7. Smart Roads and Transport Infrastructure

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7.1 The Way Towards Smart, Green and Efficient Road Transport

In recent years, rapid technological advances in computer science, machine learning and similar quantitative disciplines have led to considerable breakthroughs in communications, sensors and systems, as well as improvements towards the development of more independent Artificial Intelligence (AI). Meanwhile, wide-scale data collection and utilization have been enabled in virtually all technical fields, and the world has become increasingly connected through the Internet of Things (IoT). The transport sector has been in a process of gradual transformation as a result; for instance, driverless and fully autonomous/automated vehicles (AVs) are a major expected development stemming from these advances, but by no means the only one.

As road transport infrastructure will remain a critical component of the transport system, it will inevitably be affected by these developments and its transformation will in turn open new capabilities for road transport systems. Already, a change in scope is being observed for road infrastructure elements, alongside a different philosophy for their management. The rigidity of infrastructure elements is recognised as unfeasible in the long term, as more uncertainties emerge, frequently in tandem with crises requiring fast interventions.[1] While roads used to be considered as elements mainly providing access and bearing loads for the safe movement of vehicles, they are now examined as means of communication and information exchange, and even energy sources in parallel with their legacy functions.[2]

This prompts the question: what options are there to harness these technological advancements in order to achieve smarter, safer, greener, more efficient and more resilient transport? This paper discusses a variety of technologies and interventions, alongside their potential impacts. It also looks at the barriers to achieving these goals, before drawing appropriate conclusions.

Smart Roads and Adaptive Infrastructure

Under the umbrella of "smart" technological developments, an array of different approaches has become available for road monitoring and improvement. Smart systems are typically dynamic, adaptable and at least partially automated, in the sense that they require little manual intervention to yield their designed output or service. Several of these ideas are largely attainable today and have been implemented in prototypes or pilot studies. They therefore constitute possible starting points from which to transition to smart roads and cities.

Indicatively, smart lighting is an attainable feature of smart roads. By adapting to transport demand, as perceived by the respective sensors, the lighting network can provide targeted illumination when, whereand to the extent that it is needed.[3]

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[1] E.J. Gilrein et al., "Concepts and practices for transforming infrastructure from rigid to adaptable", *Sustainable and Resilient Infrastructure*, vol. 6, no. 3-4, 2021, pp. 213-34.

[2] E.g. S. Trubia, A. Severino, S. Curto, F. Arena, and G. Pau, "Smart roads: An overview of what future mobility will look like", *Infrastructures*, vol. 5, no. 12, 2020, p. 107.

[3] E.g. G. Gagliardi et al., "Advanced adaptive street lighting systems for smart

This is not only an efficient and energy-saving practice; it allows more harmonious coexistence with flora, fauna and natural human needs, while maintaining safety and quality of life in cities.[4] Furthermore, street lights can offer safe, well-dispersed hosting locations for more sensors, thus improving data collection overall and opening further venues for connectivity applications. For example, security can also be promoted by enabling sensors to detect incidents such as gunshots and allow fast law enforcement response.[5]

AI-based research can yield tools for road maintenance support, such as pothole detection capabilities from user-uploaded images of the area concerned[6] or from social media web scraping.[7] Such approaches can greatly reduce the required workload by city authorities and enable wider coverage of proper infrastructure maintenance through crowdsourcing, thereby reducing neglected areas and the corresponding inequality in fixing network problems.

In addition, extensive research efforts have been dedicated to smart intersections and traffic sign/signal optimisation. These technologies typically include algorithms that operate in real-time or almost-real-time conditions, with the aim of minimising multiple transport indicators such as travel delays, emissions, queue lengths, or similar criteria. Connected vehicle technology of otherwise still human-driven vehicles has improved data collection and reduced transmission times, allowing these schemes to be more refined, although many are

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cities", *Smart Cities*, vol. 3, no. 4, 2020, pp. 1495-1512.

[4] M. Palmer and R. Gibbons, *Smart lighting for smart cities. In Solving Urban Infrastructure Problems Using Smart City Technologies*, Elsevier, 2021, pp. 485-99.

[5] E.g. M. Scott, "Using streetlights to strengthen cities", Data-Smart City Solutions, 22 August 2016; Gilrein et al. (2021).

[6] V. Bhalla, "SpotholeAI-An Artificial Intelligence (AI) assistant to fix Potholes", The 36th International Conference on Machine Learning (ICML 2019), AI for Social Good Workshop, California, 2019.

[7] S. Agarwal, N. Mittal, and A. Sureka, "Potholes and bad road conditions: Mining Twitter to extract information on killer roads", ACM India Joint International Conference on Data Science and Management of Data, 2018, pp. 67-77.

targeted at fully automated vehicles instead. Some examples include reinforcement-learning algorithms that can account for incidents such as traffic flow incidents, pedestrian jaywalking, and sensor noise, whilst reducing delay times[8] or minimising vehicular emissions alongside delay time by connecting the former to the latter through traffic occupancy in a road segment.[9]

Smart Motorways

Primarily within the UK, Smart Motorways (SMs), as an infrastructure category, comprise three proposed designs that differ from the conventional type. In short, these are **(i)** Controlled Motorways (CM), which add variable and mandatory speed limits to a conventional motorway to control the speed of traffic, while retaining a permanent hard shoulder **(ii)** All Lane Running (ALR) motorways, which apply controlled motorway technology, permanently convert the hard shoulder into a running lane, and feature emergency areas and **(iii)** Dynamic Hard Shoulder Running (DHS) motorways, which apply controlled motorway technology, while sometimes using the hard shoulder as a running lane. SMs are estimated to increase the capacity of busy motorways by up to a third when replacing their conventional counterparts.[10]

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[8] M. Aslani, S. Seipel, M.S. Mesgari, and M. Wiering, "Traffic signal optimization through discrete and continuous reinforcement learning with robustness analysis in downtown Tehran", *Advanced Engineering Informatics*, vol. 38, 2018, pp. 639-55.

[9] K. Han, H. Liu, V.V. Gayah, T.L. Friesz, and T. Yao, "A robust optimization approach for dynamic traffic signal control with emission considerations. Transportation Research Part C", *Emerging Technologies*, vol. 70, 2016, pp. 3-26.

[10] UK Department for Transport (DfT), Smart Motorway Safety: Evidence Stocktake and Action Plan, 2020.

At present, in the UK alone, SMs cover 488 miles of motorways, with plans to extend the SM network by an additional 300 miles without hard shoulders by 2025.[11] SMs feature mandatory speed control, automatic signal setting in response to traffic conditions and speed enforcement using automatic camera technology. They are managed by Regional Control Centres (RCCs), which can rapidly deploy traffic officers in response to road incidents.[12] SMs have been reported to increase journey reliability by up to 22%.[13] Moreover, SMs appear to reduce environmental impacts, such as global warming potential, especially during the road safety barrier maintenance phase. Gains in environmental impacts are expected to upscale as the annual average daily traffic (AADT) and the platooning percentage of vehicles increases,[14] which are likely future outcomes, thus enhancing the sustainability of SMs.

Despite the aforementioned expected benefits and interconnectivity advantages, SMs have not been without controversy. Drivers have expressed concerns over the absence of hard shoulder coverage, as well as the scarceness and small size of Emergency Refuge Areas (ERAs). Close examination of crash data from the years 2015-18 reveals that road safety levels have not improved uniformly. Specifically, during 2015, 2016 and 2018, SMs were found to perform better than conventional motorways, while in 2017 they saw a higher number of fatalities. Following these concerns, the UK DfT has placed any future SM development on hold while a detailed review is undertaken.[15]

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[11] Royal Automobile Club (RAC), "Which motorways are smart motorways, and where will new ones be?".

[12] Highways England, *Smart Motorways Programme Environmental Assessment Report*, 2019.

[13] The Royal Society for the Prevention of Accidents (ROSPA), *Road Safety Factsheet – Smart Motorways*, 2021.

[14] M. Guerrieri, B.M.L. Casto, G. Peri, and G. Rizzo, "Smart vs conventional motorways: Environmental impact assessment under realistic traffic conditions", *Science of the Total Environment*, vol. 727, 2020, 138521.

[15] UK Department of Transport (DfT) (2020).

Beyond the United Kingdom, smart motorways are increasingly gaining ground in the European Union. The European Commission, in fact, has developed a strategy to provide European roads with a common infrastructure for smart safety, through the Cooperative Intelligent Transport System (C-ITS). Within this project, C-Roads is a joint initiative that includes most EU Member States and their roads operators (Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Hungary, Italy, the Netherlands, Portugal, Slovenia, Spain, and Sweden), plus the UK and Norway, and is aimed at deploying SMs throughout Europe. Austria has been at the forefront, with tenders launched in 2018 after a study phase and smart roads featuring prominently in the Austrian Road Safety Strategy 2021-30.[16] Italy has followed suit, running a series of technical tests since 2017 on the A22 motorway, which links the country with Germany and Austria, and is a crucial artery for Italian exports. The aim is to develop a system of self-driving trucks in digital connection with the road, by transferring data in real-time on direction, speed and external conditions.[17] Italy is also involved in a similar project on the Salerno-Reggio Calabria motorway, in the southernmost part of the peninsula. The project involves developing a set of smart infrastructures that would provide information and guidance to autonomous vehicles, as well as feature EV charging stations entirely powered by green energy through photovoltaic panels.[18] Finally, in June 2022 the automaker group Stellantis created a circular test track with embedded inductive charging, under the name Arena del Futuro (Italian for Arena of the Future). It was built as part of the A35 Bre-Be-Mi motorway, which

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[16] Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK), "Austrian Road Safety Strategy 2021-2030", 2021.

[17] M. Borsari, "Smart roads to Revolutionize travel", *Warp News*, 24 December 2021.

[18] E. Punsalang, "Salerno-Reggio Calabria In Italy Set To Be Europe's Longest Smart Road", *Ride Apart*, 2022.

links the major Italian cities of Brescia, Bergamo and Milan. The outer lane of the circle is equipped with an embedded Dynamic Wireless Power Transfer (DWPT) system, which enables vehicles such as the electric Fiat 500 used as a test car to drive at highway speeds without actually draining its battery.[19] In addition, widely circulated polls suggest that 25% of drivers have no knowledge of what SMs are and an additional 27% of drivers did not know the rules of driving on an SM, meaning that less than half of drivers are ready to navigate in the growing SM network.[20] This is an absence of critical knowledge, as the safety of any road users and vehicles which are stopped in a running lane depends on correct interpretation of SM signage by drivers. There appears to be uncertainty both in expert knowledge of SM impacts and in public acceptance of SMs.

Systems and Interventions Relating to Automated Vehicles

AI-piloted automated technologies will be adopted on a wide scale in the coming decades, with profound consequences, such as the aforementioned advent of Avs. Several smart infrastructure interventions can be expected to be added to the arsenal of stakeholders when AV technologies reach sufficient penetration levels, especially when connected Avs (CAVs) are seamlessly linked with each other and with smart infrastructure with vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technologies (known as V2X collectively).

In EU countries, a number of C-ITS have been introduced and operate in several pilot trials for participant countries. C-ITS focuses heavily on V2X connectivity and data exchange. At present, such interventions focus on providing support to drivers based on their location, while in the future they are

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[19] A. Nedelea, "This Fiat 500 EV Is Charging Wirelessly Through the Road As It Drives", *InsideEvs*, 11 March 2022.

[20] Green Flag & Brake Reports on Safe Driving, *Motorway driving*, 2020.

expected to play a pivotal role in AV integration in transport systems. In several pilot trials within C-Roads, C-ITS have been employed with ETSI ITS-G5 short-range communication technology, which is very similar to WiFi routers. As of 2020, in 18 countries and 7 associated countries more than 100,000 km of motorway are supported in such a manner.[21] It is worth noting that C-Roads and C-ITS have "day-1" potential, meaning that they are readily available to support IAV deployment from the very start. Such systems have the option of serving as an additional layer and source of perception for AV sensors, providing much-needed backup in the event that vehicles become non-operational due to mechanical failure, adverse weather, operational design domain (ODD) exceedance etc., thus increasing the traffic safety of future Avs. Similar developments are happening outside Europe, in the US, Asia and Australia, though fully independent automated vehicles (i.e. SAE level 5 as described in SAE International, 2016) are not yet completely supported.[22]

Accordingly, a multitude of impacts will emerge in the affected transport systems, either from general-traffic AV adoption or from dedicated policy implementations and interventions relevant to Avs. Following Elvik et al. (2019),[23] these impacts can be classified as:

1. Direct impacts: changes that are noticed by every road user on every trip (e.g. travel time).
2. Systemic impacts: changes in transport system boundaries (e.g. modal split).
3. Wider impacts: changes exceeding transport system boundaries (e.g. road fatalities and injuries, emissions).

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[21] C-Roads, *Annual pilot overview report 2020*, 26 June 2021; C-Roads, *The C-Roads Platform – An overview of harmonised C-ITS deployment in Europe*, 2020.

[22] SAE International, Standard J3016: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles (revised J3016: Sept 2016).

[23] Following R. Elvik, et al., "A taxonomy of potential impacts of connected and automated vehicles at different levels of implementation", Deliverable D3.1, 2019.

It is imperative to anticipate the advent of automation and to analyse and forecast the impacts of automation-based policies proactively. Within the European LEVITATE project, several AV-related infrastructure interventions have been examined. Using a combination of microscopic and mesoscopic simulation, system dynamics, operations research and Delphi questionnaires, a number of anticipated impacts have been assessed.[24] Specifically, the following effects were outlined by Gebhard et al. (2022)[25] for infrastructure interventions, among others:

- Dedicated AV lanes, which according to the Connected Automated Driving Roadmap of ERTRAC (2019),[26] are lanes which only allow vehicle(s) with specific automation level(s) to travel. Conversely, Avs would not necessarily be confined to the dedicated lane. In such cases, this would instead be referred to as a physically separated lane. It is envisaged that where a dedicated public transport lane is in operation, the dedicated AV lane would be shared with the dedicated public transport lane, allowing both types of vehicles (as is the case with current High Occupancy Vehicle (HOV) lanes). Such a dedicated lane may be fixed (dedicated to CAVs at all times), or may be dynamically controlled to vary based according to the traffic situation. Overall, dedicated CAV lanes were predicted to have limited additional impacts on most indicators. Slight benefits were estimated for congestion, vehicle operating costs, vehicle utilisation and occupancy rates, as well as public health.
- On-street parking is the most common option for both paid and unpaid parking along roadsides in urban

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[24] A. Ziakopoulos et al., Integration of outputs of WP4-7, Deliverable D8.1 of the H2020 project LEVITATE, 2022.

[25] S. Gebhard et al., Guidelines and recommendations for future policy of cooperative and automated passenger cars, Deliverable D6.5 of the H2020 project LEVITATE, 2022.

[26] ERTRAC Roadmaps, Connected Automated Driving Roadmap, 2019.

cities.[27] While it can contribute to the economy as a form of commercial exploitation of parking space, it can have negative impacts such as congestion, capacity reduction and increases in road traffic accidents. Theoretically, the introduction of autonomous vehicles offers the potential to reduce urban space requirements for roads and parking, as automated vehicles are able to park elsewhere after dropping passengers off at the destination. This gives rise to new opportunities to create more space for high-quality, liveable areas.[28] Replacing on-street parking is associated with a wide range of positive benefits, including large improvements in traffic conditions (reduced travel time and congestion), increased active mode shares, more shared mobility, better development of road safety and reduced demand for parking space. Several impacts are based on the facilities chosen as substitutes for parking space: replacement with public space is particularly associated with societal and environmental benefits (e.g. road safety, public health, energy efficiency) and can be beneficial for shared, public, and active forms of mobility. Conversely, replacement with driving lanes or pick-up/drop-off points is associated with fewer benefits, except for improved access to travel. Pick-up/drop-off points or removing only half of the available spaces also reduces the benefits to congestion due to some of the parking manoeuvres.

- Green Light Optimal Speed Advisory (GLOSA) is a traffic signal application at signalised intersections that

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[27] S. Biswas, S. Chandra, and I. Ghosh, "Effects of on-street parking in urban context: A critical review", *Transportation in developing economies*, vol. 3, no. 1, 2017, pp. 1-14.

[28] E. González-González, S. Nogués, and D. Stead, "Parking futures: Preparing European cities for the advent of automated vehicles", *Land Use Policy*, vol. 91, 2020, p. 104010; E. González-González, S. Nogués, and D. Stead, "Automated vehicles and the city of tomorrow: A backcasting approach", *Cities*, vol. 94, 2019, pp. 153-60.

> can be readily available for implementation – a "day-1" measure as noted by Mellegård & Reichenberg (2020).[29] GLOSA utilises traffic signal information and the current position of a vehicle to provide speed recommendations formulated to help drivers reach traffic lights during the green phase, thus reducing the number of stops, fuel consumption and emissions. Stopping distance, signal timing plans and area speed limit profiles are taken into account to calculate the speed recommendation displayed to drivers. The GLOSA service can also be provided to the on-board computer of a connected AV or to a smartphone application. GLOSA is not predicted to have major impacts on most indicators. Slight benefits to traffic conditions are predicted (reduced congestion and travel time), as well as halt reductions in public transport use and reduced vehicle operating costs. Potential negative effects on shared mobility rate, active travel, vehicle utilisation and occupancy rates, access to travel and public health are predicted. These negative effects may be due to a predicted increase in private vehicle travel with the implementation of GLOSA.

Road-use pricing refers to charges for the use of infrastructure, including distance- and time-based fees, road tolls and various charges aimed at discouraging drivers from accessing or remaining in specified areas with their vehicles for long periods. Road-use pricing is expected to increase energy efficiency, halt reductions in public and active transport mode sharing, increase vehicle occupancy rates, and reduce parking demand. On the negative side, road-use pricing is expected to lead to an increase in vehicle operating costs, and lower accessibility to transport overall. While arguably more relevant to transport

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[29] N. Mellegård and F. Reichenberg, "The Day 1 C-ITS Application Green Light Optimal Speed Advisory – A Mapping Study, *Transportation Research Procedia*, vol. 49, 2020, pp. 170-82.

policy than to transport infrastructure, smart infrastructure can nonetheless enable fairer, more precise and easier-to-manage road-use pricing calculations.

Discussion and Pending Issues

Naturally, there are several barriers and limitations to the implementation of smart infrastructure solutions. Several of these schemes are largely dependent on data usage, and as such can frequently require liberal data sharing.[30] Conversely, limitations in open data flows can hinder the effectiveness, affordability and feasibility of smart infrastructure and road transformation schemes. A specific example is the "silo effect" that occurs if different commercial data owners and providers are unwilling to share data due to privacy, legal liability, intellectual property, competition, interoperability, cybersecurity or cost-related issues.

Overall, it is reasonable to anticipate more innovative smart road solutions as time progresses; their standardisation and exploitation of possible interactions and synergies are challenges that will have to be tackled subsequently. Of course, systemic resilience has to be a constant consideration. As smooth operation of all smart and connected schemes is related to centralisation of information, sufficient backups and redundancies must be in place against both equipment failures and malicious attacks (i.e. cybersecurity). A closely related issue is the timelesness of smart infrastructure systems. Algorithms will continue improving, but there needs to be a minimum common ground, in the form of stable systems, in order to ensure resilience and to provide a basis for lateral synergy exploitation. Certain regulatory processes can be imposed here by supervisory authorities. Rather than restricting smart solutions, these should be aimed

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[30] SuM4All (Sustainable Mobility for All), *Sustainable Mobility: Policy Making for Data Sharing*, Washington DC, License, Creative Commons Attribution CC BY 3.0, GRA in action series, 2021.

primarily at enabling cooperation and embedding of systems and accomodating further advances, so as to create a "future proof" smart road infrastructure.

Policymakers will have to develop digital skills themselves, while cooperating with computer science experts and digital specialists. This is a crucial necessity because problems are becoming too complex, composite and multifaceted to tackle alone. Challenges such as the scalability of smart road solutions need to be addressed to ensure the smooth installation of more reliable infrastructure and smart cities as uniformly as possible. Moreover, concerted efforts are required to increase the fairness and openness of AI systems,[31] and reduce systemic inequalities in transport, exploitative contracting, gentrification effects, societal and accessibility issues and so on – after all, decision-making cannot be solely left with automated black-box processes, especially since fairness may be defined differently for each discipline.[32]

The multidimensionality of the smart road transition is evident as cities have been endeavoring to align with United Nations sustainable development goals.[33] This multidimensionality must obviously include cost-benefit analysis and prioritisation of each element and the overall economic feasibility of transport systems as a whole, together with the required legal frameworks defining the role of each actor in the system, be they supervisory authorities, road infrastructure operators and managers, road users or other stakeholders.

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[31] E.g. P. Hacker, "Personal data, exploitative contracts, and algorithmic fairness: autonomous vehicles meet the internet of things", *International data privacy law*, vol. 7, no. 4, 2017, pp. 266-86.

[32] J. Finocchiaro, "Bridging machine learning and mechanism design towards algorithmic fairness", ACM Conference on Fairness, Accountability, and Transparency, March 2021, pp. 489-503.

[33] A.A. Kutty, G.M. Abdella, M. Kucukvar, N.C. Onat, and M. Bulu, "A system thinking approach for harmonizing smart and sustainable city initiatives with United Nations sustainable development goals", *Sustainable Development*, vol. 28, no. 5, 2020, pp. 1347-65.

Conclusion

This section offers a selective examination of several advancements in smart infrastructure, which could prompt the transformation of road networks to become smarter, safer, greener, more efficientand more resilient. An array of innovative solutions exist today that are readily implementable and could lead to reductions in emissions, delay times, energy consumption and other key indicators, while maintaining or even improving safety levels overall. These interventions could take the form of smart lighting or maintenance systems, schemes for data collection through sensors, or traffic signal optimisation. Several IAV-related infrastructure interventions have been outlined as well, which will become deployable as connectivity and automation penetration rates increase. There are numerous barriers to the transition to smart roads and adaptive infrastructure. Broadly speaking, these relate to **(i)** data flow and sharing, **(ii)** transport system robustness, timelessness and scalability and **(iii)** AI fairness and equality. New challenges are largely expected to be multifaceted and multidisciplinary, thus necessitating increased familiarity with new technologies, together with the increased transparency and openness of smart technologies themselves.