted and causing an undesired disturbance. LED-based street (public) light is a cost-effective and sustainable choice for cities today. LEDs have many advantages, including lower energy consumption, longer lifetime, improved physical robustness, and faster switching.

Public lighting is becoming increasingly innovative, it reduces light pollution and saves on CO_2 emissions, electricity, and management costs. In the number of weather conditions and various traffic situations the lines on the road and along the road become difficult to see, road surface reflectors providing the desired clarity have been innovating. Depending on the traffic situation, road surface reflectors are an excellent way to draw the attention of traffic to, for example, an embossed structure in the road causing tyre noise if crossed. The advantage of placing road surface reflectors is that you give an audible, palpable, and visible addition to the road safety of the road, reducing the number of unilateral crashes. The reflectors are applicable for marking the road, for guideway dangerous curves and traffic inhibiting measures [50].

The future of street furniture could directly affect the day-to-day life of people. At the back of technology growth, there are speculations that we could have park benches which are Wi-Fi hotspots, lampposts which charge your electronic device, and litter bins (recycling bins) that can inform the local authorities when they are full[20]. Technically, future smart lighting appliances should compete with the IoT ecosystem in several areas: health and wellness with LED systems, lighting systems with advanced sensing, optical communications, and location services. Moreover, this lighting system uses wired and wireless connections.

New types of on-street infrastructure like smart lamp posts are an accelerator of smart cities. Smart lampposts are often adopted to reduce energy use, as well as to enhance public safety. This technology provides services such as Wi-Fi hotspots, electric vehicle charging facilities, information dashboards for maps and directions, real-time traffic updates, and car parking vacancy space information. Several cities around the world have deployed smart lampposts. Recently Hong Kong deployed smart lamp posts, which enable real-time collection of the city data such as weather, air quality, temperature, people, and/or vehicle flow related information for city management and support for various applications of smart city initiatives. In the U.S several cities have deployed versions that include microphones and related AI technology, for example, Los Angeles and Schenectady, N. Y[21].

There are as many as 90 million lampposts in Europe of which three-quarters are over 25 years old. EU wants to upgrade 10 million lampposts, making them solar-powered smart lampposts able to deliver a range of smart city services, and providing bases for a city-wide network of 5G connected sensors to monitor vehicle and pedestrian traffic flows[22]. The deployment of 'smart lampposts' could potentially save Europe €2.1bn every year according to analysis which was conducted by Sharing Cities, a Europe-wide Smart Cities organisation.

3.2. Vehicles

3.2.1. Connected and automated driving

Automated driving (also called self-driving, driverless, unmanned, or robotic car) is no longer a futuristic dream, it's becoming a reality. Frequently companies are announcing their commitment to developing and launching automated vehicles, and many of these announcements note the "level" of automation being developed. SAE has created international definitions for the levels of automation for vehicles consisting of five levels each with an increasing amount of automation and a decreasing amount of driver involvement. In level three (SAE Level 3), an automated system can execute some parts of a driving task and monitor the driving environment in some instances, but the human driver must be ready to take back control upon request of the system. In level four (SAE level 4), an automated system can execute the task of driving as well as monitoring the environment, without the need for a human driver to take back control but limited to certain environments and

[20] Future of street furniture: https://www.broxap.com/2017/12/future-street-furniture/ (Accessed on 27 November 2019)
[21] Smart Lampposts: https://www.scu.edu/ethics/focus-areas/internet-ethics/resources/smart-lampposts-illuminating-smart-cities/ (Accessed on 25 November 2019)
[22] https://www.weforum.org/agenda/2019/06/the-eu-wants-to-create-10-million-smart-lampposts/ (Accessed on 15 August 2019)

conditions. These systems are currently being tested by companies such as Google, Uber, and Volvo. The highest level (SAE Level 5) of an automated system can perform all driving tasks under all conditions that a human driver could perform [51].

The future of the automated vehicles industry will be driven by decreasing operational costs, increased safety, traffic efficiency, and environmental objectives. The revolution offers an opportunity to transform the way people and goods are moved. It could increase productivity, bring a new travel experience, and free up urban land like parking lots when shared vehicle use is increasing and private ownership of cars decreases. However, the introduction of connected and automated driving will require special traffic management and good infrastructure. Both physical and digital infrastructure would have to be capable of guiding vehicles, and communication among the vehicles and infrastructure should be possible [52]. This will allow the connected and automated vehicles to function in mixed traffic environments [36]. Furthermore, the wide-scale deployment of automated vehicles will create a potential for the reorganization of land use in urban areas. It will impact street design, intersections design, adjacent land use, lane width, and kerb management [53].

The automated vehicles, in due course, will significantly change the way city streets look. The space in the city currently reserved for parking will be reduced drastically, which in turn gives more space for cyclists and pedestrians [54]. This could be reduced when fewer vehicles are driven and when parking is taking place in the outskirts, or vehicles are driving while waiting for the next users. For planning, it is essential to predict how automated vehicles will affect travel and the consequences for land use, roads, parking, public transit demands, traffic problems and weather policies. Vehicles rely on public infrastructure and impose external costs, so they require more public planning and investment than most other technologies [55].

According to [55], experience with previous vehicle technologies can help predict automated vehicle deployment. There is considerable uncertainty concerning the benefits of an automated vehicle concerning costs, travel impacts, deployment speed, and consumer demand. That is, many predictions ignore significant costs and risks, rebound effects and potential harm to non-users. On the other hand, lower transport costs and freeing the driver from driving tasks could also lead to more people choosing a car as a transport mode (instead of public transport), and subsequently, increase congestion and air pollution [10].

For example, research by [56] has predicted that driverless cars could worsen traffic congestion in the coming decades, partly because of drivers' attitudes to the emerging technology and a lack of willingness to share their rides. The evidence suggests that as riders switch to automated vehicles, there will be an adverse impact on public transport. With most commuters not interested in ridesharing, this could increase periodic peak vehicle flows, which is likely to increase traffic congestion over the next 30 years or so. Another research that investigated the potential impact of automated driving draws a conclusion based on the result of four scenario tests, shows that improvements in roadway capacity and quality of the driving trip may lead to large increases in vehicle miles travelled, while a shift to per-mile usage charges may counteract that trend [57].

There are several EC funded projects in the field of Automated Road Transport and the related field of intelligent transport that aimed to address the aforementioned challenges[23].

- ADAS&ME – a project develops Advanced Driver Assistance Systems (ADAS) that incorporate driver/rider state, environmental context and adaptive interaction to automatically transfer the control between vehicle and user.
- ARCADE – a project that aims to build consensus across stakeholders from all sectors on a sound and harmonized deployment of Connected, Cooperative and Automated Driving (CAD) in Europe and beyond.
- AVENUE – a project that aims to demonstrate that autonomous vehicles will be a key element of the solution for the public transportation services of tomorrow.
- CoEXist – a project that aims to systematically strengthen the capacities of road authorities and other urban mobility stakeholders in preparation for the transition towards a shared road network with an increasing share of connected and automated vehicles (CAV) at higher automation levels.
- HEADSTART – a project that aims to define testing and validation procedures on specific functionalities of Connected and Automated Driving (CAD) functions, including key technologies such as communications, cyber-security, and positioning.
- ICT4CART – a project that aims to provide an ICT infrastructure architecture to address existing gaps in connected and automated driving. This high-level architecture will ensure performance and resilience for different groups of applications according to the needs of higher levels of automation (SAE level 3 and SAE level 4).
- INFRAMIX – a project that aims to design, upgrade and adapt both physical and digital elements of the road infrastructure, ensuring uninterrupted, safe and efficient traffic in the transition period with automated and conventional vehicles.
- interACT – a project that aims to develop novel, holistic interaction concepts for automated vehicles, that will enable their integration in mixed traffic environments safely and intuitively.

3.2.2. Electrification

The zero-emission transition is essential to meeting our climate change targets and improving air quality, particularly in urban areas. The technology already exists to make it happen. New transport modes such as self-driving vehicles and ride-hailing services must be at the forefront of this change, leading it and not holding it back [58]. In addition, EVs are a potential solution for alleviating the traffic-related environmental problems, which particularly promotes ultra-low and zero-emission vehicles. It has been anticipated that future mobility will be relying on electric vehicles and as a result, numerous innovations have been undertaken. In this respect, *Citroën* has revealed its vision for the future of mobility in cities, the *AmiOne Concept* electric vehicle, designed to be an alternative to both shared bikes

[23] https://ec.europa.eu/inea/sites/default/files/art_brochure-2019.pdf (Accessed on 11 January 2022)

and cars, which is called an “urban mobility object”, an ultra-compact concept car for unlicensed drivers[24].

The transition to an increasingly low emission fleet of cars and freight vehicles is also anticipated to significantly reduce the current issues surrounding roadside nitrogen oxide emissions, carbon, and some of the other pollutants. The emission of EVs depends on the received renewable energy, production processes and components of the vehicle and the batteries as well as their recycling. Around the world, many manufacturers have been providing different EVs models on the market, for example, Mercedes-Benz B250e, BMWi3, Tesla Model 3, and Nissan-LEAF. However, it is less clear how electrification will impact heavy goods vehicles (HGV), with the battery requirements of HGVs proving more demanding than with light-weight vehicles [59]. Trolleybuses are also coming back for discussion[25].

Based on power supplement and propulsion devices, EVs could be classified as the pure electrical vehicle (PEV) with no internal-combustion engine, hybrid electrical vehicle (HEV), and fuel cell electric vehicle (FCEV). The PEV and FCEV exhibit the most potential to reduce roadside emissions. Plug-in hybrid electric vehicles (PHEVs) are considered as potential candidates to compete with internal combustion engine vehicles (ICEVs) in terms of driver expectation, driving range and fuel economy [59]. EVs can be charged with plugging to the residential streets-posts, attaching them to the kerbs, parking over inductive pads, and driving to super-fast charging bays that will replace petrol stations.

Although the developments concerning batteries for electric vehicles are difficult to predict, instantaneous charging batteries will become available in the short term. The success in this would not only remarkably contributes to the emission but also congestion, safety, and ease the pressure on the parking areas. With the lack of charging facilities for EVs either expansion or alternative solutions are needed. In this regard, the UK has launched the world’s first national charging network for electric vehicles. Charging stations, for electric vehicles, that are easy to access and free to use.

There are different ways of charging EVs – including lamp-post charging, induction pads, electrified roads, and fast-charging hubs. The charging speed and location of these and other chargingpoints potentially have a significant impact on kerbside use. EV chargepoints need to be positioned carefully, whether on-street or off-street, to ensure ease of use and minimise the impact on pedestrians and to be accepted by communities especially where there are already parking places shortages. The location of chargepoints has a strong influence on how often and how easily they are used by residents, businesses, and visitors. As new street furniture, on-street chargepoints need to be positioned carefully to avoid negatively impacting the road users and street facilities.

[24] https://www.dezeen.com/2019/02/25/citroen-ami-one-concept-car-for-unlicenced-drivers/ (Accessed on 20 June 2019)
[25] Trolleybus: https://www.britishtrolley.org.uk/trolleybus (Accessed on 20 June 2019)

Innovations in EV chargingpoints have been undertaken by leading companies and start-ups across the world. For example, a start-up company *Trojan Energy* is installing 200 of its kerbside EV chargers across Brent and Camden as part of a trial in London. The technology has no permanent footprint or street clutter as the hardware is only visible when a vehicle is charging. Each charge point is slotted into the ground with a flat and flush connection[26]. The transition to wireless charging removes the need for drivers to plug in with a charging cable, instead of enabling them to charge their vehicle by parking over an inductive pad sunk beneath the ground, according to UK based company - *Connected Kerb*. Longer-term, induction charging will be the path to the electrification of all parking bays without the street furniture and cable clutter that dominates EV charge point technology today.

Regarding the length of charging time, the time it takes to charge an electric vehicle can be as little as 30 minutes or more than 12 hours depending on the size of the battery, the speed of charging point, and other factors such as power source – electric supply type, AC and/or DC. A typical electric vehicle with a 60kWh battery takes under 8 hours to charge from empty to full with a rate of 7kWh charging point. A battery with more than 43kWh reaches 80% within 20 to 40 minutes. Too long charging time has an impact on the use of kerbside in urban areas. A combination of overnight charging at home/residential areas and top-up charging could also ease the charging time on kerbsides. On-street residential charging can be used where there are no off-street parking and long stayed car parking.

Many initiatives are working towards making parking cheaper or easier for EV drivers to encourage people to switch to EVs; however, it is also important that appropriate parking restrictions are set and enforced on the streets with limited chargingpoints. Local authorities need to adopt regulations to restrict the length of stay during the day in popular locations such as city centres and provide service for topping-up during the day. Furthermore, clear signage and painted bays help EV drivers find chargepoints, understand any restrictions and should prevent them from being blocked by petrol or diesel vehicles [60].

Regardless of the widely promoted use of electric vehicles over its counterpart diesel and petrol-based vehicles, there is a pressing question that has been asked by experts. That is, considering the whole supply chain, are EVs as green as promoted? The sources of raw materials such as cobalt and lithium mining, the way batteries are made and transported, and how countries use batteries (recycling or throwing it) might not imply that the whole supply chain of electrification is clean. While experts broadly agree that plug-in vehicles are a more climate-friendly option than traditional vehicles [61], they can still have their environmental impacts. For example, how much coal is being burned to charge up those plug-in vehicles and electric grids need to get much cleaner and reusing lithium-ion batteries requires extensive testing for their reliability.

[26] https://www.fleetnews.co.uk/news/latest-fleet-news/electric-fleet-news/2020/08/13/kerbside-electric-vehicle-charging-trialled-in-london (Accessed on 2 April 2020)

The most plausible technologies are renewable diesel, and hydrogen vehicles, which are real green, practical, cost-effective, and available on the market. Some renewable types of diesels are high-performing and have low carbon emissions. *Neste MY Renewable Diesel* is an example of that. It is made from 100% renewal materials (waste and residuals), results in up to 90% less greenhouse gas emission over the fuel's life cycle when compared with fossil diesel and is fully compatible with all diesel engine and diesel fuel distribution infrastructure[27]. Irrespective of the raw materials chosen, the composition and quality of Neste MY Renewable Diesel are always the same. Neste MY Renewable Diesel is available on the market in the Netherlands[28].

3.3. Vulnerable road users

Motorised road travellers have become safer over recent decades; however, VRUs such as pedestrians, cyclists, and motorcyclists are becoming the major group of people killed and injured on roads, particularly in urban areas [62]. VRUs are defined in the ITS Directive as "non-motorised road users, such as pedestrians and cyclists as well as motorcyclists and persons with disabilities". ITS applications in recent years assisted in reducing the number of fatalities. ITS-based road safety and security applications have proved their effectiveness, but the overall benefit for society depends on their wider deployment, though at the same time, some safety-related issues require further attention, e.g., Human-Machine Interface (HMI) [63].

V2P systems serve purposes such as safety and cater to several VRU groups. These systems deploy other communication technologies and use different mechanisms to interact with the users considering varying characteristics. These elements may be considered as a design parameter of V2P systems. Thus, the traffic demand of VRUs will be integrated into ITS, contributing to improving road safety, reducing congestion, increasing economic efficiency, and improving air quality [63].

In another way, these systems must integrate into the design of pedestrians and bicycle-oriented space of streets and corridors. Well-designed bicycle and pedestrian facilities are safe, attractive, convenient, and easy to use. From the street design perspective in D1.2 of MORE WP1, it was mentioned that research guidance material for link functions of streets and particularly for motorised vehicles are more consistent in MORE cities than the guidance for the active modes waking and cycling. Pedestrians are positioned high in the hierarchy of street users but have the lowest levels of detail and consistency in the researched guidance, particularly for placement function. It was identified that a major problem in planning for the pedestrian is how to deal with bottlenecks. Space requirements for cyclists, buffer zones, and widths of cycling facilities are quite similar in each of the different cities and countries. Cyclist

[27] https://www.neste.com/products/all-products/renewable-road-transport/neste-my-renewable-diesel#b51bb131 (Accessed on 12 July 2021)
[28] https://tamoil.nl/neste-my-renewable-diesel (Accessed on 12 July 2021)

infrastructure should cover current and future needs and infrastructure should provide enough space for non-standard and standard users [64].

In addition to systems and design features, there are multiple data-driven innovations to improve VRUs safety and accessibility. For example, San Francisco-based mobility analytics company, Streetlight Data, has incorporated VRUs data to its insight software platform to help transportation planners and new mobility companies better understand the travel pattern of cyclists and pedestrian across the entire city[29]; London based, Vivacity, use AI to improve the insight of traffic through its sensor hardware by continuously providing anonymous streams of data on all forms of urban mobility including cyclist and pedestrians[30].

3.3.1. Pedestrians

Pedestrians/runners are the most vulnerable road users to collisions with vehicles and bicycles. Of these disabled and elder people are the most at risk for fatality and injury. According to [65], the main problem that hinders the safety and comfort of pedestrians is the speed of vehicles. High speed has many indirect effects on the real and perceived risk of pedestrians [62]. Most of the current and future needs of pedestrians can be addressed by improving the quality of public space, safety, air quality, and noise reduction.

The major future challenge for pedestrians is how automated vehicles interact with the elderly, vision impaired, children, and people with disabilities. Although technologies are being developed for automated vehicles to successfully detect pedestrians in advance of most fatal collisions, the current costs and operating conditions of those technologies substantially decrease the potential for automated vehicles to radically reduce pedestrian fatalities in the short term [66]. The development in micro-mobility and the shared use of footways/sidewalks with other road users would pose another impact on pedestrians [65].

Despite these challenges, there have been many developments for improving the position of pedestrians and cyclists in road traffic, in particular, the safety of pedestrians. For example, the significant changes in intersection geometry, signalisation, driver behaviour, and technology of automobiles in urban areas affect the ability of blind pedestrians. One of the solutions to overcome this problem is voice-activated technology. Using a voice-activated tool that communicates with the surrounding infrastructure, a blind pedestrian could request an extension if they need more time to cross the street.

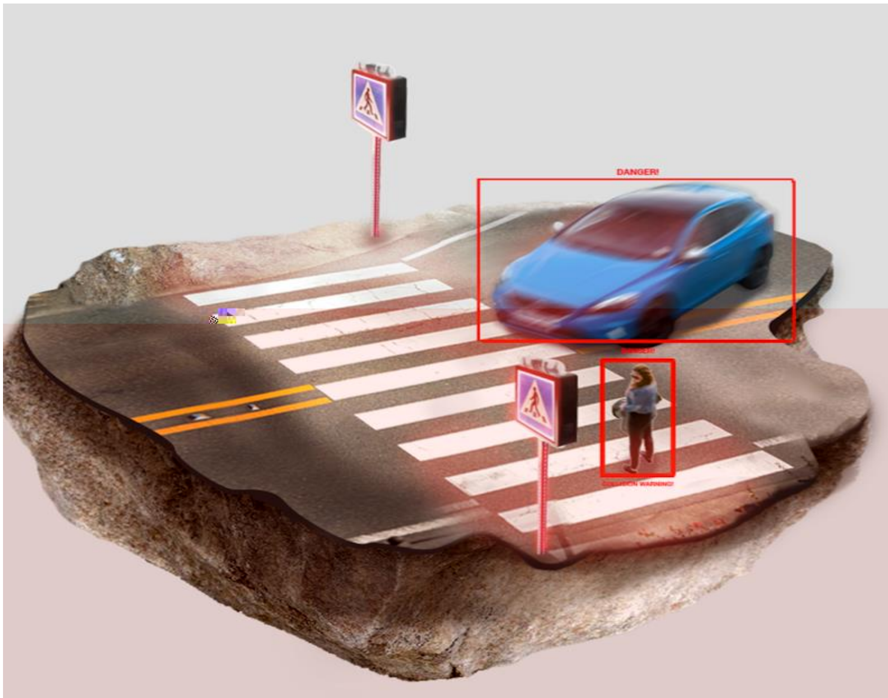
Companies like *Bercman Technologies* created Smart Pedestrian Crosswalk (SPC) to address a large number of road-accident fatalities involving pedestrian crossings. SPC is a smart traffic sign that can be used anywhere, where increased pedestrian safety and data input are required. SPC uses AI, V2X, sensor fusion and more than 30 different features to adapt to different traffic situations and weather conditions. The solution will leverage our V2X

[29] https://www.smartcitiesworld.net/news/news/streetlight-data-launches-standalone-bike-and-pedestrian-analytics-tool-4694 (Accessed on 20 December 2019)
[30] https://vivacitylabs.com/ (Accessed on 20 December 2019)

technology to alert vulnerable road-users of cars and other vehicles approaching the crossing, and be alert vehicles the presence of pedestrian crosswalks and vulnerable pedestrians in the vicinity ensuring that the driver is aware of them and can take the appropriate action [67].

A new 3D road marking on zebra crossing in London has been introduced by infrastructure service firm *FM Conway*. The 3D effect on the road surface aims to encourage drivers to lower their speed when approaching crossings, improving safety for pedestrians and other road users. Another British company has developed a crossing point designed to detect people and automatically alert cars. The system uses cameras directed at the pavement to monitor pedestrians, as they are approaching strips are illuminated across the road to warn vehicles. The technology is designed to provide greater protection to people who step into the road without looking[31].

Figure 7: V2X technology equipped smart pedestrian crosswalk



Source: www.Traffictechnologytoday.com (Accessed on 19 December 2019)

3.3.2. Cyclists

As the number and speed of motorised traffic flow increases, the safety issues of a cyclist in the corridors of the cities need attention. Based on the definition by a Dutch technology platform for transport, infrastructure and public space (CROW) mentioned in [65], the needs

[31] https://www.highwaysmagazine.co.uk/Did-you-see-the-Zebra-crossing/4715 (Accessed on 23 May 2019)

of cyclists as road users are coherence in network links between origin destinations, directness to avoid detours and delay, safety and comfort, and attractiveness, which means minimise noise exposure.

Many modern cities throughout Europe recognise that providing space for cycling creates efficient and attractive places to live. People are motivated to cycle because it is faster than being stuck in a traffic jam, journey times are highly predictable, and it is a fun and social way to travel and also provides an easy way to introduce healthy exercise into a daily routine. Only by providing proper infrastructure can these benefits be achieved. The permeable street network facilitates direct movement around an area for walking and cycling[32].

One of the key technological advances that can have a significant impact on future scenarios for local and regional transport systems is the growing popularity of Electrically Assisted Pedal Cycles (EPACs) – bicycles that add a small electric boost to the pedal movement. EPACs constitute currently 10% of the EU bicycle sales market with 15-20% growth each year.[33]

EPACs impact on road infrastructure

New, higher standards of infrastructure are needed to tap into the potential of EPACs, because of several reasons:

- Longer distances travelled necessitate higher design speed (curve radii, visibility splays, sight distances), less interruptions and conflict points.
- Because of wider demographics of users, including the elderly, the infrastructure needs to accommodate longer reaction times (which affects e.g. stopping sight distance) and lower contrast sensitivity (quality of lighting, signage, horizontal markings).
- Elderly cyclists also draw more atMCID 7/Lang (e92595.2 841. 0 595.2 841.92 d)-MCID 3/Lang (en-

A comparison of already proposed new standards and guidelines for cycle highways is available in the Cycle Highways Manual[34], developed in the frame of the CHIPS (Cycle Highways Innovation for smarter People transport and spatial planning) project. However, there are still many uncharted areas and knowledge gaps. For example, although several of the analysed documents recognize the need for adopting higher design speeds for cycle paths, they fail to provide any concrete geometric requirements above 30 km/h.[35]

EPACs increase demand for secure and theft-proof bicycle parking, because of the significantly higher value of an EPAC compared to a normal bicycle. This affects the design of housing; workplaces and all other buildings where longer parking might be necessary. Consequences and recommendations are discussed further in the ECF report “Making buildings fit for sustainable mobility”.[36]

EPACs impact on governance structures

Cycling infrastructure has traditionally been a municipal competence. As EPACs enables longer bicycle trips, it becomes more and more necessary to extend the cycle network planning and development from a strictly local level to include regional or in some case even national level. A cycle highway connecting two cities can cross 10 or 20 municipal borders. The municipalities might have different priorities, and e.g. a cycle highway that connects A to B through a short stretch in C might not be of any direct benefit for C. At the same time, the user expects a consistent standard of infrastructure, wayfinding or maintenance on their way to work.

An example of the new approach is the plans for a cycle highway network in Flanders that aims to be the backbone for local or provincial networks. The cycle highways will connect 258 municipalities with 122 routes, with a total length of 2700 km, uniform standard and signposting.[37]

EPACs impact on social inclusion

The small electric boost provided by EPACs allows the elderly to continue cycling for longer, providing them with an independent mobility option, and health benefits of moderate physical activity.

Additionally, many agglomerations that attempt the transition to more sustainable transport and further on, to “city of places”, face the conflict between residents of core urban areas, with shorter commuting distances and good access to public transport (often perceived as more affluent, that “can afford” to walk or cycle) and much more car-dependent suburbs.

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[34] https://cyclehighways.eu/design-and-build/design-principles.html (Accessed on 28 April 2020)
[35] An interesting exception is “The manual for the design of cycle paths in Catalonia”, providing horizontal/vertical curve radii and stopping sight distances up to 50 km/h.
[36] https://ecf.com/what-we-do/bicycle-parking (Accessed on 6 February 2020)
[37] https://fietssnelwegen.be (Accessed on 6 February 2020)

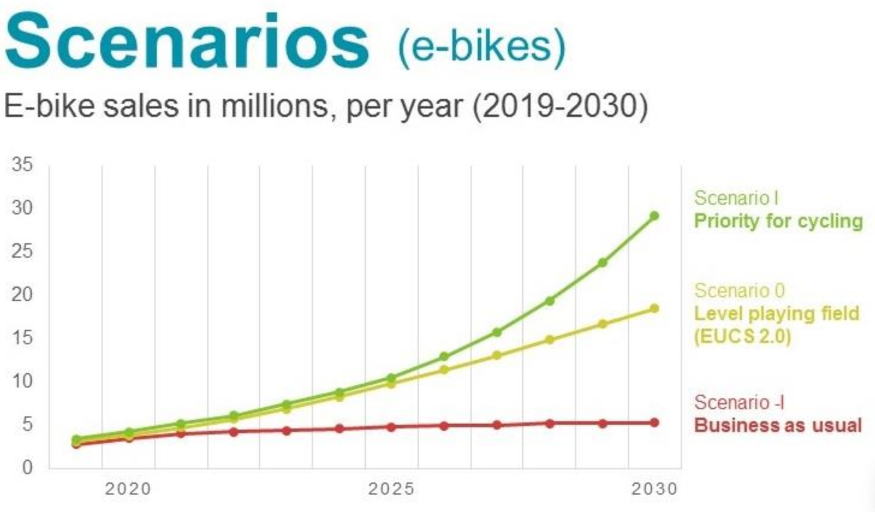
EPACs help to address this conflict by providing sustainable means of transport also for longer commuting distances and less densely populated areas – assuming that the new vehicles will be accompanied with suitable infrastructure. The significantly higher price of EPACs can be attenuated through purchase subsidies provided at national, regional, or local level, which can also have a social component.

Future scenarios of EPACs

Further development of EPACs can have a serious impact on future scenarios, including for example efficiency of different infrastructure investments. For example, in a study on cycle highways undertaken by a Dutch consultancy firm *Goudappel Coffeng*, estimated savings of time spent in congestion varied by a factor of 3.5 (between 3.8 and 13.2 million hours per year) depending on how much more the use of electrically assisted bicycles increases.

Based on the data from the (e-) bike market reports released by CONEBI and the general trends in the mobility sector in urban and suburban areas, ECF identified 3 main scenarios until 2030. The essential features of the scenarios depend on technological progress, but also the regulatory and fiscal environment, as well as matching infrastructure development.

Figure 8: Range of scenarios in terms of e-bike sales identified by ECF (Eurobike presentation, September 2019)[38]



38 https://ecf.com/news-and-events/news/what-would-happen-if-we-prioritised-cycling (Accessed on 13 January 2020)

3.4. Advances in alternative modes

3.4.1. Micro-mobility

Micro-mobility (e.g., shared bikes and electric micro vehicles such as segways, hoover boards, and e-scooters) is one of the fastest-growing modes of transport worldwide. These small, most of the time, electric-powered vehicles, can potentially connect different transport modes to make journeys quicker and easy - particularly trip stages perceived as too long to walk in lower-density areas with low Public Transport frequencies.

Micro-mobility is a term that emerged recently (since 2016) [68] and the literature is still struggling to find a solid definition. In 2019 Micro-mobility is associated essentially with shared e-scooters but this is far from the truth. Once we have a closer look, the type of vehicle included in what can be considered Micro-mobility is vast, not so recent, and rapidly evolving. Some definitions include the traditional pedal bicycle, used for more than a hundred years in our cities. Even the powered stand-up scooters are a quite old mode of transport patented at the beginning of the 20th Century. But it was the shared business model allowed by the ubiquity of mobile phones, and the smaller size and efficiency of lithium batteries that was the fertile ground for the proliferation of Micro-mobility services in the last few years. The variety of new small vehicles in the streets is growing and it is very difficult to say what kind of new vehicles will appear in the future.

E-scooters continue to rise in the global market, especially in North America, Europe, China, Japan, and other countries. E-scooters are most popular across European countries since the year 2019. The countries where the fastest growth of private e-scooter use has been observed in the year 2019, are Spain (498% growth per year), France (132%), Germany, Italy (286%), Poland, Austria, Netherlands, Belgium, and Switzerland [69]. A total of 55% of all e-scooters are in Spain and France alone. The main European cities flooded by shared e-scooters today are Madrid, Paris, Barcelona, Berlin, Milan, Rome, and Nice. Although the US-based e-scooter renter companies *Lime* and *Brid* getting ground in Europe, there are several European e-scooters rental start-ups (e.g., *Dott, Wind, Voi, Tier*) that have been received mega-funds, and make aggressive expansion plans and commitment to sustainable practice.

In many cities of Europe, bike lanes and wider pavements can be used by e-scooters, though regulations vary from country to country. Increased use of both e-bikes and traditional bicycles has been enhanced by major infrastructure improvements across cities in Europe which have all invested significantly to support alternative mobility solutions for consumers, especially e-scooters. On the other hand, due to the rise in e-scooter related accidents many cities have been standardising the legal frameworks for payment, safety, and parking. Hundreds of accidents, some serious and even fatal, have been reported from across Europe. Consequently, countries that have implemented e-scooter safety regulations include France, Germany, Austria, Belgium, Finland, Norway, Spain, Portugal, and Sweden.

In some of the countries like Germany and France, strict rules on the speed of the e-scooter, accident insurance, age limit, safety precautions related to driving on the pathways, and road traffic-related regulations were introduced. In 2019, Germany formulated a regulation that allows the use of light electric vehicles including e-scooters and segways on public roads. The city of Cologne and Berlin are among other German cities flooded with thousands of e-scooters. In the same year, France legalised the use of e-scooters and similar devices but banned them from footpaths, highways, and rural roads.

In Belgium, it is now legal to ride e-scooters on public roads if their speed is limited to 25 km/hour. In Sweden, e-scooters must have brakes, an audible warning device, such as a bicycle bell, and riders younger than 15 years of age are required to wear a helmet. In Spain, the national traffic authority sets a speed limit of 25 km/hour for e-scooters and requires them to be insured[39]. In Austria, e-scooters riders must use bike lanes and only use the sidewalk, if permitted. In the United Kingdom, it is illegal to ride e-scooters on pavements, public roads, or in cycle lanes. However, the UK government is running trails of e-scooters around several local authorities. E-scooters used in the trails are currently limited to a maximum speed of 15 km/hour.

One of the most common criticisms related to e-scooters is the fact that users park them improperly – simply tossing them aside or leaving them in the middle of nowhere. E-scooters should not be parked in spots that block pedestrian walkways, driveways, building entrances, bus stops, and crosswalks. Cities authorities have also been regulated unconsidered parking of e-scooter. Paris now insists that parking is only allowed in designated areas. As of 2020, the parking of e-scooters and e-bikes in Berlin only be allowed in specially reserved areas[40]. Cities like Paris and Lisbon have taken installing dedicated scooters parking nests as a remedy to the e-scooter parking challenges.

Technical characteristics of micro-mobility vehicles

Micro-mobility vehicles are polymorphic, and several attempts have been made to circumscribe and classify them. Most definitions include maximum weight and speed, characteristics that limit the maximum kinetic energy of the vehicle. But other technical characteristics can be also important if a city wants to align its micro-mobility vehicle policies with their long-term strategic sustainable mobility policy – namely size-footprint and environmental impact.

The maximum weight of micro-mobility vehicles has been set between 500 kg (the original definition) [70] and 227 kg [71]. This range might include micro-cars. The maximum speed for the definition of Micro-mobility vehicles usually ranges from 25 km/h[41] and 45 km/h (28

[39] https://www.eltis.org/resources/case-studies/overview-policy-relating-e-scooters-european-countries (Accessed on 9 December 2020)
[40] http://www.citymayors.com/transport/e-scooters-europe.html (Accessed on 13 January 2020)
[41] In Europe this is an important threshold. Pedelecs, defined as bicycles with pedal assistance up to 25 km/h and with an auxiliary electric motor having a maximum continuous rated power of up to 250 Watts.

miles/h)[42]. Whatever the limits adopted, it is consensual that the range of vehicles that might appear in the near future could defy the current morphologies that include, powered or not vehicles, and an enormous range of characteristics (autonomous delivery robots, segways, hoover-boards, unicycles, e-bikes, micro-cars, and so on). Therefore, it will be most probably necessary to create subgroups within the definition.

At least for the near future and as a quick way to fix the legal gaps, regulators should consider the benefit of aligning the requirements placed on micro-vehicles with existing frameworks. What seems reasonable is that for all vehicles under 35 kg and speed limits of 25 km/h the most requirements placed could be aligned with those applicable to the traditional bicycles and pedelecs. And maybe with small adaptations, the micro-mobility vehicles above these limits could be aligned with the technical requirements of a moped (hence some micro-cars are called moped car).

The main technological advances in Micro-mobility vehicles will happen mainly through durability of the materials and the battery. The vehicles in the future will have certainly more range. The shared vehicles will use new materials to make them more robust, more stable, more waterproof (longer lifespan and therefore less environmental impacts).

Considering the characteristics of the battery we could be on the verge of a power revolution. Big technology and car manufacturing companies are all very aware of the limitations of lithium-ion batteries and heavy investments are being poured into improving the characteristics of batteries. It is reasonable to anticipate batteries that will power much further micro-mobility vehicles without the need for charging. Also faster charging times in solar-powered docks/hubs and using swappable batteries will reduce considerably the environmental impacts of the current model of using free-lance “juicers”[43].

Infrastructure

In urban areas, public space is a limited and scarce resource. The way this space is distributed by the different transport modes is a message of where the City’s policy and practice stand, and a major constraint or opportunity for the city to move towards sustainability. The danger of micro-vehicles upon vulnerable users is a legitimate concern but should not obscure the fact that motor vehicles represent a much greater fatality risk to pedestrians, both in absolute terms and per unit of vehicle travel [72]. There are two aspects to consider in terms of infrastructure needed for micro-mobility vehicles - space to circulate and parking.

Given their vulnerability and low speed, micro-mobility is a challenge in terms of safety when circulating on the carriageway. On the other hand, the safety of pedestrians is negatively

[42] In the USA Class 3 electric bicycle provides assistance only when the rider is pedalling, and that ceases to provide assistance when the bicycle reaches the speed of 28 miles per hour (45 km/h).

[43] A job where you gather electric micro-vehicles, charge them and drop them off across the city.

impacted where micro-vehicles are used and parked on sidewalks. To adapt the future and present infrastructure to micro-mobility vehicles it is vital to protect the sidewalks and to make sure micro-mobility users can ride safely without using the footways.

Technology may offer solutions to prevent sidewalk riding and limit speed in pedestrian areas. However, the current GPS location does not have precision enough to detect sidewalk riding and parking (however is reasonable to predict that 5G connectivity combined with GPS and other technologies will complement embedded sensors to enable vehicles to determine their precise location within centimetres). But e-scooter companies are working to develop sidewalk detection solutions using vehicle sensor data to assess road conditions during the trip. A Dublin Start-up claims to be able to achieve the 10cm positioning accuracy using GNSS/GPS positioning with an integrated correction service (Real-Time Kinematic - RTK)[44].

To improve the safety of micro-vehicles off the sidewalk reducing and managing the speed of motorised vehicles will be key – future segregated micro-mobility lanes and existing and future cycleways will not solve all the origin-destination routes. Even the current segregated cycleways in the few main streets that have them will probably be too narrow for a desirable exponential growth of cycling, broader cargo bikes, and other larger micro-vehicles. Moreover, if micro-mobility includes vehicles until 300-500 kg and speed limits of 45 km/h, then it is quite clear that part of these large micro-vehicles cannot be allowed in current cycleways.

Therefore, most technological advances will have to come from the car industry to address the safety of micro-vehicles. To help cities to manage and reduce speed limits of motorized vehicles Intelligent Speed Assistance (ISA) will be imposed on new cars sold in Europe from 2022 and there is potential for this to become a global standard. ISA uses a speed sign-recognition video camera and/or GPS-linked speed limit data to advise drivers of the current speed limit and automatically limit the speed of the vehicle as needed. Autonomous emergency braking (AEB) systems are already being installed on current model passenger cars and can reduce rear-end collisions by 38 percent according to research based on real-world data [73]. Autonomous Emergency Braking is becoming increasingly common on modern passenger cars and normally consists of an automatic brake function that operates for speeds up to 30km/h or 50km/h.

However, it makes sense for micro-vehicles in the lower range of weight and speed to use cycleways when they exist. And expand dedicated safe spaces where the volume and speed of traffic deemed to be politically impossible to reduce to safe levels – This new canal instead of cycleways start to be called “slow lanes”, “micro-mobility lanes”, “third lanes” “BEST lanes” (Bikes Electric Scooter Transportation).

The potential proliferation of Autonomous Delivery Robots (currently being piloted in several cities) and the need to protect sidewalks from motorised vehicles, is also a good reason to

[44] Real Time Kinematic is a technique used to increase the accuracy of GPS signals by using a fixed base station which wirelessly sends out corrections to a moving receiver.

create zones and a network of low traffic at low speeds using part of the city network. Being calmed traffic zones or dedicated lanes.

Dockless micro-vehicles are left on the sidewalks because there's often no other place to leave them. Parking of micro-vehicles on the sidewalks is currently a major enforcement challenge. Most of the last generation of shared micro-vehicles are dockless exacerbating the sidewalk parking problem. This abuse of the sidewalks for parking is one of the main problems that cities and the industry will have to solve in the future.

Apart from regulatory measures to help to minimize the problem, there are already some technological solutions currently being tested – geofencing being the most promising. Once again, the protection of the sidewalks will need a precision much higher than the current GPS. Geo-fencing is a feature in a software program (in this case shown in the mobile renting platform) that uses GPS or radio frequency identification (RFID) to define geographical boundaries. Geofences can restrict speed, access (reducing speed to zero), and parking (where users cannot start nor end trips). Lisbon in cooperation with e-scooter and shared bike operators is testing extensively geo-fencing.

Concentrating micro-mobility vehicles in parking hubs in dense urban environments can be a way of tackling the parking problem (providing these in abundance and banning parking outside these hubs). These could be simple low-tech bike parking modular spaces, allowing the parking of shared private micro-vehicles. But also, could provide charging possibilities, wireless, electronic info-points. These hubs if powered by solar cells should not require excavation and trenching, which will reduce implementation time and costs. Also, if these parking hubs are easily movable, the parking network can be optimized once demand patterns reveal themselves through usage. They can also be removed during the winter months.

Solar cells can power the parking hubs and their wireless communications. Solar cells make modular parking hubs feasible, as they eliminate the need for excavation to connect the station to underground power lines. The bike-sharing systems in Boston, Washington, D.C., London, Montreal, and Rio de Janeiro have already stations that are powered entirely by solar energy and are completely wireless. These future micro-mobility parking hubs can include offering cargo bikes for large purchases, electric-assist bikes, and bikes for children, e-scooters, and so on.

On the other hand, the evolution of micro-mobility is changing how people move daily. This will bring new challenges for the national policymakers and city officials. A report by International Transport Forum (ITF), proposes a range of safety improvements for micro-mobility that are related to vehicle design, fleet operation, infrastructure, regulatory enforcement and training [74].

3.4.2. Airborne drones and flying taxis

A drone or a UAV typically refers to a pilotless aircraft that operates through a combination of technologies, including computer vision, AI, object avoidance technology, and others. As automated and collision-avoidance technologies improve, drones are expected to be able to perform increasingly complex tasks. In a business aspect, the emerging global market for business services using drones attracts investment into drone technology. There are several ways through which drone technology impacts society, from delivery service to vacuuming ocean waste. Drones have been drastically changing areas such as emergency response (ambulance drone), construction planning and management, personal transportation (e.g., autonomous aerial vehicles, AAVs), and retail[45]. UAVs are also used to monitor pedestrians. The monitoring of pedestrian activity is challenging, primarily because its traffic levels are typically lower and more variable than those of motorized vehicles. Compared with other on-the-ground observation tools, UAVs could be suitable for counting and mapping pedestrians reliably and efficiently [75].

In transportation, autonomous aerial vehicles, drones for delivery (airborne drones) would be expected to highly impact mobility. Companies such as *EHANG* and *Lilium Aviation* have been building AAVs for passenger transportation that would function in an urban environment without plenty of obstacles. California-based *Uber*, South Korea-based *Hyundai*, and German air taxi start-up *Volocopter* are among other companies that work towards the realisation of electric vertical take-off and landing aircraft (flying taxi). In the retail industry, drones are being used to deliver goods from local retailers or logistics centres to destinations. Business investment activities are also focusing to increase both land and air delivery efficiency, as it impacts the whole operation of logistics. For example, at the 2019 AI conference, Amazon announced that the drone deliveries will start rolling out in select US cities within months. Most recently, Vertical Aerospace, a Bristol-based company that develops affordable electric aviation solutions has announced plans for a flying taxi, the *VA-1X*. The *VA-1X* is an important technical milestone for the urban air mobility industry. Capable of carrying up to five people (four passengers and a pilot), the VA-1X is set to be the world's first certified winged all-electric Vertical Take-Off and Landing (eVTOL) aircraft and could start commercial flights as soon as 2024 [76].

Drones for delivery reduce emission, congestion, and solve the last mile problem by providing an alternative route of delivery in urban settings as well as a shortcut to infrastructure. For small deliveries, footway drones would be also a solution to optimise the routes and avoid congestion on the main streets. They are expected to use pedestrians' footpaths, therefore, very clear markings are required to manage the safe landing of drones on the footpath. Possibly streetlights can play a role by projecting a symbol and detecting the presence of pedestrians in the area. In [77], the drawback and benefits of using drones in the delivery process in an urban area were analysed. Three delivery processes: a delivery process where only trucks are used, only drones are used, and a hybrid transportation system where trucks are equipped with drones are analysed in terms of transportation cost, emissions, and congestion. The numerical results suggested that hybrid transportation has

[45] https://www.cbinsights.com/research/drone-impact-society-uav/ (Accessed on 27 January 2020)

the best trade-off between efficiency and reduction of negative externalities, i.e., CO_2 emissions and congestion.

The operation and exploitation of technology present many challenges – including the legality, weather issues, safety, package size, and theft crime. Another challenge of commercial drones is permission to fly in restricted air space. However, seemingly there is a promising emerging report in the UK that allows drones to use air space along with traditional aircraft. The report includes the architecture for an open-access unmanned plane management system and scenarios such as managing permissions to fly drones in restricted airspace and multiple operations in uncontrolled space[46]. This could give a huge opportunity for countries to successfully accommodate commercial and private drones' operation beyond the line of sight.

In the COVID-19 era, drone deployment offers a learning opportunity for how airspace regulation could be updated to ease their use beyond emergency response. Positive experiences with drone deliveries and other services they can provide could lead to a permanent shift in attitudes towards drones that may go beyond the immediate use of drones during the crisis. Since the onset of the Coronavirus crisis, drones have been deployed to deliver medical supplies, collect or dispatch lab samples, deliver daily necessities to confined citizens, monitor social distancing, make public announcements, or disinfect public spaces. Drone operators around the globe have begun to cater to new demands induced by COVID-19. They deliver supplies, medical and other, with a minimum of human interaction, thus helping to limit the risk of human-to-human transmission of the Coronavirus. Among the countries that use drones for contact-free delivery processes in the crisis are China, Ireland, Switzerland, and Ghana. Countries that use drones for surveillance and enforcement are France and Italy. Countries that use drones for hygiene applications, for example, sanitizing large spaces are China, Korea, and the USA. Overall, it appears that even if countries prefer a cautious approach to drones, establishing a regulatory framework for drones now that takes into account concerns beyond safety may help improve emergency responses in the future [78].

3.4.3. Digital and on-board rail signalling

Nowadays, railways are in the mindset of a profound transformation, driven by key emerging digital technologies like 5G, big data, IoT, cloud computing, automation, AI, and blockchain. These technologies are providing new solutions but are not limited to the efficiency of railway operations, infrastructure and predictive maintenance, and control and signalling systems. With these breakthroughs, digital development provides a unique opportunity for railways, to increase their share of transportation, and to become an integral part of the transition toward greener, more sustainable transportation. In recent years, rail companies have widened the

[46] https://www.gov.uk/government/news/new-laws-to-combat-illegal-use-of-unmanned-aircraft-and-modernise-airspace (Accessed on 11 December 2019)

range of services, notably through managing rail customers' expectations through the website, monitoring ticket reservation and purchasing habits, improving operators' information and payment systems through a combination of on-board information and leisure services.

On-board rail signalling - for example, route signalling and speed signalling inform the driver of the t and sustainability of inland water transport are among the multi-modal alternatives considered in the MORE project.

3.5. Transport policy and traffic management

3.5.1. Transport policy

Transport is integral to most of the activities in the society; it is therefore dealt with through policies at all levels, at global, the EU, national, regional, and local levels. At the EU level, environmental policies and legislation deal with monitoring, emission reduction and air quality improvement in which Environmental Noise Directive, National Emission Ceilings Directive, and Cleaner Air for Europe Directive, vehicle emission limits, and fuel quality are the common transport policies. National transport policies deal partly with the translation of EU policies into national legislation. The regional and local level plays an important role in practical land-use decisions which again have an important impact on transport demand as well as on the choice between transport modes faced by individual users [79].

Regional and city authorities are the major public stakeholders in ITS and are largely responsible for ITS safety aspects. They have set regulations on the transport system to bring safety, efficiency, environment, and sustainable transport. Cities have different requirements due to varying policies within countries and policies are changing over time. For example, environmental policies in many countries encourage the use of public transport and bicycles over private motor vehicles. Regarding safety policies, Directive (EU) 2019/1936 of the European Parliament and of the Council of 23 October 2019 introduced amendments on Directive 2008/96/EC on road infrastructure safety management[49]. The key changes in the directive on road infrastructure management are but are not limited to periodic road inspection, network-wide safety assessment, and exchange of best experiences between the Member States. For example, Member States shall ensure that the needs of vulnerable road users are considered in its implementation of the procedures[50].

Moreover, a recent policy of ‘Vision Zero’, aiming at being free of deadly and catastrophic motor vehicle accidents and achieving ‘zero carbon emissions’ from transport in urban centres, will highly impact transportation in urban areas. Thanks to the development of automated vehicles and other advanced driver assistance systems, traffic density is expected to be reduced and travel efficiency is expected to be improved [1]. This development will highly contribute to realise Vision Zero. The achievement of these policies is centred on traffic demand and data collection/sharing needs to be integrated into traffic management systems [80].

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[49] Directive (EU) 2019/1936 available at: https://eur-lex.europa.eu/eli/dir/2019/1936/oj (Accessed on 16 December 2019)
[50] https://ecf.com/sites/ecf.com/files/key_changes_in_the_rism_directive_20191206.pdf (Accessed on 20 January 2020)

3.5.2. Traffic management

According to proposals by urban traffic engineers and traffic managers, traffic congestion in the cities of the world can be dealt with by - 1) expanding the capacity of the urban network, which cannot be implemented by many cities due to high cost, urban density, and traffic volume; 2) traffic assignment through broadening traffic information using software applications; 3) optimising the capacity of urban traffic network through traffic signal control and ramp metering. According to [81], the fourth approach to deal with is traffic congestion is traffic prediction.

Efficient traffic management and UTC systems that are capable of meeting modern transport policy obligations and desires are needed to attain the traffic demands and optimal road-space utilisation. The recent technological developments and ITS, have offered a wide range of additional possibilities and ways for managing traffic. Modern methods including pricing policies and restrictions, enforced using new technologies, data collection, and treatment of users. Future mobility patterns will continue to change, because of demographic shifts, flexible work environment, new technologies, automated vehicles, trends in the economy and technological innovations in the field of traffic information such as C-ITS will make it possible to develop further traffic management innovations. Traffic management of the future needs to be flexible with a quick response to changes in supply and demand and achieve a range of policy objectives. Currently, to solve traffic problems, the practice of most road authorities is developing their traffic management system aiming for increased throughput, effectively distributing traffic across the network, regulating the inflow of traffic, and preventing spillbacks.

Traffic management systems are composed of a set of applications and management tools to improve the overall traffic efficiency, pollution and emission, and safety of the transport systems. It gathers the information from heterogeneous sources to identify potential hazards and to provide services to control them. Although there is no unique way to categorise traffic management systems, literature shows a different way of classifying TMSs. The review by [82], classified TMS as “Infrastructure-free TMS” and “Infrastructure based TMS”. The first one presents the fully distributed TMSs including cooperative congestion detection, congestion avoidance, and accident detection and warning, whereas the latter, including traffic light management, congestion detection, route suggestion, and speed adjustment.

Traffic management systems can be traffic safety management and traffic flow management. Traffic safety management focuses on VRUs and environmental safety, whereas traffic flow management focuses on traffic optimisation and traffic signal control. Priority policies for public transport (buses, trams, and taxis), emergency vehicles, and pedestrians have been integrated into most traffic control systems [34]. There are several urban traffic control and management systems around the world that control and manage traffic. These include but are not limited to Split, Cycle, Offset Optimisation Technique (SCOOT), Sydney Coordinated Adaptive Traffic System (SCATS), Method for the Optimization of Traffic signals In Online controlled Networks (MOTION), ImFlow, and Real-time Hierarchical Optimised Distributed Effective System (RHODES).

Split, Cycle, Offset Optimisation Technique (SCOOT)

By maximising the use of live data from vehicle detectors, SCOOT quickly adjusts traffic signal settings to reduce vehicle delays. SCOOT responds rapidly to changes in traffic, but not so rapidly that it is unstable; it avoids large fluctuations in control behaviour as a result of temporary changes in traffic patterns. It coordinates the operation of all traffic signals in an area to give good progression to vehicles through a network. There are many tools available within SCOOT to manage traffic and meet local policy objectives such as favouring particular routes or movements, minimising network delay, delaying rate runs, and gating traffic in certain areas of the city. SCOOT can follow trends over time in traffic flow and local short-term changes; however, as the optimisation procedure only allows a small amount of change to split, cycle and offset times, then SCOOT could be constrained by this during a sudden change in flow [83]. Currently, SCOOT is used in over 350 towns and cities globally[51].

Sydney Coordinated Adaptive Traffic System (SCATS)

SCATS works on a combination of coordinated vehicle actuation and fixed time plans as it uses a library of fixed time plans which have been developed to work in specific scenarios. It operates at two basic levels; the "upper level" which involves offset plan selection and the "lower-level" which involves the optimisation of various junction parameters such as split and cycle times [83]. SCATS is very good at coping with heavy flows which are close to saturation; however, its biggest performance weakness is the optimisation of offsets, which has an impact on the progression of vehicles between regions. SCATS can provide priority for buses and trams through a three-tiered system (high, medium, and low). SCATS has ITS interface that can support up to 100 connections for the exchange of data with third-party ITS applications [84]. SCATS is installed in over 1800 cities in 40 countries[52].

Urban Traffic Optimization by Integrated Automation (UTOPIA)

UTOPIA is a hierarchical-decentralized traffic signal control strategy that minimises the total time lost by vehicles; however, public vehicles are prioritised. UTOPIA is based on an optimising cost function depending upon vehicle delays and stops, delays to public transport and deviation from reference plan and historical signal timings. At a local level, it applies a microscopic model to estimate the state of the intersection, at the area level it applies traffic model to monitor the state of the whole controlled network, and at the town level, it integrates the congestion information and data from other systems such as bus travel times. It tracks public transport over a road network and gives them special clearances at traffic signals. UTOPIA is widely used in over 50 cities across the globe[53].

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[51] SCOOT: https://trlsoftware.com/products/traffic-control/scoot/ (Accessed on 16 July 2019)
[52] SCATS: https://en.wikipedia.org/wiki/Sydney_Coordinated_Adaptive_Traffic_System (Accessed on 16 July 2019)
[53] UTOPIA: https://www.swarco.com/products/software/urban-traffic-management/utopia (Accessed on 17 July 2019)

Real-time Hierarchical Optimised Distributed Effective System (RHODES)

Similar to UTOPIA, RHODES architecture is based on a three-tiered hierarchy: the highest-level assigns traffic to the network to determine base levels of traffic, this takes into account evolving traffic demand and network geometry. The level below is based on predicted platoon arrival patterns to determine signal timings. Finally, at the junction level, the movements of individual movements are modelled [83]. It responds to the stochastic behaviour of traffic in two significant processes: prediction of traffic flow and estimation of traffic parameters such as travel time, queue discharge rate, and turning probabilities. A benefit of this approach is that it includes the effects of the upstream traffic signals in the intersection control optimization problem. It responds to the natural behaviour of traffic flow.

ImFlow

ImFlow is a traffic signal optimisation application. It optimizes traffic flows through intelligent management of available road capacity and can even eliminate the need for major investments. It enables the road authorities to control traffic based on the traffic policies of the city such as requirements for environmental targets, smooth flows on the key routes, prioritisation of public transport or stimulating bicycle flows [85]. For instance, based on the position of the bus, the ImFlow algorithm calculates how long traffic lights need to be green, and give priority or longer green time depending on the policy objectives granted; however, the priority depends on the schedule (early and late). ImFlow has three primary control modes that can be configured to fit the traffic scenario, these are adaptive optimisation of traffic, local optimisation of flow, and green wave optimisation across a series of intersections[54].

Method for the Optimization of Traffic signals In Online controlled Networks (MOTION)

MOTION consists of a network and local level and builds enhanced dynamic traffic state estimation and prioritisation of public transport. It operates on four different functional levels:

- Data acquisition - for network incident detection, and origin and destinations.
- Dynamic traffic model - estimation of the most important individual traffic streams and analysis of traffic by determination of current traffic status.
- Optimizing control variables - iterations of common cycle times and split times are carried out to determine the optimum green times.
- Decision - the new signal programs are compared to the current signal program.

Optimisation Policies for Adaptive control (OPAC)

OPAC is a computational strategy for demand-responsive decentralized traffic signal control. The strategy has the following features: (1) it calculates controls that approach the theoretical optimum; (2) it requires online data from upstream approach detectors and neighbouring

[54] ImFlow: https://dynniq.com/product-and-services/mobility/imflow/ (Accessed on 12 July 2021)

intersections; and (3) it forms a building block for demand-responsive decentralized control in a network [86]. It can operate as an independent smart controller, as well as a coordinated system.

Scalable Urban Traffic Control (SURTRAC)

SURTRAC is designed for urban road networks, where there are multiple, competing traffic flows that dynamically shift through the day. By controlling each intersection locally, responsiveness to real-time traffic conditions is maximized, and by communicating planned outflows to neighbouring intersections larger corridor flows can be established on-demand to match actual traffic flow volumes [87]. It optimizes the performance of signals for the traffic that is actually on the road, improving traffic flow for both urban grids and corridors.

The Prodyn Real Time Traffic Algorithm

PRODYN - is the traffic control method that has been developed over the last decades since the 1980s. PRODYN is an algorithm able to compute in real-time the best signal settings concerning the delay criterion for any flow demand in traffic networks [84]. It decomposes the large urban traffic system into several smaller traffic systems (decentralised) and bases optimisation on dynamic programming.

There are several more urban traffic control and management systems – including Universal Traffic Management System (UTMS), Green Link Determining (GLIDE), The Real-time Urban traffic control system CRONOS, and others.

Furthermore, a traffic signal control strategy that achieves different policy objectives- e.g., gating and queue reallocation, avoiding air pollution hotspots, and encouraging modal shift at the edge of the built-up area is the state-of-art traffic control. This can be achieved in various ways by optimisation at different control levels- at an intersection or network level using algorithms convenient for further development of ITS applications and external data fusion. In this regard, it is expected that cooperative and connected ITS will improve the current state-of-the-art control systems. There have been researches that conducted on the integration of Cooperative vehicle infrastructure such as CAM and probe-vehicle data as an input into the control systems, for example, [85] proposes different algorithms that improve the queue measurement. Adaptive traffic controllers based on cooperative infrastructure could take over the traditional control systems.

Some cities are investing in traffic management in urban areas. For example, Transport for London (TfL) has partnered with Siemens to improve traffic management for the next generation. At project costs of £1b and to be accomplished in 10 years it will deliver a new world-leading traffic management system that will use new data sources to better manage road network, reduce congestion and as a result reduce delays and support people choosing healthier travel options and therefore improving air quality. This will help TfL make much better use of road space by optimising the traffic light timing to support various policy goals.

Over the years, numerous technologies have been used to improve traffic management systems (TMSs). Most recently, AI is also being used in TMS [88]. AI-based applications coupled with cameras installed at the traffic junctions, which provide a tool to detect and identify vehicles have been paving the way for AI applications for traffic management. Although the deployment of such systems is in an infancy stage, most researches are based on traffic simulations, which are not tested on real traffic. There are few applications of AI in traffic management systems that have been fully or partly tested in real traffic on the road. The applications are mainly employed to address different use cases – including vision-based traffic detection and monitoring (e.g., Vivacity Sensor Video Analytics[55]), traffic signal optimization (e.g., Vivacity AI for traffic signal control[56], *Surtrac*[57]), traffic classification (e.g., *iTHEIA* an AI-enabled video-based traffic counting and classifying system[58]), and traffic data analytics to manage and monitor traffic in urban areas (e.g., *NoTraffic*[59], *The City Brain* [89]).

3.6. Interactions of the components

Figure 9: Different components of the transport system

The integration of the above components of the traffic system and transport policy would allow bringing the optimal solution for the traffic problem and the use of road space. The interaction of the core transport components – including different modes, infrastructure, the network, and the flow is key for sustainable transportation. Moreover, interactions of

[55] https://vivacitylabs.com/technology/video-analytics/ (Accessed on 23 July 2021)
[56] https://vivacitylabs.com/technology/junction-control/ (Accessed on 23 July 2021)
[57] https://www.rapidflowtech.com/surtrac (Accessed on 28 July 2021)
[58] https://www.irdinc.com/pcategory/artificial-intelligence.html (Accessed on 12 July 2021)
[59] https://notraffic.tech/

automated vehicles with other vehicles, with the infrastructure and with other road users have to be addressed and user acceptance has to be ensured before the deployment of automated transport solutions. According to [90], the effective achievement of multimodal transport needs three important future developments:1) Optimising of individual modalities and making them efficient, 2) optimising the overall mobility system concerns structurally influencing the choice of modality, 3) real-time information for all various modalities and bottlenecks.

Furthermore, harmonization of EU cross-border and national regulations, standardization of procedure and solutions, ethical, legal and environmental, and safety are key factors as well. Nevertheless, the architecture of combining management, policy, and service will be challenging.

4. Mobility services

4.1. Services for people

Transport service for people comprises of the demands of people who use transport infrastructures – including road and public services. Transport services are provided to all groups of people such as the disabled, children, and the elderly. In particular, mobility and transport services can help older and disabled people to carry out daily activities with minimal risk of injury. Elderly people can use walking sticks and frames, mobility scooters and powered wheelchairs. Services that provide older people who no longer drive with possibilities that make driving easier are needed [91]. This sort of transport is the mode of micro-mobility. Other transport services including ICT-based payment systems and efficient traffic management coupled with parking play a great role in services for people. In this regard, shared mobility and mobility as a service will impact future transport services.

4.1.1. Mobility as a Service

Mobility as a Service is the provision of transport as a flexible, personalised on-demand service that integrates all types of mobility opportunities and presents them to the user in a completely integrated manner to enable them to get from A to B as easily as possible.

Over the long term, rather than having to find, book, and pay for each mode of transport separately, the MaaS platforms will allow customers to plan and book end-to-end trips using a single interface. The future of MaaS is not limited to individual mobility, the approach can also be applied to the business world and the movement of consumer goods [36]. For example, Helsinki has transformed its transport network into a door-to-door mobility on-demand system, named, *Whim app*. The first MaaS commercial app offers personalised travel plans based on pay-as-you-go or monthly subscription tariffs. These travel plans are designed to be flexible for the individual and to integrate the city's public transport and private options - whether train, taxi, bus, carshare, or bike-share. There are multiple MaaS pilots around the world, for example, *UbiGo* in the city of Gothenburg, *Qixxit* and *Moovel* in Germany, *Beeline* in Singapore, *and SMILE app* in Vienna, *Bridj* in Boston and Washington, and *Communauto/Bixi* in Canada [92].

Most notably through the emergence of on-demand private car hire firms such as *Uber* and *Lyft*, which have rapidly become commonplace in cities worldwide, Mobility-as-a-Service is an evolving concept of how consumers and businesses move away from vehicle ownership towards service-based transport. A prerequisite for MaaS is the solution for the last mile problem, and that is the value of this development [93].

Mobility as a service requires new business models for intelligent transport and data-driven inter-modal transport optimisation. Innovative, technologically sophisticated operations of ride-hailing networks, car, and bicycle-sharing systems, mobile trip-planning and ticket apps, and other new mobility services are going to win users in the cities around the world. Service for goods including a new form of logistics is causing the supply chain to change due to advancements in technology and transport systems.

Despite the exciting developments in Multi-modal MaaS aggregation, car subscription services, on-demand mobility, and commercial vehicle innovation, mobility services require an innovative business model and regulatory standards. Public authorities still struggle to balance the user experience offered by MaaS, with policy objectives of economic growth, social inclusion, space optimization, environmental benefit, and citizen health and wellbeing. MaaS requirement index enables operators and authorities to understand the optimum level of regulation and policy needed to achieve their objectives as pointed in [93].

According to [94], Cities, regions and local transport providers are in many cases already providing integrated mobility offers, though the scale and coverage of these differ widely across the EU. Where new mobility services are developed, the policy environment (at EU, national or local level) should ensure these contribute to sustainable mobility goals. City and regional authorities need to be involved in the development of policy around MaaS at EU and national levels. Through new models of governance and with public sector leadership, to avoid environmental, economic and social dysfunctions, MaaS should not be regarded as a distinct player from the policy. It can only achieve its goals if integrated with other measures such as low emission zones, on-street parking policies, personal/workplace mobility management, etc.

4.1.2. Shared mobility services

Another transport service that continues to grow is shared mobility. Shared mobility is the use of vehicles, motorcycles, scooters, bicycles, or other travel modes normally owned by the public or private person or mobility providers. Shared mobility provides the users with short-term access to different travel modes to meet the diverse needs of users. According to [95], expansion of services such as car-sharing, ridesharing, and car rental, there are more and more alternatives to private vehicles.

Shared mobility is changing the way people move around cities. It needs to understand how this is reshaping the city, and how to effectively adapt to these changes. In the cities, trips will shift from being one mode to multi-modal. In this regard, a variety of shared mobility applications are appearing - including but not limited to Business-to-Consumer (B2C) Apps, Peer-to-Peer (P2P) Apps, and public transit Apps services. Mobility service models that are designed to meet user needs such as public or private, membership-based or non-membership-based, P2P can be offered to the travellers. Mobility services based on business models such as B2C, Business-to-Government (B2G), Business-to-Business (B2B), and P2P can be offered. Shared mobility also includes operational models, which can be a station-based round trip or One-Way, and Free-Floating One-Way [95].

Shared mobility will be likely to result in fewer vehicles on the road because of sharing vehicles sequentially and a ride simultaneously. This would benefit the cities to optimally allocate the road space and has diverse gains in the reduction of environmental and congestion challenges on the corridors of the urban areas. However, the complexity of service and the issues of data sharing would challenge the full execution of the service in the cities.

Shared mobility services might impact service quality, the cost of mobility, citizens' access to opportunities and their use of public transport. Shared mobility also improves connectivity across the area for the population because it will help increase the use of existing bus and rail networks. The integration of Shared Mobility solutions in the urban and regional mobility market can aid the region in achieving decarbonising goals while promoting improved equitable access, affordable transport and economic productivity [51]. Shared mobility may lead to less pressure on parking space in cities [90], as more cars can be offered by providers and reduce vehicle ownership.

According to an *A.T.Kearney* review, the estimated number of global car-sharing members has increased from 7 million to 27 million between 2015 to 2018. However, only a small group of members use car-sharing regularly and people still value the inherent advantages of private car ownership[60]. The review also draws recommendations for action, for example, close collaboration with city administrators, selecting car-sharing cities based on population density, and targeting potential younger customers through marketing efforts.

Figure 10: Shared mobility

Source: Space market research[61]

Shared micro-mobility services

Micro-mobility service (e.g., shared bikes and electric scooter services) is one of the fastest-growing branches of transport service. It merges into every different type of transport to make the journey of people quicker and as easy as possible, particularly for the first/last mile problem often encountered in the cities. Based on the convenience and cost, micro-mobility service can be an alternative to cars and public transport in crowded cities. Further mixing micro-services with public transport and shared mobility give people a much greater variety of choices. Among many use cases, micro-mobility services increase access to public

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[60] https://www.de.kearney.com/documents/1117166/0/Car+Sharing.pdf/3bff4a9a-1279-b26f-3b23-8183f14979ce?t=1567671915045 (Accessed on 23 May 2019)
[61] https://thetrustedchronicle.com/ (Accessed on 23 May 2019)

transportation, reduce the number of cars on the road, lower environmental footprint, and provide convenient methods of transport for short trips – all while cost-effective[62]. These companies to get packages out to customers much faster than before. Transport based on automated vehicles will make tracking and delivery even faster. The rise in services in e-commerce such as the use of digital platforms, automation of logistics and supply has been increasing the demand for transport services such as kerbside parking and loading.

Not surprisingly, an effective logistics sector is now recognized almost everywhere as one of the core enablers of development, which is affecting a wide range of business sectors. In Europe, the logistics market is estimated to account for more than 10% of the European economy. The logistics industry has an impact on the corridors which connect to the main networks (TEN-T) connecting big cities and ports in Europe. Therefore, the logistics industry needs to innovate with new technologies and methods. A notable prospect of the freight and logistics sector in Europe is the possibility of multimodal logistics[66]. Innovations in logistics cover a broad range of technologies - including Big data and advanced analytics, AI, robotics and automation, IoT, 3D printing, Augmented and virtual reality, Bionic enhancement, Blockchain, Digital twins, Next-generation wireless, quantum computing, automated vehicles, Cloud and APIs, and Unmanned Aerial vehicles [67,68] [97], as depicted in *Figure 11*.

The first wave of automation using intelligent robotics has arrived in the logistics industry. Driven by rapid technological advancements and greater affordability, robotics solutions are entering the logistics workforce, supporting zero-defect processes and boosting productivity. With technological advancement in AI and development in sensors and vision technology, the capability of automated driving will fundamentally transform the way vehicles are assembled, operated, and serviced. From the manufacturing side, 3D printing will add new diversity to manufacturing strategies [98]. It enables companies to produce almost anything, layer by layer within the boundaries of a single 3D printer, which has a significant impact on the logistics, particularly, disruption of supply chains. Broadly, it undermines the sense of long-road transportation and centralised production sites.

AI stands to improve supply chain efficiency with its prediction and vision recognition capabilities and by driving intelligent workflow automation and delivering new customer experiences. The competitive advantage of AI through data-driven decision-making and reduction of costs increases the acceptance by industry leaders. On the other hand, high capital costs and requirements for the implementation of AI is key challenge.

Blending the digital and physical worlds, augmented reality (AR) can augment logistics quality and productivity, empowering workers with the right information at the right time in the right place. Virtual reality (VR) technology enables logistics providers to design, experience, and evaluate environments in a digital world for optimizing material flows and training

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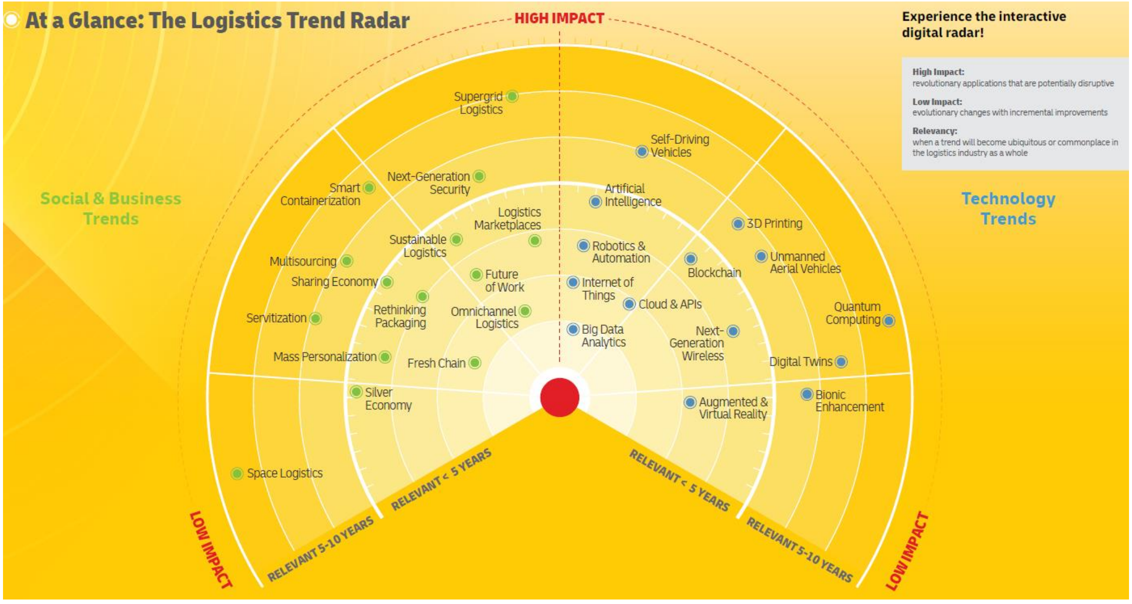
[66] https://www.mordorintelligence.com/industry-reports/european-freight-logistics-market-study (Accessed on 10 December 2020)
[67] https://www.bizjournals.com/bizjournals/how-to/technology/2016/09/7-technologies-transforming-logistics-industry.html (Accessed on 8 December 2020)
[68] https://www.koganpage.com/article/8-key-innovations-that-will-transform-the-supply-chain-logistics-industry (Accessed on 8 December 2020)

processes. Big data analytics in logistics offers massive potential to increase operational efficiency, improve customer experience, reduce risk, and create new business models [97].

Figure 11: The Logistics Trend Radar



Source: The Logistics Trend Radar 2020, DHL Trend Research, 5th edition [97]

In the logistics industry, robotics such as Unmanned Aerial Vehicles (UAV) or drones deliver from point-to-point and automated operations. Drones are capable of making an inventory in a logistic warehouse, transporting goods by air. It has numerous advantages, low shipping costs, reduced urban traffic and emission, and faster delivery of goods[69]. World-leading logistics companies such as Amazon have tested UAVs in the logistic service.

Scope for underground logistics would also impact the transport of goods. Underground freight transport deals with automated transport of general cargo by vehicles moving through an underground tunnel network. Underground freight transport can be an alternative for road transport, for instance in the combined development of intermodal freight transport by rail and urban freight transport. Although in theory people always see advantages in sustainable improvement of urban transport and logistic, the lack of practical application and accurate benefit analysis makes it difficult to implement and promote the underground logistics system [99]. Research by [100], indicated that compatibility and simplicity acted as neither a barrier nor an enabler, but try-out opportunities and context consistency acted as a barrier to implement underground logistic systems in addition to costs and project management challenges. However, recently there are few possibilities for the implementation of underground logistics, for example, Las Vegas approves Elon Musk's underground tunnel plan for cars. The proposal indicates that the underground loop systems offer reduced costs,

[69] https://www.stocklogistic.com/en/the-use-of-drones-in-logistics/ (Accessed on 9 December 2020)

less disruption to pedestrian and vehicles traffic, and faster construction than traditional above-ground options.

5. Components of future mobility

Future transport and mobility will be experienced and managed based on the future state of the uncertainty in demand, vehicles, and infrastructure. There will be significant growth in population and prosperity with increased road use and travel with fewer boundaries between modes of transport, and widespread use of automated vehicles through MaaS. An integrated mobility led by social, economic, and technological trends will be the future mobility.

Furthermore, the new development in technologies will determine the way we think about our future mobility needs. Automated driving, connectivity, shared mobility, electrification, and micro-mobility services will dominate the future mobility services. Fast-growing communication technology and digitalisation have been altering the expectation and desires of people towards the future mobility. The promising evolution of automated vehicles and robotics will also alter transport operations. A reduction of car numbers on the roads, combined with electric and automated vehicles in the future, could have a significant effect on emissions and the efficiency of transport. These changes could bring enormous benefits to the transport for people and goods. They could make transport safer, easier, and more inclusive while minimising its impacts on the environment and could boost productivity and investment [58].

Figure 12: Visualisation of a potential future urban scene with mixed transportation mode

Source: Department for Transport [58]

These advancements in disruptive technologies and patterns of transport demand will make the future scenarios of transport and infrastructures more uncertain. Practical steps towards the operation and deployment of new solutions need to take over the forthcoming challenges in the transport system. However, if technological changes are not effectively managed, they could have undesired effects, such as increasing congestion or reducing sustainable travel [58]. In the MORE project, we foresee different future components of future mobility, which consider the progress in the technical development and deployment of ICT-based ITS, the increase in population and urbanization, and the use of road space in urban areas.

5.1. A new pattern of transport services

As new technologies continue to evolve new patterns of transport services are being introduced to achieve the demand and efficiency of operation in the transport sector. While the overall travel demand has continued to rise, individuals have reduced car ownership and look to network operators to provide the infrastructure that guarantees a high level of services. Cities will be able to provide infrastructure and regulatory frameworks to operate services.

The future demand for transport services can be affected by the overall advancement in technology and the prosperity of the economy. In this regard, we could imagine that the transport system can be affected by flexible working hours and places. For example, future companies can allow their employees to work from home and/or to share offices with other companies based on employees' residences. The wider use of automated processes powered by AI will be expected to decrease the number of cars and pedestrians on the road, through advanced delivery robots and flying cars. From the infrastructure side, new pedestrian crossing solutions such as sliding and flexible road crossings will be built. The progress in these and future transport scenarios will bring significant change to the current transport services, although the parallel development in non-transport technologies would be still disruptive. Moreover, the demographic composition of people will demand a variety of transport services, for example, young people like to travel more.

5.1.1. Special services based on intelligent vehicles

As the technology and associated infrastructure evolve, it will effectively take the level of connected and automated functions from limited to fully connected and automated. Full implementation of automated driving such as automated vehicles and drone services will solve legal, social, and transport issues; as a result, special services for people and goods based on automated driving can be expected. Addressing advances in transport modes and their operations and developing solutions that can cope with these new developments can be exploited to further increase the benefits for the MORE project as their introduction scales up.

Planning of pick-up and drop-off can be solved with dynamic allocation of lanes when there is a high demand on a certain road, combining lower demand drop-off and pick-up with stops at traffic lights, authorising a passenger with reduced mobility to stop at one specific point and adding dynamic drop-off/pick-up areas for last-mile transport or even converting part of a lane into a temporal parking area.

Connectivity and automation eventually impact most of the logistics in the transport service, lowering the emissions for heavier vehicles and innovations in last-mile deliveries are the basics in the urban logistics landscape. Automated vehicles will be an enabler for MaaS, particularly for last-mile transport solutions. The expansion and full functionality of MaaS will influence future transport services. Providing the regulatory issues, aggregation of multi-modal services into MaaS would be anticipated to change the mobility service for people and goods. The integration of micro-mobility, bicycles, and automated vehicles in MaaS drastically change both the operation and use of the transport services. Based on the review of user needs in the design of the major urban TEN-T feeder routes, under *WP1 D1.1* of the MORE project, it is stated that modal shift is important for the efficiency of the delivery of goods and environmental pollution. Modal shift from big trucks to commercial vehicles, automated vehicles, and drones are suggested as the best solution for the last mile transport challenges.

In this aspect, there is remarkable progress in the deployment of AVs into existing transport services. For example, the Department for Transport is supporting the review of regulatory frameworks for the safe deployment of automated vehicles in the UK, led by the Law Commission of England and the Scottish Law Commission. The review also consists of the use of AVs as part of a modern public transport network and on-demand passenger services [58].

5.1.2. New services due to technology and demographic changes

In the future, potential changes in demographics, working practices, and new transport products will bring new transport services. Europe is facing unprecedented demographic changes (an aging population, low birth rates, changing family structures, and migration). The changes in demography and lifestyle have an important impact on the future demand for all forms of transport. As identified in *WP3 D3.2*, future road users' needs will be based on demographic changes, lifestyle, disruptive technologies, and future business models enabled by technology. For example, the elder generation focuses on the safety and affordability of transport services, while the younger generation focuses on quality, personalised and technology-dependent services. Younger people are less likely to own cars than previous generations and are driving less, due to factors such as staying in education for longer, moving into long-term employment, starting families later and the cost of driving [58].

The timely progress that could influence the need for new transport services in the future is a smart city. As cities become more and more congested, it becomes increasingly clear that our current urban infrastructure is no longer fit for purpose so smart cities are the next step forward easing the challenge due to new services appearing and progressive urbanisation. Moreover, the concept of smart cities would help to solve issues related to congestion, traffic delay, and public safety and security [101]. Smart cities are expected to enable the sharing of quality data across transport infrastructure, transport mode, and ICT-based information infrastructure of the cities. Providing the security and privacy issues smart cities will bring new patterns of transport services which can alter the operation and practice from both demand and transport provider sides.

Another service that could change due to dynamics in demographics is public transport. Public transport is a good way to reduce congestion and environmental and health-harming emissions in urban areas. In the past decades, various developments have been made to improve public transport services – including the development of public transport infrastructure, time scheduling and ticketing, operation and governance, and safety. In the future, developments in both technical and societal will allow the users to decide easily between various travel alternatives, use automatic payment, and integrate travel subscriptions to different public transport services.

Analysis of the robustness of current public transport strategies to the uncertainty trends and creation of the knowledge base for a further strategic process is required to lively enhance public transport services of the future. In this regard, Public Transport Norway [102], has designed a comprehensive scenario for future public transport in Norway. Four scenarios that provide a shared frame of reference for a future public transport that is constantly changing and characterised by significant uncertainty are designed. Scenario 1, mobility revolution - the customer's travel habits have drastically changed after COVID-19; public transport players can utilise technology and become the agent of innovation for sustainable mobility. Scenario 2, fragmented mobility service - the customer's travel habits have changed drastically after COVID-19, but the public transport players are not able to transition quickly enough to provide individualised means of travel and are therefore less relevant. Scenario 3, back to basics - the customer's travel habits are developing in line with the pace observed before COVID-19, while a new regulatory framework has led to the public transport players losing the right to sell tickets to their customers and are therefore a less relevant instrument for achieving the sustainability agenda. Scenario 4 individualised on the surface – the customer's travel habits are relatively unchanged from before COVID-19; the public transport players utilise technology in a good way and the public transport players are the agents of innovation for sustainable mobility. In the process of creating these scenarios, customers' travel habits and the role of public transport as a community developer were identified as the primary axes to drive the scenarios. Considering the different roles of public transport players, the implication and criteria for the success of each scenario are detailed in the report.

Furthermore, electrification, automation, and sharing mobility are the disrupting mobility integrated services that will be in demand in the next years. It also can be a potential synergy to integrate automation and electrification and further provide robotic taxis, self-driving shuttles, and delivery robots. Digitally enabled business models will bring new transport services include ride-hailing and mobility as a service.

5.1.3. The future of mobility and pandemics

The emerge of pandemics and epidemics are the main global challenges to the economy and society. Apart from their impact on people's health and consequential fatality, they highly disrupt the way people live and travel around the world. Contiguous infectious diseases such as SARS-CoV-2, dengue fever, and the avian flu greatly affect almost all forms of transportation. Witnessing the recent outbreak of the COVID-19 have a severe impact on society and the economy. Governments' restrictions to slow down the spread of outbreaks lead to damages to global economic operations, and consequently have a significant impact on the transportation of goods and passengers. As a result of travel restrictions and lockdowns, the demand for personal mobility decreases, and at the same time, the demand for e-commerce and home delivery has exploded. Most of the changes in the complexity of economic operation and nature of mobility will remain in the medium to long term.

Organizations within the mobility system need to develop strategies that will help to shape the future, provide options to respond to different outcomes, and offer assurances in case of unforeseen setbacks. As highlighted in the report by [103], mobility patterns and activities would be affected across three major categories – global, behavioural, and technology/market.

- Global: passenger demand growth; socio-economic inequality; e-commerce; city topology transformation.
- Behavioural: working from home/flexible working; travel safety consciousness; healthier mobility lifestyle; re-spacing and retiming of trip patterns.
- Technology/market: digitalisation of offerings; acceptance of new forms of mobility as part of the system; market consolidation of private mobility players; intelligent transport systems.

The pandemic allows city governments and transport authorities to shape more sustainable, resilient, and human-centric urban mobility systems. According to research by [103], many of the cities involved in the study have already been regulating the mobility systems and their components. The regulations include urban space allocation, transversal mobility mode planning, and new mobility regulations. They also enable other mobility system sectors including new governance arrangements for better collaboration across the systems and reassessment of investments in the mobility infrastructure. Nevertheless, other key players do not recognise the urgency to radically change the system.

I the short term, the COVID-19 crisis is likely to harm the scalability of MaaS, as the MaaS business model largely revolves around trips performed with mass transit and shared mobility modes that have suffered from collapsing demand. In the medium term, MaaS can contribute to increased system resilience by providing more choice of mobility options and ease of use. In the longer term, MaaS certainly has the potential to positively influence mobility patterns and behaviour in a way that will align much better with the uncertain post-COVID environment.

Post-coronavirus, supply chains will not be the same as they were pre-coronavirus. In the ‘pre-new normal’ phase, resilience, demand, transportation, warehousing-related topics, and workplace operational practices will become critical issues. Supply chains will re-shape themselves around resilience, with more diversified manufacturing, and multiple sources of supply. In the journey from lockdown to ‘pre-new normal’ and then to new realities transportation and warehouse networks might have to be re-configured to ensure more flexible, but still cost-effective supply chains. Workplaces will see changed practices around social distancing. Supply chain innovation will be essential and collaboration along the value chain will be the enabler for future business success [104].

The COVID-19 crisis, therefore, offers a unique window of opportunity for authorities and operators to significantly reshape mobility systems and logistics. Transport authorities have a critical role to play to accelerate change by “framing” and “enabling” the mobility system.

5.2. Advances in space management

In the future, streets, kerbside, and public places are expected to smoothly accommodate the activities by people and other transport components. There are many expectations regarding the transformation of mobility in urban areas. As an example, people will smoothly coexist with vehicles and facilities, the walking area will be smooth and entertain people. Mobility brings the use of dynamic routes and lines, cities may turn into playgrounds, and public places are more pleasant and attractive to go out. Furthermore, kerbside management will be transformed from static and single function to dynamic and multi-functioning areas. The evolution of technologies and vehicles will change how cities look; mainly ICT and data will transform the design and use of road infrastructure and kerbs in the cities.

5.2.1. ICT-assisted road-space design and use

The next generation of urban infrastructure, creating dynamic and intelligent streetscapes will transform the smart city which benefits air quality, reduce congestion, safety, and other benefits. Smart infrastructure and intelligent mobility are the future of our cities[70] [105]. With an increasing focus on creating more compact, sustainable and liveable cities, the design and use of road space will be flexible. The planning and development of roads are expensive and occur over long periods. As a result, integration and use of ICT-assisted roads ensure the efficient and best use of current infrastructure and possibly reduce the need for future large investments in new roads. These indicate that smart assets are the potential way to improve the use of road space in urban areas.

The future ITS deployment involving automated vehicles and V2X communications infrastructure is likely to significantly improve traffic flow. The expected mixing of automated with conventional vehicles, as well as the technologies involved in the near future will also be challenging, for example, operating both on the same road infrastructure. However, these require ICT-assisted road space design and use. In this regard, there are several promising developments. The considerable advances in information management, use of sensors and drones, and a range of other technologies would improve a good practice of the service if included in road design and construction. Over the next years, the road assets should become resilient, easy to maintain, and easy to build, by focussing on automated design, data improvement, automated construction, maintenance, and inspection through robotic construction and drones. This enables inspecting and managing transport infrastructure and smart roads, controlling the whole process with cabled and Wi-Fi-enabled sensors, instantly

[70] The next generation of urban infrastructure. Creating dynamic and intelligent streetscapes, Trueform Digital.

and simultaneously “talking” to cars, as well as to the surrounding infrastructure, traffic control centre and emergency services.

Transformation of public space would require redesigning of the existing road infrastructure with help of IoT, which in turn contributes to the realisation of automated driving on busy urban streets is viable. In cities, successive additions of transport modes have constrained pedestrian sidewalks and cycle paths to minimal width, and at the same time two-way roads, car parking, and bus stops occupy the greater part of space. In an experiment done by [106] that deals with a busy urban street in Copenhagen (Gammel Kongevej street, stretches 1.8 km, and 18 m wide), imaginative assumptions for designing public space with AVs have been experimented. The design proposal utilises IoT, where embedded sensors, lights, and transmitters allow vehicles to communicate with road infrastructure. Rather than having fixed street infrastructures, LEDs that can reallocate space by changing traffic volumes are exploited. The design experiment focused on how pickup/drop-off areas could be integrated into the already crowded streets while allowing an extension in the width of cycle lanes to meet increased travel demand by micro-mobility services.

The experiment considered the following design requirements [106].

- Residents in the inner city would be banned from owning personal cars, and wide (3.5 m) cycle lanes would be provided adjacent to footways. Other transport modes (e.g., micro-mobility) that use the bicycle lanes would always have a priority including over people joining/alighting AV shuttles and wishing to access the footway.
- Fixed on-street parking and bus stops are removed, and AV shuttles do not have fixed stopping points but are free to stop anywhere along the road - then half the width of the cycle lane will then transform into a temporary boarding/alighting space for passengers, with cyclists filtering into the 50% width cycle lane. The enforcement of the remaining lane (buffer area) is enabled through sensors by monitoring the user’s duration in the buffer area, and a road surface only returns to normal once the user has left the area.

Another promising future ahead is electric road systems: emerging infrastructure technologies that charge electric vehicles while on the move could start to play a role in decarbonising the road traffic within the next decade. However, stakeholders felt that electric road system is unlikely in an investment plan at this time [107].

5.2.2. Advances in kerbside management

Space which people often think is just for car parking is space on the public road next to the footway (i.e., at the kerb). Examples of kerbside use can include, bus stops, cycle and car parking, waste collection, servicing and deliveries. In the urban areas, there are very high and often competing demands for the use of kerbside space – including pedestrian crossing, variety of parking use, loading and unloading. Due to changing travel trends and the introduction of various transport modes, the demand for street and kerb space use is tremendously increasing. Furthermore, these developments are promoting a rethink of parking policies and how we use kerbside.

Parking space is a scarce and valuable resource impacting traffic flow, congestion, and economic vitality. On-street parking is the most convenient parking option and a critical resource for supporting retailers. On-street parking time limits and documentation of parking occupancy are effective tools to understand and manage parking resources. Effective on-street parking management establishes efficient area (streets) use and prevents negative impacts on traffic, pedestrians, and cyclists. The on-street parking goal is pursued using a wide range of components, including marking, designing the space and signs, setting time limits, charging fees, and others. The secret to parking success is on-street parking management, which in turn enhances space management in time. Several recent developments are prompting a rethink of parking policies and the use of the kerbside. With new mobility services, car ownership is going to decline, but as more goods and services are delivered to doorsteps there will be increasing demands for short-stay and drop-off/pick-up space, and more goods and services delivery. Thus, advances are needed in on-street parking and loading management – and, more generally, advances in kerbside management.

The development in intelligent kerbside management such as KERB[71], Virtual Parking System (VPS)[72] offered by UK innovation and research allows the commercial vehicles to book the virtual loading bay and parking bay allowing drivers to load and unload in close proximity to their delivery point without causing congestion and without the risk of receiving a Penalty Charge Notice (PCN) while saving time and fuel. Furthermore, in this area, a holistic kerbside management platform, which contains smart parking solutions, data-driven insight from kerbside data, and payment solutions has been developed[73] called *AppyParking*[74].

Another emerging practice that appears to offer a novel approach for introducing urban change, is the increasing use of temporary parking and dynamic lanes (e.g., bicycle lanes). For instance, *FlexKerb*[75] has been designed to allow connected and automated vehicles to function with cyclists, pedestrians, and other road users for maximum efficiency. A single segment could function as an automated vehicle rank at rush hour, a cycle path at lunchtime, a pedestrian space in the evening and a loading zone overnight, using embedded LEDs of different colours to indicate its function.

Despite the growth in parking-related new technologies, effective parking management has become more of a challenge; however, there are a few promising comprehensive solutions, Conduent Transport [76]providing an integrated solution for kerbside management. It builds on

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[71] https://kerb.works/netherlands/groningen (Accessed on 26 December 2019)
[72] Loading bays: http://www.citylogistics.info/policies/london-uk-starts-testing-virtual-loading-bays/(Accessed on 3 December 2019)
[73] Holistic kerbside management platform: https://appyway.com/kerbside-management/ (Accessed on 3 December 2019)
[74] Solution to parking:https://siliconcanals.com/news/london-parking-funding-news-appyparking/(Accessed on 3 December 2019)
[75] https://www.arup.com/news-and-events/arup-shortlisted-in-competition-to-make-streets-fit-for-driverless-cars (Accessed on 5 December 2019)
[76] https://transportation.conduent.com/solutions/curbside-management/ (Accessed on 5 December 2019)

next-generation technology, providing data integration and embracing complex solutions with a single back end to help manage scarce kerbside space and achieve goals like promoting access, achieving Vision Zero, creating a modal shift, and mitigating congestion. A new and innovative application for parking that integrates payments and kerbside restrictions maps for intelligent parking has been widely used by drivers in the UK.

5.3. Data-driven intelligent transport systems

5.3.1. ITS solutions based on FCD

Augmentation of data from various sensors technologies into ITS data sources and applications will have a tremendous impact on enhancing transport management systems. Floating Car Data is derived from vehicles that are circulating in the traffic network and providing information about their trajectories. The vehicles’ path and travel time are extracted from the position, direction, and speed information of vehicles generally equipped with either cell phones and/or GPS. FCD provides speed and travel time estimates across the entire road network, whereas fixed sensors typically only provide speed or flow estimates on highways or major roads and on rare occasions can supply sparse travel time data. Travel time information is usually extracted from fixed sensors (e.g., vehicles' inductive loop profiling sensors, Bluetooth, and video surveillance registering license plates) on the side of the road. Therefore, FCD can greatly improve the estimate of the traffic state and prediction of the travel time that is traditionally based on data from fixed sensors.

In many research works, the potential of FCD data and roadside data were investigated and empirically compared. In paper [108], proper utilization of travel information from FCD would benefit the cost of installation and maintenance of roadside sensors. In the paper [109], the travel times from FCD on a certain road segment can be used to predict travel times for another segment of road in the network. It is also researched that FCD is capable to detect recurrent congestion or bottlenecks. Furthermore, as vehicle communication and connectivity, cellular coverage and em17(o)-8(f)-4( )-4(t)17(h)2 for s.W3(n)-8(t)17( )17(ca)-8(n)-8( )1..79 6re systems. With the fast-growing wireless-communication market, cellular positioning technologies are becoming one of the important means of monitoring real-time traffic status, providing traveller information, measuring transport system performance, and estimating travel demand.

The forthcoming 5G technology is crucial to fasten communication and real-time data sharing among automated driving, between vehicles and infrastructure, and IoT systems. Staying connected using a 5G wireless network would ensure that vehicles are constantly monitored and managed by traffic management as it assures their efficiency and safety. Traffic demand data from a 5G network can speed up the operation of traffic management operation and provide accurate data with additional features. Real-time traffic demand data can be easily accessible from devices connected by the 5G network.

The [112] paper describes the relevance of mobile data for traffic demand estimation, transport, and traffic management. This has more advantages in terms of the content of information and economic benefit than investing in roadside sensors. The [113] paper analyses the potential of Mobile Phone Data (MPD), which can be used for improving the structure of OD-matrices in transport models as well as indirect use for determining traffic flows. The [114] paper describes a new architecture of urban traffic management that is based on new technologies such as 5G wireless network and Mobile-edge computing (MEC).

Thus, every new generation of cellular networks requires smaller cells to provide increased data rates over the same frequency spectrum. This means that more accurate data will be available on the number of cell phones and the speed of the movement for the classification. This data is valuable for traffic management purposes. In the cellular-based approach, there is no special device required for the vehicles and no specific infrastructure is built around the roads. It is cheaper than conventional detectors and provides greater coverage potentials. Further traffic data is obtained continuously instead of isolated point data. Although the technology is easier to install and maintain, due to privacy issues, and coverage of users from the entire population the data requires more processing.

5G cellular network will generate a tremendous amount of data that could be used to enhance the efficiency of transport and its externalities. For example, commuters' data collected through phone applications will help to discover users' behavioural profiles and trends in transport demand. But the coverage of 5G will not be homogenous due to the problem of recovering the investments in sparsely populated areas. These may cause the need for basic conventional infrastructure.

5.3.3. Data from air quality monitoring sensors

Nowadays, with the advancement in technologies, air quality monitoring sensors are becoming not only more precise but also faster at measuring. Devices are becoming smaller and cost much less than ever before. New sensors to measure air quality will enable better measurements of the current situation in cities. If these sensors are strategically placed, the data can be used for online modelling to support environment-friendly traffic management.

The developments in sensor and communication technologies have also made the deployment of small, portable, and relatively low-cost air pollution sensors more convenient. This makes air pollution monitoring possible in many more locations, generating data. By integrating and analysing these data and possibly data from other sources such as IoT and smart assets, it would be possible to understand the traffic flow on the corridors and to influence and monitor air quality in the urban environment. Historical and real-time air quality data can be used to quantify the current and future impact of air pollution on our lives. By combining air quality data with other traffic data, cities and transport authorities can work towards sustainability and efficiency of transport based on richer information.

5.3.4. Big data acquisition and analytics

Increasing the collection and use of mobility data will help unlock the potential of big data analytics. FCD data from 5G cellular networks and other sensors are the potential sources to optimise and manage transport systems. Following the introduction of automated and connected vehicles into the fleet, adaptive automated traffic control, navigation, and collision avoidance systems are required that collect and process the abundant data [115]. In-vehicle and traffic sensing sensors generate a huge variety of data such as image data for which computer vision could be used. Due to vast progress in cameras image and video data, it would also be advantageous to use this to analyse road traffic.

Big data analytics can significantly impact the transportation sector: optimization of transit schedules by analysing the demand and predicting the impact of maintenance, road work, congestion, and accidents; it impacts freight movement and routing optimisation; predictive maintenance. For mobility, big data analytics can help with planning and managing transportation networks and designing and optimizing services to meet transportation needs. Big data analytics includes a wide range of specific tools and techniques that can be used to gather insights from data; specific techniques include data mining, predictive analytics, and text mining [8]. Machine learning and AI are the most popular techniques to extract useful insights from big traffic data.

Artificial Intelligence (AI) has been impacting and driving technologies, predictive maintenance based on the data from sensors and route optimisation, innovative road surface materials leading to improvements in maintenance cost, improved safety in bad weather conditions, CO_2 emission reduction, and noise reduction. Road closures due to maintenance are among the top reasons for traffic congestion. Predictive maintenance is a promising solution for increasing the availability of roads. When sensors detect the quality of the road is nearing a point where maintenance is required, it can be scheduled at a convenient time, rather than having to close the road for an urgent problem during rush hour. Recent advances with big data in this area are promising.

There are quite diverse areas of application in transport where AI will bring promising impact including, predicting traffic demand, predicting the deterioration of transport infrastructure, signal control of traffic at road intersections, dynamic route guiding, classifying the traffic state as incident or incident-free, identifying driver groups with certain behaviour, the transport planning process. Optimisation resulting from this can support designing an optimal transit network for a given community [9] [10].

Furthermore, AI in transportation has an impact on automated vehicles, smart highways, drones, automated ships, smart rail, and smart cities. AI-led- automated transport could help to reduce the human errors that are involved in many traffic accidents. However, challenges, including unintended consequences and misuses such as cyber-attacks, biased decisions about transport, ramifications for employment, and ethical questions regarding liability for the decisions taken by AI in the place of humans must be taken into account [10].

Examples of big data analytics applications are knowledge from large-scale data collected from sensors, travel surveys, and socio-demographic information extracted to understand driving volatility [116]. In [117], a method that enables modelling the potential consequences of new technologies and services using a variant of the fuzzy cognitive map (FCM) approach was developed. *Data Hub* a traffic data visualisation tool developed by Urban Transport Group (UTG) is a unique link for that visualization that can be inserted into reports, websites, and social media channels. Furthermore, a highways technology company *gaist*[77] who are providing quality data regarding infrastructure and assets in the UK launched an Artificial Intelligence research hub to make a cost-effective and informed decision about transport infrastructures.

Thus, the accessibility of big data from various sources can potentially lead to a revolution in ITS development, changing ITS from a conventional technology-driven system into a more powerful multifunctional data-driven intelligent transportation system. Big Data analytics, especially the application of AI has the potential to make traffic more efficient, ease traffic congestion, free driver's time, make parking easier, and encourage car-and-ridesharing.

5.4. Dynamic traffic management and signal control at a network level

5.4.1. Integration of new data and AVs to traffic management and control

Traffic management and control systems rely on information from traffic flow sensors. These sensors can be in-road sensors, above-road, and roadside sensors. However, due to installation, maintenance cost, coverage area and many reasons, alternate data sources to supplement information provided by conventional sensor measurements are essential. Alternatively, C-ITS and sensors generate a huge amount of data that can be analysed and supplement information for traffic management.

The current traffic management and control systems solely rely on the information from traffic flow sensors that capture the presence or passage of vehicles in a particular location. However, due to installation, maintenance cost, coverage area and several reasons arise from sensors, alternate data sources to supplement information provided by conventional

[77] https://www.gaist.co.uk/intelligence-for-highways (Accessed on 23 July 2019)

sensor measurements are essential. This provides richer information about traffic flow and management, which improves the reliable ICT-based sustainability of the transport system.

The significant development in communication and sensor technology will provide additional and alternative data that enhances ITS. For example, data from cooperative and connected mobility from road-side and on-board units provide richer information for intelligent traffic management. In addition, data from navigation systems transmitted on a cellular network such as FCD, data from Road-side Units received from vehicles such as CAM, and data from mobile networks can be fused to improve the efficiency of traffic management systems. In the future, the efficiency of traffic control can be enhanced with individual route information, provided that accurate data is provided by individual road users. In this aspect, route information from automated vehicles is expected to be used for the optimisation of traffic signals and estimate traffic state. Sensor data fusion and integration of data from UTMS will improve traffic management and control.

5.4.2. Road network coordination

A strategic view of the entire urban network, with improved detection and communication technologies, is required to enter the next evolution of urban traffic control. New intelligent traffic management and control strategies that operate at the network level will substantially increase the efficiency of traffic flow, reduce negative environmental impacts, and meet differing policy objectives. Traffic management and control that effectively coordinates and manages traffic on the complex network will be the solution of the future. Signal coordination methods have been widely investigated to improve the performance of traffic control systems in the urban road network. Due to the large-scale road network and numerous time-varying parameters, a basic challenge faced by these methods is the high computational complexity. The method proposed by [118] decomposes the network into several arterial roads and scattered intersections. The method solves the problem by coordinating several principal arterial roads and several isolated intersections on the boundary of the area.

There are several situations where intersections adjacent to each other should be coordinated. Signal coordination along an arterial corridor will significantly reduce both overall travel time and delay for vehicles using that corridor. The main way to manage traffic on the corridor is through a green wave and gating. Gating (either queue relocation or ramp metering) and green wave solutions coordinate a series of intersections based on the traffic flow along the road. Gating is essentially holding/releasing a platoon of vehicles driving to intersections, which can be a part of a green wave along the corridor.

Green waves can be achieved by signal control coordination. In this regard, signal coordination means that traffic signals along the arterial road are synchronised, which creates smooth traffic flow. The most effective strategy for guaranteed green waves is static control; however, semi-static control and adaptive control are considered the best solutions in the market now. Adaptive control has advantages due to its flexibility in the control algorithm, yet it needs to be stable enough to be accepted by users. For example, SCOOT along the arterial road. On the other hand, there are also traffic management applications that efficiently handle the traffic on intersections, e.g., ImFlow. Other than static controllers, Agent-Based (AB) control has higher flexibility and can, therefore, exploit the solutions for automated driving and new data sources much better. Combining the green wave solution and gating into agent-based dynamic traffic management can minimize the number of stops and delay time, and optimise the location for gating.

The future solution can be, for example, a solution that combines the Agent-based (AB) adaptive control algorithms such as ImFlow and Reference-Plan-Based (RpB) adaptive control algorithms such as SCOOT. The fact that SCOOT works effectively on arterial roads, while ImFlow works effectively at smaller networks, a solution that combines the benefits from both would be required. By combing the good aspects of the two algorithms, a solution that performs optimally at a network level can be developed. However, this solution is only feasible when there is infrastructure (e.g., sensors). This network coordinating solution is expected to manage complex networks based on the detection data and data from external sources such as UTMS and FCD.

5.5. Smart cities

A smart city is a place where traditional networks and services are made more efficient with the use of digital and telecommunication technologies for the benefit of its inhabitants and business. It means smarter urban transport networks, upgraded water supply and waste disposal facilities, and more efficient ways to light and heat buildings. It also means a more interactive and responsive city administration, safer public spaces that are meeting the needs of an aging population[78]. The big part of the ICT framework is essentially an intelligent network of connected objects and machines that transmit data using wireless technology and the cloud. IoT solutions and sensors are active and expanding rapidly. With help of the aforementioned technologies data collected from citizens, devices, buildings, and assets are then processed and analysed to monitor and manage traffic and transport systems, power plants, utilities, water supply networks, crime detection, information systems, hospitals, schools, and other community services. For example, connected traffic lights receive data from sensors and vehicles, connected vehicles communicate with parking meters and EVs charging docks, and nearest drivers.

Although the creation of the infrastructure and deployment of the systems in the framework is still in the early stages, the preparation and initiatives that enhance the development of smart cities are promising. One of the initiatives is supported by European Commission called Smart City Marketplace. Smart City Marketplace brings together cities, industry, small businesses, banks, research, and others and is the main framework for the development of future smart cities to improve urban life. Today cities and their municipal partners are investing in smart city applications that drive better city outcomes in the area such as energy, water, building, lighting, and transportation.

[78] https://ec.europa.eu/info/eu-regional-and-urban-development/topics/cities-and-urban-development/city-initiatives/smart-cities_en (Accessed on 23 February 2021)

According to *ESI ThoughtLab*[79], the key findings from a global survey of 100 cities conducted from *Building a Hyperconnected City* program showed how cities can go beyond current smart solutions to become “hyperconnected” hubs generating economic, social, and environmental benefits by linking key elements of their urban landscape - including transportation, public health, energy, water, security, and sustainability. The cities surveyed reported that they will spend $141 billion on smart city projects in 2019, which amounts to an average investment of $1.4 billion per city.

However, to lower the physical and digital obstacles and increase the pace of the deployment of solutions, cities should look to leverage existing and proposed investments in physical assets, communication networks, and smart city solutions. The obstacles of the deployment of sensors and smart devices into urban areas can face both physical world and digital world challenges[80]. Adding new physical sensors to urban infrastructure in public space requires extraordinary work to keep the devices and physical infrastructure orderly and in good operation. Another concern about the physical world is ownership of infrastructure and the process of gaining approval to attach new sensors or devices to public infrastructure. Where, the digital world obstacles include technology concerns like power, communications, data ownership, privacy, expense, and application values. This requires a cost-effective capture of data, communicating it to the cloud, and creating applications that create new insight and value.

Smart Cities will be an evolving ecosystem, comprising a range of systems that exchange data, which will only add further risks. Despite its development, there are security issues that could affect citizens' privacy or the failure of critical functions. In this regard, the National Cyber Security Centre of the UK has developed a set of cybersecurity principles to guide players in designing, building, and operating connected places systems (or digital and cyber-physical systems) securely [119]. This guidance will help authorities build awareness and understanding of the security considerations needed to design, build, and manage their connected places. *Principle 1:* develop understanding and context of their connected places about the impacts, risks (related to confidentiality, integrity, and availability of data), cybersecurity governance and skills, suppliers’ role, and legal and regulatory requirements. *Principle 2*: designing of their connected places, which includes the architecture based on the design principles, design to reduce exposure, design to protect data, design to be resilient and scalable, and its monitoring based on log events from the systems. *Principle 3:* managing their connected place’s privileged access securely, supply chain, its life cycle, and managing incidents and planning responses and recovery of them.

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[79] https://www.stantec.com/en/news/2019/global-survey-100-cities-reveals-roadmap-smart-city-best-practices (Accessed on 6 January 2021)
[80]https://smartcity.cioreview.com/cxoinsight/looking-at-a-smart-city-deployment-model-nid-24109-cid-134.html (Accessed on 6 January 2021)

6. Challenges and threats of mobility

ITS applications are expected to provide safer travel to commuters, manage traffic to reduce road congestion, and offer information for various mobility services. Security and privacy of data sharing between different entities of an ITS are the keys to sustainable and safe transportation. Applications that involve vehicle safety or sharing personal information need to be secure against network attacks [120]. Without security and privacy, attackers could easily utilise the traffic control system, to collect people's daily movement history, extremely abuse Big Data sources, and even cause accidents on purpose. To overcome security threats related to ITS applications, security procedures and algorithms have been developed, e.g., IEEE 802.11p standard. Although vehicles are communicating on a standardized network, the vulnerability of the systems, the vehicle or computer on wheels to cyber-attack needs attention. The progression on the internet and cellular communication leads to a new era that is called the Internet of Vehicles (IoV), which will require attention for security and privacy [121]. There may be many more cross-cutting issues that arise in efforts to improve mobility. These could impact the specific component of the transport system.

6.1. Data privacy

Growing trust in Big Data, increasing smart infrastructure, and the IoT have profoundly impacted the regulatory environment experienced by transportation professionals. In traditional methods, the privacy of individuals is protected by simply removing personally identifying information from datasets. However, this may no longer be an adequate means of protecting an individual's privacy as modern transportation is based on more intelligent and connected technologies. To improve transportation efficiency, individual traveller's data including video surveillance, connected vehicle data, data from mobile devices, location data, and smart card data can be shared in real-time. The technologies used to track people, facial-recognition cameras, license plate readers, mobile phone data, and the use of other emerging technologies in cooperative and automating driving raises privacy concerns. In addition to real-time data sharing, transport authorities use traffic data to solve transportation problems. However, they must use personal information under broad regulations to protect individuals' privacy and ensure that transportation-related data is used responsibly.

As a result, in transportation, collecting, sharing, and owning personal data has to be compliant to EU General Data Protection Regulations, GDPR. For instance, for data produced by applications like shared mobility, micro-mobility, and smart mobility in general. According to GDPR concepts, cities are data controllers that collect and use data for their own defined purposes. Mobility operators (users) are data sources from which information is collected, and third party-technical service providers are data processors [122].

6.2. System security

Despite the many potential benefits of Intelligent Transport Systems, the associated increase in vehicle/infrastructure electronics and communications raises security issues. The transport system is gradually migrating towards automated and electric. ITS has operational systems of various technologies that are combined and managed to improve the operating capabilities of the overall system. The ITS applications including road safety applications exploit wireless

V2X communications between surrounding ITS entities such as vehicles and road infrastructures. The design and deployment of these applications require special attention regarding privacy, authorisation, robustness against external attacks, and other security constraints [19].

Moreover, with the growth of V2I and other modes of communication in transportation, the system security of each connected device needs to be addressed [121]. In this aspect, connected vehicles are considered as the key enabling technology to improve road safety and foster the emergence of next-generation cooperative intelligent transport systems. Since vehicular communications and ITS applications technologies heavily rely on wireless communications, they are prone to several threats and attacks that can affect their functioning. The attacks could be Denied of Service attacks (DoS), jamming attacks, Sybil attacks, broadcast tampering, GPS spoofing/position faking, and message tampering [19]. The innovation in connected and automated driving is most important to make transport more secure and improve efficiency. Thus, the path forward should incorporate a comprehensive approach to cybersecurity that makes connected and automated vehicles and the associated ecosystem secure, vigilant, and resilient.

6.3. Other cross-cutting issues

Governance and regulations

Transport systems can be managed by authorities at local, regional, and national levels. For example, highway systems can be manged by National authorities. Creating boundaries for management and funding of the road transport systems and service required standard agreement among the parties involved. These issues may require the standardisation regarding operation of transport systems and services across regions.

New mobility concepts

It is evident that majority of mobility services including shared mobility and micro-mobility have been emerged in recent years. Their introduction has been impacting road infrastructure, transport modes, and operation of transport in urban areas. Thus, such new mobility concepts would have an impact on the transport ecosystem, to give an instance, traffic signal modelling and priority services at an intersection may need adjustment to accommodate the new modes of traffic.

Natural disaster

An unexpected change in weather conditions and natural disasters must be taken into consideration while designing and constructing road space. Moreover, natural disasters – including disease outbreaks, floods, and tsunami are among others that can disrupt transportation operations. Some of these events allow people to choose a certain mode of transport over others, to give an example, people may use public transport rather than a bicycle and personal car during the snow season.

7. Example of the applications of advanced technologies: traffic data analytics

7.1. Introduction

The revolution in new ITS, sensors, C-ITS applications, and IoT devices have been generating a vast amount of data. These data have the potential to enhance transportation and solve transport problems. Traffic Data and other transport data come from various sources and need to be integrated to use it for the intended purpose. As a result, the acquisition and analytics of traffic data are essential to transform future transportation and its operation. Nevertheless, to make use of the data a number of issues will have to be addressed - including data accessibility, handling, security, and analytics.

To get the most value from data, transport sectors and transport infrastructure providers have to acquire data either at primary (collect data regardless of whether there is an immediate use case for it) or secondary way (data is acquired either from internal or other sources for specific use cases) depends on the specific mobility use cases. In this regard, cities would acquire data to understand transport demand and manage the traffic flow. ITS infrastructure providers acquire data to assess the performance of the systems and to make improvements based on the insights from the data. Depending on the scale, data acquisition might require big data architecture; however, starting on a small scale can be useful for them to understand the data better and foresee future opportunities. Using the opportunities, data can help to make more reliable and robust decisions and improvements in transportation.

A big data software solution that combines data from a traffic controller, ITS, and connected road users would potentially help to improve traffic control and management. Specifically, data from traffic control can be used to analyse the functional performance of the systems and also give quick insights into how a road intersection or network is performing. Roughly one intersection equipped with ITS systems and sensors is expected to generate about 50 GB of data per year, then cities with 100s or even 1000s of these intersections require a smart data-driven solution that changes raw data to Key KPIs, which indicates the improvement needed. Then, these KPIs can be visible on a user-friendly dashboard with which users can get a quick overview of traffic intensities, waiting times, system performance, and other traffic efficiency parameters. The analytics solution can also map the traffic performance and recommend improvements. This kind of data-driven approach helps the cities and ITS providers to monitor, manage and measure traffic flow along the roads. Furthermore, measuring the performance of systems based on insights from the data will support enhancing and innovating ITS applications.

The analysis in this section mainly focuses on the data from different types of traffic controllers, in particular, to analyse the control plan stability based on SPaT data. As most C-ITS systems rely on the traffic control plan information, therefore, exploring the stability of the traffic control plan and characterizing the situations contributing to it need to be analysed empirically. Where stability means when the TTG and time to red TTR predictions are accurate and consecutive predictions do not deviate too much. ITS applications including in-vehicle information e.g., GLOSA should give advice based on the accurate signal time plan. Moreover, green wave, signal optimization, and cooperative systems all rely on the predictability of the TTC.

7.2. Green Light Optimised Speed Advisory

While ITS focuses on digital technologies providing intelligence placed at the roadside or in a vehicle, C-ITS focuses on the communication between those systems. C-ITS application systems are developed based on the communication between vehicles and between vehicles and infrastructure. Primarily designed as safety systems between vehicles, the safety can also be enhanced by services such as in-vehicle speed advice, road work warning, weather condition, and intersection safety. Regarding the applications based on V2I communication, particularly between vehicle and traffic controllers a stable signal plan is essential to maintain safe and smooth traffic flow. Furthermore, due to the promising introduction of automated vehicles and the wide use of cooperative systems, C-ITS applications communication between infrastructure (traffic light control) and vehicles needs to be accurate and provide reliable information. Consequently, traffic control which provides a stable control plan will be the most trusted choice for C-ITS applications for speed advice, e.g., GLOSA, and in-vehicle information, e.g., *GreenFlow* priority services[81].

The functionality of the GLOSA system is as follows; the traffic controller sends the MAP and SPaT data to the GLOSA system and based on this and other information it provides speed recommendations and can extend the green phases to allow a higher number of vehicles to cross the intersection. The GLOSA algorithm works based on the signal phase scheduled, remaining green time, and information from a vehicle (speed, position, acceleration) to recommend an appropriate speed. It informs approaching vehicles of the best average speed to pass through on green on the intersection or to slow down to make green waves on the road network. The signal plan from SPaT messages should be stable and with acceptable quality to sustain the credibility of the cooperative systems and even the controller. This data, especially the TTG and TTR predictions are expected to be accurate because the fluctuation in the predictions directly leads to wrong (or inaccurate) speed advice and safety problems on the intersection.

In the future, cooperative systems information provided to driver/vehicle should be capable of improving traffic efficiency in a mixed environment of conventional and automated vehicles, therefore, the quality of information needs to be as accurate as possible. As the performance of GLOSA is based on the traffic signal plan, analysis of the stability of the signal plan of different traffic controllers is also important, which in turn helps to figure out the ways for improvements.

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[81] https://dynniq.com/product-and-services/mobility/greenflow-priority-services/ (Accessed on 12 November 2019)

7.3. The goal of the data analytics

From the transport technologies, traffic control methods are among the core component of traffic management in the areas. Traffic control with a stable traffic signal plan under different traffic situations would be anticipated to improve traffic efficiency and meet environmental needs. The C-ITS application GLOSA is based on the signal plan of traffic control and gives speed advice to a driver. With modern control technologies and adaptive dynamic control, the stability of the control plan would be possibly affected by the priority policies, dynamic demand, and other traffic situations. Therefore, analysing the performance of these technologies would help to identify and characterise situations where C-ITS applications such as GLOSA and other in-vehicle information systems can be used. Furthermore, it would help to improve the control methods and/or identify the other factors associated to control plan instability.

The stability of control plans for ImFlow has been studied in different researches. For example, in the EU funded project, MAVEN, the efficiency of ImFlow was studied being used for highly automated driving in urban areas. In the research, the efficiency of traffic control is evaluated based on different use cases such as the performance of GLOSA, platooning, priority management, and green wave. These show whether the controller is ready to manage traffic when automated driving is introduced in regular traffic. A configurable plan stabilization element has been added to the optimization algorithm of ImFlow preserving the highly efficient adaptive performance and still having drivers receive reliable speed advice to pass a green light or slow down to form green waves. The stabilization coefficient helps to overcome overly frequent changes of signal plan and to increase reliability and accuracy of predictions for the time to green [123].

In this investigation, the main goal is to quantify and analyse the quality of TTC predictions from real data, i.e., SPaT messages. Specifically, to measure the stability of time to green and time to red predictions to compare different control methods regarding the quality of predictions. Analysis of the reliability of the prediction would contribute to the improvement of traffic safety, unnecessary delay, environmental gain, smooth traffic flow, and credibility of the systems (TSCs). When a traffic signal plan is accurate, remaining green time, remaining red time, expected green time, queue information, and speed advice information will be provided for the road users. These real data-driven insight helps the MORE cities to assess the traffic management technologies that will fit with modern C-ITS applications, e.g., GLOSA. The results are expected to indicate the ways of improving traffic control technologies so that they can handle different traffic dynamics and policies.

7.4. Quality information provision to drivers

There are some benefits when we provide information for a driver/vehicle to make informed choices for action at the intersection in the queue or approaching an intersection. In addition to speed advice, the stability of TTC predictions affects the action taken by the driver in different traffic situations. For example, if we compare a situation where a vehicle is in a queue or alone during the red phase of a traffic light. The information that can be provided to a driver is ‘now it is your turn, and the traffic light is almost green’ or ‘your turn is next’ or ‘it is not your turn yet other queues will be processed first’.

Potentially, the information content would be the remaining red/green time and reason for extra waiting time. Conveying this information to a driver/vehicle have multiple benefits as opposed to the driver estimating to act during driving. Based on the information, if stopping is inevitable for vehicles at the current speed, speed advice will be to slow down to pass the light and have an environmental gain. Providing reliable information increases the obedience of drivers to speed advice. These, in turn, improve traffic safety, increase traffic flow and energy efficiency by reducing vehicle stops.

7.5. Approaches and methods

To attain the goal, we followed four sequential approaches, these are data collection and pre-processing, defining quality measures, calculating KPIs based on the quality measures, and comparing the stability of the predictions between different traffic control systems. The methods of defining KPIs are elaborated as follow:

Three generic KPIs that enable us to quantify the quality of predictions are defined. These KPIs indicate the level of stability of the control plan for a specific traffic control system on a certain road intersection or signal group. The KPIs are defined from prediction quality measures, namely, Error and Jump/Gap. Error (E) is the difference between actual predictions (TTC_a) made by the controller and the real predictions (TTC_r) or reference predictions, see equation (7.1). Error measures how far the actual (observed) predictions (TTC_a) differ from the real predictions (TTC_r), which means the accuracy of predictions. Ideally, E is expected to be zero, which means errors are zero when an executed signal plan is equal to the real prediction. This can only be certain when we use fixed time control.

$$Error(E) = TTC_a - TTC_r \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7.1)$$

Jump or Gap (J/G) is defined as the difference between two consecutive TTC predictions. It measures how stable the predictions are at each time step. The gap is expected to be equal to the duration between two consecutive predictions. The larger the gap, the less the C-ITS applications- including speed advice be acceptable by drivers.

$$Gap\ (G) = TTC_t - TTC_{t-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7.2)$$

To make comparisons based on the above measures, relative (or normalized) forms of measures are defined, Relative Error (RE) and Relative Gap (RG). These measures can be normalised relative to real prediction or actual-time intervals. RE is a percentage of the error relative to the real prediction, see equation (7.3). RG is the percentage of the gap between two consecutive predictions relative to the actual time difference between them or the minimum of the consecutive predictions, see equation (7.4).

$$RE = \frac{TTC_a - TTC_r}{TTC_r} x100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7.3)$$

$$RG = \frac{TTC_t - TTC_{t-1}}{t-(t-1)} x100\% \ldots (7.4)$$

Generic quality measures (KPIs) are defined based on errors, gaps, relative errors, and relative gaps. The KPIs are defined to quantify the trend and variability in the predictions, which are mainly based on statistical measures like averages and dispersion. The average based KPIs are Mean Absolute Error (MAE), Mean Absolute Gap (MAG), Mean Relative Error (MRE), Mean Relative Gap (MRG), and Proportion of Jumps (PJ), whereas dispersion based KPIs are Mean Square Error (MSE) and Mean Square Relative Error (MSRE). In this investigation, we will focus on MRE and PJ. Mean Relative Errors (MRE) is the average of RE over a given time interval or signal state, refer to equation (7.5). It measures the average deviation of actual predictions from real predictions, which can indicate the general performance of the system.

$$MRE = \frac{\sum_{i=t}^{t+k} RE_i}{K} \ldots (7.5)$$

Where, K = (t+k)-t, is a time length of the interval or duration of green/red phase, t- is a timestamp. K can be also many events that occurred within the time interval.

The proportion of Jumps (PJ) measures the probability that a deviation from real predictions can occur within a given time interval or per signal state. It is defined as the proportion of the number of positive or negative or both gaps between two consecutive predictions over a certain time interval or per signal state, refer equation (7.6).

$$PJ = \frac{(\#\ of\ gaps)}{K} x100\% \ldots (7.6)$$

PJ is a general measure that considers any kind of observed gap; however, the magnitude of the gap and the sign of the gap highly matters. The gaps from the real prediction can be zero (no deviation) or downward (negative deviation) or upward (positive deviation). The up-ward jump indicates that the actual prediction is greater than the real prediction. In this case, when the information based on these predictions is communicated to a driver, the traffic light is changed to the next state earlier than the time provided for a driver. Depending on how far the deviation is from the real value, there are situations where the driver can tolerate the deviation (e.g., 1 to 5 seconds); however, the prediction gap greater than the certain threshold can cause traffic safety problems and/or delay in traffic. For example, when the traffic light is red, a high proportion of negative gaps may not lead to a serious problem but when the traffic light is green, a high proportion of negative gaps lead to serious safety problems.

7.6. Dataset description

To analyse the stability of predictions we used SPaT data collected from different types of traffic controller systems including actuated and adaptive. For each control type, data from multiple intersections on multiple days were collected. Data were extracted from a cloud service based on *MQTT* protocol. An MQTT server stores data from ITS, which was initiated under the Talking Traffic[82] program, a cooperation between commercial and public parties to create innovative, nationwide, real-time traffic technology in the Netherlands. The SPaT data comprises timestamp, signal-id, signal-state, and TTC. Where, TTC is the time that remains to the next signal state, for example, from Green to Red. The data for one month has been collected and processed to conduct the analysis.

7.7. Results

In this section, the results from SPaT data analysis for the fully adaptive control system ImFlow and other TSCs are presented. First, we discuss the results based on SPaT data collected from ImFlow configured at five intersections, second, we discuss results obtained from the analysis of other TSCs such as vehicle-actuated. ImFlow is a state-of-the-art traffic control and management system that integrates various modalities and configuration policies - including adaptive optimization, local optimization, and policies (e.g., priority policies). On top of ImFlow, multiple applications give real-time information to trucks, pedestrians, and cyclists. Considering its functionality in a different range of traffic scenarios, the control plan stability from ImFlow is analysed based on real data.

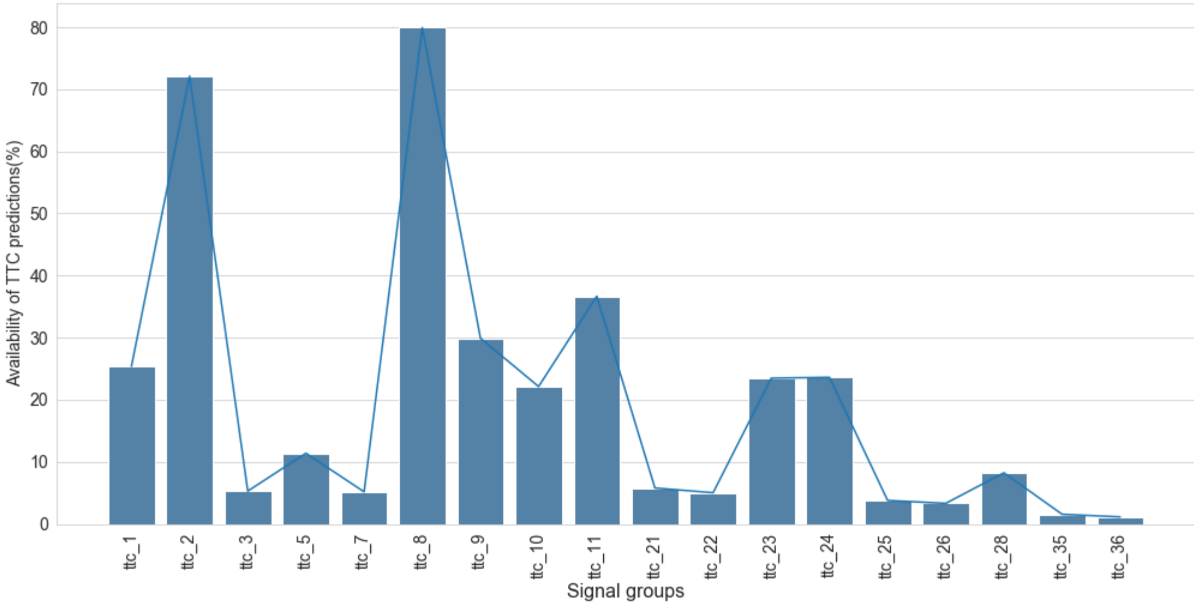
We did data analysis from ImFlow in two phases, first, data from one intersection of the Helmond network (HEL904) are analysed; Second, data from multiple intersections of the Helmond network (HEL101, HEL102, HEL904, HEL905, HEL906) are analysed to see the pattern in instability of the signal plans at the network level.

Using data from HEL904, we checked the availability of the predictions for different signal groups. As shown in *Figure 13*. It shows that signal groups 2 and 8 have a high percentage of availability of the TTC predictions. Signal groups 2 and 8 are vehicle-type signal groups, which move through the main direction of the intersection. Vehicle-type signal groups, 1, 9, 10, and 11 have the second-highest percentages. These signal groups are driving to the left and right sides. From cyclist-type signal groups, 23 and 24 we have predictions of about 20%. Therefore, for this intersection, we can say that more predictions are available for the signal groups guiding the main direction, although the availability of the predictions is related to traffic demand and traffic intensity.

Once the availability of the predictions was explored, the percentage of time each signal group served is calculated and compared. The results confirm that the signal groups with high percentages of availability of predictions are the busiest (active) signal groups. Based on the temporal analysis, for the active signal groups, there is a clear pattern in green time between day and night. That means on average the light stays green longer during off-peak hours and shorter during peak hours. This indicates the amount of control needed to manage the traffic on the specific intersection, which in turn indicates the time at which information to road users can be useful.

[82] https://dynniq.com/talking-traffic/ (Accessed on 14 October 2019)

Figure 13: Availability of time to change predictions in percentages (1-11 vehicle-type, 21-28 cyclist-type, and 35 and 36 pedestrian-type)

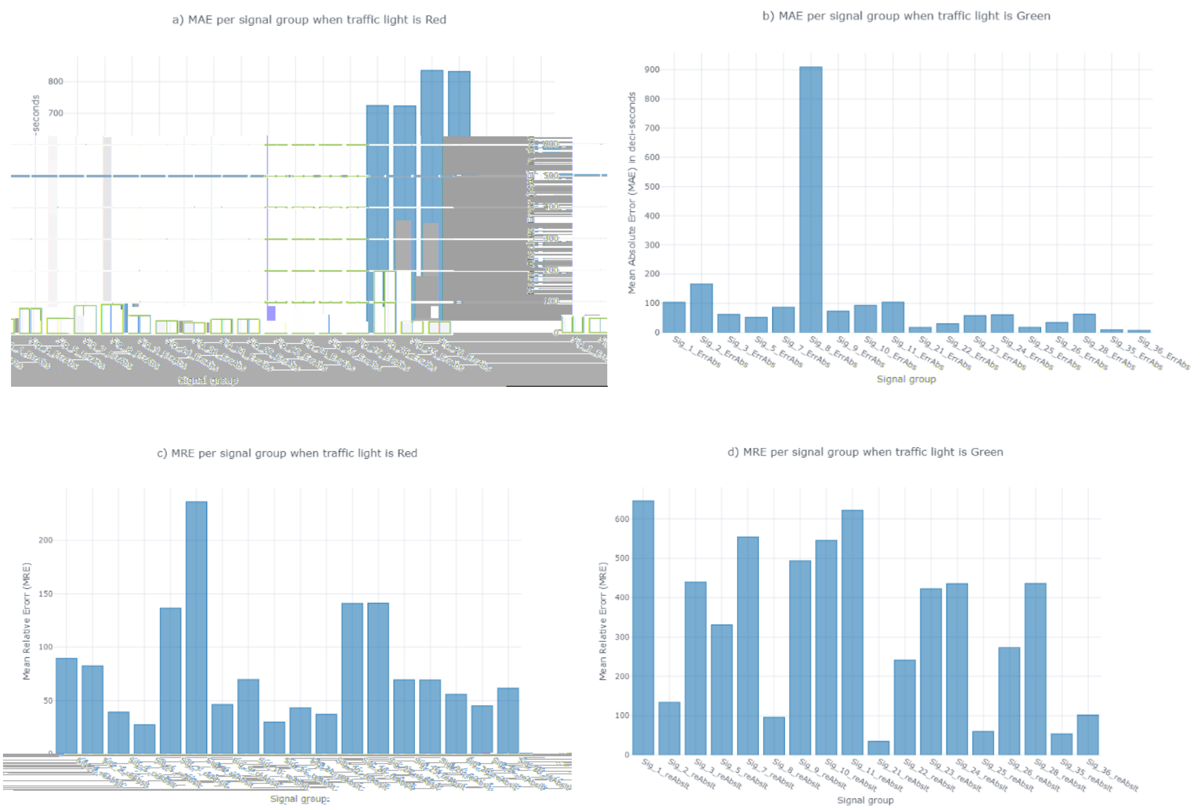


To compare different signal groups and prediction quality over time, prediction quality measures were calculated. First, we quantified the quality of predictions by errors and jumps/gaps, then, we computed aggregate measures such as Mean Absolute Error (MAE) and Mean Relative Error (MRE). MAE measures the average time deviation from real predictions as presented by *Figure 14* (a) and (b). *Figure 14* (a) shows that on average all signal groups have prediction errors of less than 70 deci-seconds (7 seconds) when the traffic light is red. For cyclists-type signal groups (e.g., Sig_25_ErrAbs, Sig_26_ErrAbs) the values are a bit higher. When the traffic light is green all the signal groups have prediction errors of approximately less than 10 seconds, except for signal group 8, which has an error bar of about 81 seconds. Overall, for most of the signal groups, the average prediction errors are approximately less than 10 seconds.

The KPI, i.e., Mean Relative Errors (MREs) were calculated for different signal groups. From *Figure 14* (c), we can see that signal group 8 (*Sig_8_reAbslt*) has the highest average relative prediction errors when the traffic light is red, next to it, vehicle-type signal groups 7, 1, 2 and cyclist-type signal groups 23 and 24 have comparable higher prediction errors. When the traffic light is green these signal groups relatively have fewer MREs, refer to *Figure 14* (d). For example, signal groups 2 and 8 relatively have smaller MREs, 136 and 97 respectively. On the other hand, signal groups 3, 9, 10, 11 have larger MRE values. This may imply the predictions for signal groups along the main direction are relatively stable when the light is green, compared to that of signal groups to the side-left and side-right. In general, we can observe that the predictions are relatively stable when the traffic light is red compared to when it is green. There is also fluctuation (randomness) in prediction errors over time for active signal groups, which could occur due to other side traffic status.

The results show that more than 90% of negative jumps occurred compared to positive and zero jumps in consecutive predictions, which means often the actual (observed) predictions are greater than the real predictions. In addition, we analysed the MRE and the proportion of jumps per traffic state and per time interval (every 10 seconds before traffic state changes). As ImFlow is adaptive traffic control, the length of time for which traffic light is green/red varies from stage to stage. Although the time length for each state varies from stage to stage, it measures an overall average of relative errors and the proportion of jumps per signal state. The result helps to characterize the stability of the control plan over time and per traffic signal state. For example, the average proportion of jumps can indicate the probability that a jump can occur every minute when the traffic light is green or red.

Figure 14: Mean Absolute Errors a) and b), Mean Relative Errors, c) and d)



The second analysis is based on the data from multiple intersections (HEL101, HEL102, HEL904, HEL905, and HEL906). We selected these intersections based on the traffic situations and the layout of the network. Intersections, HEL101 and HEL102 are adjacent to each other and closer to the middle of the city, where the rest are on the corridor. Using the above prediction quality measures, comparisons were made between intersections and between signal groups. Regarding the availability of the predictions again signal groups along the main direction relatively have high percentages of TCC predictions, except intersection HEL906, which is located upstream of the network.

MAEs were calculated for all signal groups from five intersections. For most of the signal groups, when a traffic light is red, on average the errors are less than 10 seconds with a standard deviation of approximately 6 seconds. Exceptionally for signal groups 1, 2, 4, 8, and 9 from HEL906, and cyclist-type including 27 and 28 from HEL102, and 24 from HEL05 the average error is greater than 10 seconds and with a variance of approximately 15 seconds. When the traffic light is green, on average prediction errors are approximately 5 seconds, which is better than when the traffic light is red.

To make a comparison between intersections, and also between signal groups. MREs are computed and compared between different signal groups, vehicles, cyclists, and pedestrians. *Figure 15* presents the MREs calculated for vehicle-type signal groups moving across the right-side and main direction when the traffic light is red and when the light is green. *Figure 15* (a) presents the MREs for signal groups moving to the right side of each of the five intersections. Signal groups 1 and 7 from four of the intersection are observed with relatively high MREs. When we compare signal groups moving through the main direction, signal groups 2 and 8 from intersections located on the corridor show high average prediction errors, refer to *Figure 15* (b). Both signal groups moving through the right-side and the main direction have bigger MREs when a traffic light is green compared to when the traffic light is red. From these, we can say that the prediction errors are larger for the main directions (Through) than for Side-right and Through-left. This might indicate that traffic flow across the main direction can be affected by the traffic situation from conflicting signal groups and the traffic demand. When we compare intersections based on the main-direction movement, the intersections on the corridor have high relative prediction errors.

From this, we can conclude that there are no significant differences among intersections regarding the quality of predictions but there are significant differences among signal groups. For example, between main-direction and side direction, and between cyclists and pedestrians. Even though prediction errors depend on the type of signal groups, we can generalise that prediction errors are relatively smaller when a traffic light is green. This may be because the signal plan for the green phase depends on the minimum green time configured for each signal group.

In addition to the analysis of SPaT data from ImFlow, we extracted and analysed data from other types of TSCs. The main goal is to investigate the accuracy and stability in the signal control plan and compare different types of TSCs regarding the stability of TTC predictions. There are several types of Traffic Signal Controllers: static, semi-fixed, actuated, adaptive, and stabilised adaptive TSCs, where semi-fixed is the best for GLOSA application. In [33], several control methods are compared concerning traffic efficiency, plan stability, and the resulting speed advice performance based on traffic simulation. The research introduces a new control method, which is specifically designed for maintaining efficient traffic control while adding stability to the control plan, named stabilised adaptive control. In the research, it was suggested to further investigate the stability weights and the relationships between quality measures such as MRE and MSRE. As a result, further investigation is made based on real data.

Figure 15: MRE for different signal groups from multiple intersections (HEL101, HEL102, HEL904, HEL905, and HEL906), a) vehicles move right-side at a red light; b) main-direction at a red light; c) right-side at a green light; d) the main direction at a green.

To evaluate the different Traffic Signal Controllers, in literature the indicators often used are waiting-time, throughput, queues length, delay, travel time, speed, environmental, and others, which are based on the traffic light signal plan. The accuracy of the traffic signal plan is key for the efficient functioning of cooperative ITS solutions. For example, recent development in C-ITS has enabled the realization of a green wave with speed advice through GLOSA. The heart of the effectiveness of GLOSA functionality is the time to green prediction, which is given by Traffic Signal Controllers and therefore the predictions must be stable. For adaptive traffic controllers, the key success for ensuring green waves through actuated control system installed in Apeldoorn, and HEL904 is a fully adaptive control system installed in Helmond. The quality of TTC predictions for semi-actuated, actuated, and fully adaptive controllers are investigated and compared.

The stability of the control plans is compared based on the quality measures and KPIs defined based on the generic statistical theory. These are MAE, MRE, and JP, see Equations (5) and (6). The values of the KPIs are compared between signal groups and the trends in them are compared over time. For example, when comparing TSCs based on MAE from motorized signal groups, a fully adaptive controller (HEL904) has an average prediction error between 3 to 9 seconds during the red phase and 5 to 15 seconds during the green phase. When comparing the TSCs based on MRE, A050 is better during the red phase followed by *205136* but when the light is green *205136* is better than other TSCs. During the red phase, *205136* is outperforming other TSCs with a minimum proportion of jumps of 91.7% and a maximum of 95.4 jumps. The next TLC with a minimum proportion of jumps is HEL904. Likewise, we can compare the TSCs based on the results in *Table 1*.

Table 1: Measures of errors in TTC predictions from different types of TSCs

TLC-name	**TLC_id**	**Signal group**	**Red phase**			**Green phase**		
			MAE (sec.)	MRE	PJ (%)	MAE (sec.)	MRE	PJ (%)
205136	7aa40082	Vehicles	20-50	50-80	91.7-95.4	10-65	67-110	94.0-95.0
		Cyclist	-	-	-	-	-	-
		Pedestrian	-	-	-	-	-	-
x27VRA	792a0082	Vehicles	70-150	60-85	99.5-99.7	15-60	120- 500	99.5-99.7
		Cyclist	70-120	65-80	99.5-99.7	30-240	130- 180	99.3-99.8
		Pedestrian		63-80	99.5-99.7	25-42	100-150	99.3-99.75
A050	796800a0	Vehicles	5-35	50-65	95.7-99.7	5-15	150- 800	94.0-100
		Cyclist	6-15	40-50	99.6-99.7	5-95	140- 600	93.6-97.7
		Pedestrian	7-15	45-60	97.8-99.2	3-6	50-60	100
HEL904	79ad01cd	Vehicles	3-9	30-150	90.0-98.0	5 -15	95 - 700	78.0-96.0
		Cyclist	72-83	40-140	86.5-97.5	2 -6	34- 430	94.0-99.5
		Pedestrian	4 sec.	45-60	97.0 -97.5	7-10	50-100	100

As observed, the quality of the signal plan is different from the controller to controller during the green or red phase. The results also show that motorised signal groups from all TSCs have a proportion of instability in TTC predictions above 90%. These differences may occur due to a signal control method or intersection topology layout that each TLC controls is installed on, traffic demand in the area, and other configured parameters. Therefore, further investigation is required to identify the factors associated with the accuracy and instability of the control plans.

Moreover, the stability of the signal plan can highly affect the safety of VRUs (e.g., cyclists and pedestrians). Pedestrians and cyclists are disturbing factors for adaptive control when it comes to predictability because once they are detected they are immediately waiting and therefore the control plan has to be adjusted on a short horizon to keep the waiting time low. According to [33], a high potential with green wave success increases from 44% in the baseline up to 72% when the GLOSA function is used with ImFlow for cyclists. In this study, we compare different TSCs regarding the performance of predictability for cyclists and pedestrians (see Table 1).

7.8. Summary and outlook

Data analytics in transportation can help to unlock tremendous value to create a more efficient transport system. For example, help to optimally design routes and improve transport safety and services. About the efficiency and safety of the traffic, traffic control methods are widely used with C-ITS applications such as GLOSA. The GLOSA algorithm can stabilize the flow on the network to avoid traffic saturation on the corridor gates. The algorithm provides speed recommendations and can extend the green phases to allow a higher number of vehicles to cross the intersection, e.g., at an off-peak time, for example, to lower the overall waiting time or to reduce emissions. In the MORE project, GLOSA application is one of the identified technologies that can improve traffic flow on the stressed corridors. Taking the benefits of GLOSA into consideration and because the GLOSA algorithm is based on the signal control plan, in this section, we analysed the stability of the signal plan of different traffic controllers.

This investigation compared several TSCs concerning signal plan stability. The results show that the predictions are highly available for signal groups moving through the main directions of the road intersection. For most of the TSCs, the quality of predictions is relatively poor across the main direction. This can be due to traffic demand and the flexibility of the control algorithms. Based on the temporal analysis, the instability of predictions depends on the time of the day and the signal phases. There are differences in the quality of prediction among different traffic controllers when the traffic light is green or red, which indicates when to give information or speed advice and for which signal groups. In conclusion, identifying all these differences will help to improve the systems and to make the right choice of C-ITS applications such as GLOSA and in-vehicle information systems, which in turn contribute to traffic efficiency and environmental benefits. Furthermore, multiple aspects could contribute to the stability of the traffic control plan. These can be traffic intensity, configured priority policy and the impact of other traffic such as pedestrians and cyclists. Therefore, to identify the factors contributing to the instability of the predictions, further analysis of traffic demand data will be needed.

8. Discussion and conclusion

The main objective of the MORE project is to promote the redesign of existing urban main roads and streets to accommodate multi-modal and multi-functional requirements and to address problems of congestion, noise and air pollution, and safety. MORE believes that identifying new technologies for enhancing the digital and physical transport infrastructure of the corridors is vital, for optimal use of road-space both physical and digital infrastructures in the cities need to be enhanced. The revolution of transport and non-transport technologies, dynamics in the demand for transport services and demographics are exerting an impact on the transport systems- including road infrastructure. Thus, it is important to explore the deployment challenges and future opportunities that come with the revolution of technologies. The applications of technologies for improving the sustainability of the transport networks, from economic, environmental, and social perspectives have to be analysed.

In this deliverable, technologies and methods that are relevant for transportation and road-space management are reviewed. Traffic systems and transport planning, and mobility services for people and goods are also reviewed. Furthermore, components of future mobility applications are described and elaborated with a few examples. Based on the extensive review and analysis of these topics the following key conclusions are drawn. The conclusions are centred on different aspects that can be taken into consideration during the planning, design, management, and operation of the road space. These aspects include but are not limited to the role of ICT and data in ITS development, sensors for variety data, automation for sustainable transportation, and electrification for greener transport. The innovations in road infrastructures and construction material technology, the rise in alternative transport modes, and their impact on vulnerable road users are also described.

The potential impact of ICT and data on transportation is twofold: 1) it improves the data exchange between transport infrastructure and road users, 2) it improves the operation and management of transport systems and services. In both cases communication of data between road users is crucial. With a rise in internet coverage, the real-time exchange of data between physical road infrastructure and road users is faster than ever. As a result, ITS applications, IoT devices, and cell phones generate a huge amount of data - Big data. To use these data for improving transportation, traditional data management systems and analysis cannot handle them, therefore, instead, cloud-based data management and computing solutions are becoming popular. Apart from C-ITS (V2V, V2I, V2X) data exchange, information from external data sources (e.g., sensors) can be also used to manage and control traffic on the road network. In transportation, there are various sensors providing data for public use, to sense and count traffic, and provide information about traffic conditions. They play a vital role in the ITS: enabling automated driving, reducing crashes, promoting smart parking, measuring and monitoring pollution, detecting traffic and incidents, remotely inspecting road infrastructures, and providing quality data used for improving information provision to road users.

Connectivity, sensing technology, and data are bringing tremendous opportunities. Using AI these data can be analysed to gain insights that help to improve the sustainability of mobility, efficient use of limited space, and operation of transport services. Besides, a traffic management system fused with a piece of diverse information is more efficient; based on data analytics insights cities will be able to allocate road space and kerbs more dynamically and flexibly; cities can plan and manage transport based on reliable information in real-time, in turn, they can improve transport services. For example, the functional performance of ITS systems can be assessed by analysing log data. These include analysis of SPaT data to measure the signal plan predictability of TSCs, analysis of diagnostic information for predictive maintenance, and analysis of other traffic data to characterise the performance of ITS systems. All of these have considerable importance for transport systems, as they provide access to travel information, opportunities to share transport modes, and improve efficiency and safety. Although the transformation in ICT and sensing technology fosters sustainable transport, data privacy and system security, standardisation of the deployment strategies, and computability of current infrastructure are among the big challenges for future mobility.

When we come to control technologies (either vehicle or traffic control), there has been continuous development in this domain. Vehicle control systems are integrated during design with which the vehicle automatically controls when it interacts with for example pedestrians and cyclists. Although newly developing cars and automated vehicles are fully integrated with control systems, the systems are expected to integrate further into a combination with IT and communication technology. Regarding traffic control technologies, currently, there are several control programs that dynamically optimise traffic signal timing. These traffic control mechanisms minimise traffic delays, give priority to buses and emergency vehicles, and extend the green time for other road users. Moreover, due to the huge potential of data and increasing use of AI-based ITS applications, data-driven traffic management systems will be expected. These systems can be fused with new data sources to better manage the road network. The effective functioning of the control technology – including vehicle control, traffic control, and detection systems heavily relies on the accurate position of an object or car. Positioning systems such as GPS and digital maps provide digital information regarding the position and velocity of the vehicle. On the other hand, accuracy, response time, and precision are the main issues that need improvement in the development of positioning systems.

One of the most disruptive technologies that are highly changing the landscape of transportation systems is automation - including automated vehicles, robotics, and drones. Connected and automated vehicles are expected to decrease operation costs, improve safety and traffic efficiency, environmental efficiency, and free up spaces in urban areas. Despite the benefits, CAVs cannot easily be functioning with the existing physical and digital infrastructure. As a result, new (improved) traffic management systems, good road infrastructure and kerbs that accommodate C-AVs, VRUs, EVs, and micro-mobility vehicles are essential. In addition, there is concern regarding the kind of business and property model that will prevail in the future - mainly shared public mobility. Most probably both models will coexist, but nobody is sure which one will be the dominant form because it will depend more on fiscal policies (will transport modes pay their real externalities or not) and other car restriction policies (namely parking).

Congestion in dense urban areas can be alleviated through alternative automated transport modes such as drones, inland water transport automation, and flying taxis. The evolution in these modes is expected to intensely change the logistics and movement of people in the cities. Although these are solutions to congestion and environmental pollution, one of the challenges in exploiting and operating drones and flying taxis is the permission to fly in restricted air space. On the other hand, ground transportation technologies such as delivery robots and e-bikes need regulations to operate safely on the road (e.g. legal permission to use the sidewalk). As the misuse of the applications may have negative impacts on safety, health, and other societal impacts.

As an alternative to fuel-based vehicles, electrification is a potential solution for alleviating traffic-related environmental problems. Apart from the challenge concerning battery development and lack of charging facilities, electric vehicles are realising zero-emission driving. Both car-producing companies and the authorities need to collaborate in solving problems related to batteries and infrastructure to integrated charging facilities. Nevertheless, the whole supply chain of electrification does not imply that EVs are completely clean. In this regard, renewable energy-based vehicles including hydrogen vehicles, and renewable diesel could play an important role in this aspect.

New and existing infrastructure elements need to be designed and adapted to address future traffic scenarios in a flexible, fast, and cost-effective way. The future road-space design focuses on promoting walking and cycling and will be based on new types of on-street infrastructure. Smart lighting and smart lamp posts, better-tailored road markings and information to significantly impact parking and use of kerbs. Digital road infrastructure that enhances traffic control and the connectivity among the road users, and structural flexibility and durability of pavements (e.g., self-healing and plastic roads) are also among the new infrastructure. In the future, ICT-assisted design of road-space that enhances economic benefits, social benefits, and environmental benefits are the strategies to optimise the use of road-space in urban areas. Moreover, with the utilisation of data science, communication technology and IoT, the physical infrastructure will be efficiently used.

Mobility services for people and goods are becoming more innovative to support the increased demand for convenience, safety, and speed of transportation. MaaS provides a flexible, personalised on-demand service that integrates all types of mobility opportunities. In this integration, shared mobility (e.g., car-sharing, bike-sharing) and micro-mobility (e.g., Mobike and dockless bike) are the enablers of mobility services for people. Shared mobility has a positive impact on space allocation in cities and has diverse gains in solving congestion and environmental problems. Micro-mobility has a huge potential to ease first-mile/last-mile problems and promote multimodal transport. The simulation results confirm that with the existing infrastructure and traffic signalling automated shuttles and pods can provide transport services. Regarding transport for goods, changes are initiated through automation, technologies like 3D printing, and underground logistics. With the revolution of these technologies and data analytics, future logistics will rapidly be transformed.

To sum up, advances in communication technology (e.g., 5G), IT (e.g., internet, AI, big data) and sensing technology (e.g., wireless, low-cost sensors) have increased the pace of innovation in transport systems. For example, automation, new mobility services and a need for new modes of travel transform how people, goods, and services move. On the other hand, the diverse demand for transport, demographic changes, and changes in business models are bringing new opportunities as well as threats. New mobility services for intelligent transport, technologically sophisticated operations of ride-hailing networks, car and bicycle-sharing systems, mobile trip-planning and ticket apps, and other new mobility services require new business models.

As opportunities, data and connectivity are changing mobility and parking, transport is becoming more automated and cleaner, new transport modes are emerging, transport demand and choices are becoming dynamic, new digital-enabled business models are emerging, and new transport services for people and goods are evolving. However, fundamental solutions of sustainable mobility depend on human behavior and related factors. The potential benefits of certain technology depend on how people use it and react to its operation. Regardless of the technologies deployed, a driver could cause congestion on the road (highway) by for instance changing driving behavior such as lane change.

Finally, the implementation of advanced technologies and intelligent transport systems needs proper road space design, both physical and digital infrastructure. Furthermore, threats and challenges associated with the advancement in technologies should be taken into consideration during design of road space and streets.

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