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Guidelines for the implementation of SMARTI: Sustainable Multifunctional Automated Resilient Transport Infrastructure

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Abstract

The World's transport infrastructures (TI) network is facing fast changes due to population growth, mobility, business trades and globalization. More challenges are coming from unforeseen natural and human-induced hazards, including climate change's effects. Meanwhile, technology development continues apace, and new solutions from multi-disciplinary sectors could help solve the main challenges faced by the TI industry. This work presents "SMARTI", a vision that aims at engineering and implementing concepts such as Sustainability, Multifunctionality, Automation and Resilience within the design, construction and management of TI. As a result, the paper provides roadmaps for each of the above-mentioned pillars, identifying aims, current practices and stepping stones that infrastructure managers, policymakers and governors should consider toward more sustainable TI within 2030.

Keywords: Sustainability; Multi-functional transport infrastructures; Automated infrastructures; Resiliency; Innovative materials and construction processes; Smart Infrastructures

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1. Introduction

The World's transport network has developed over thousands of years, emerging from the need to allow more comfortable trips for Roman soldiers to the modern smooth roads enabling modern vehicles to travel at high speed and allow heavy airplanes to take off and land safely. However, in the last two decades, the World has been rapidly changing in terms of population growth, mobility and business trades. This is creating greater traffic volumes and demand for minimal disruption to users. In addition, unforeseen natural and human-induced hazards, such as climate change and more extreme weather events, are adding new challenges to the complete efficiency and safety of transport infrastructures (TI). At the same time, developments in Intelligent Transport Systems, vehicle design, mobile and wireless communications, and sensor technologies continue apace and must be transposed and fully implemented in the current TI network (Reeves et al., 2013; Schiller & Kenworthy, 2017).

In order to meet both European strategic energy and climate targets for Smart, sustainable and inclusive growth, Smart, green and integrated transport, and ensure the transition to a low-carbon economy by 2050 (FEHRL National Road Research Centres in Partnership, 2012), Europe needs to invest in research and training to modernize infrastructures and management practices and avoid spending billions of Euros on maintaining the existing European surface transport infrastructure networks (European Commission, 2020b, 2020c). In fact, some infrastructure has experienced a fast rate of deterioration as a result of poor design/construction or more demanding loads than anticipated, and many transport infrastructures are getting close to the ends of their design lives. It is for this reason that European policies forecast a future transport system that is resilient, resource-efficient, climate- and environmentally friendly, safe and seamless for the benefit of all citizens, the economy and society (The Royal Academy of Engineering, 2012). This is seen to happen with "smart" and integrated solutions in transport infrastructure design, maintenance and operations that are estimated to contribute to a 25% reduction in fuel and energy consumption for today's vehicles. However, policies do not indicate clear solutions for this problem. Although it seems that "Smart" appears to be a panacea that will improve society in a multiplicity of ways, there is no common definition in its usage. There is no policy that specifies it.

SMARTI ETN project was conceived within this framework. SMARTI ETN was a 4-year Marie Skłodowska-Curie European Training Network (ETN) funded within the European Union's Horizon 2020 Programme. SMARTI ETN core constituted of eight institutions allocated in six countries: United Kingdom, Ireland, Denmark, France, Spain and Italy. The consortium developed the vision of the world in which we might travel after 2030, when the TI paradigm will necessarily shift to SMARTI: Sustainable Multi-Functional Automated and Resilient Transport Infrastructures.
SMARTI ETN aimed to set up a multidisciplinary and multi-sectoral network to form a new generation of engineers and to provide, to both academia and industry, prototypes and guidelines to progress toward a SMARTI network. The program was finalized in 2021 and allowed to undertake 15 research projects that culminated in developing specific technology concepts, decision-making frameworks and/or asset management methodologies for roadways, railways and airports. Starting from these outcomes, four roadmaps to implement sustainable, multi-functional, automated and resilient TI within Europe by 2030 were proposed.

2. Methodology

SMARTI can be designed by adopting smart (elegant) solutions to face the challenges the sector is experiencing, e.g. sustainability, resiliency, and automatization. With this knowledge, the SMARTI vision was shaped around four main pillars for the TI networks of the future and represents the fundamental challenges for designers and features that TI should acquire across Europe in new or existing roads, railways and airports, whether at local or at the network level (Fig. 1):

- Sustainable (S) TI designed-to-last and re-uses secondary materials to reduce natural resources consumption and reduce at the minimum construction energy requirements;
- Multifunctional (M) TI built to be quiet and capture energy to power lighting, signage or even the electric vehicles themselves;
- Automated (A) TI with capability of monitoring their own condition, and enable cooperative vehicle-infrastructure systems to be introduced, where speed and lane guidance systems could be controlled automatically;

- Resilient (R) TI to maintain services in face of natural and human-induced hazards and with the ability of fast adapting to change and eventually self-repairing.

TI professionals must be aware of the upcoming challenges. Having them in mind, engineers should embrace innovations to design, build and manage TI. Therefore, the SMARTI programme created an intersectoral and multidisciplinary ETN with experts of the four main pillars (SMAR) and 15 early-stage researchers (ESRs) who worked alongside to transfer the knowledge to the stakeholders of the TI sector. The SMARTI ETN project developed (Fig. 1):

- Prototypes, SMARTI solutions developed from the 15 ESRs involved and conceived in the form of technologies, asset management methodologies or novel decision-making frameworks. These smart solutions considered various levels, ranging from materials to infrastructure components to an even bigger scale from the network level to cities/province/regions. They included innovative materials and testing procedures, innovative technologies, i.e. sensors, and models for the infrastructures' modelling and decision-making tools to assess and manage the infrastructures' sustainability and resiliency (Lo Presti et al., 2022).
- Guidelines for the implementation in Europe and beyond, defining the stepping stones to follow in the following years to reach SMARTI by 2030. The guidelines considered each of the four pillars and are herein presented.

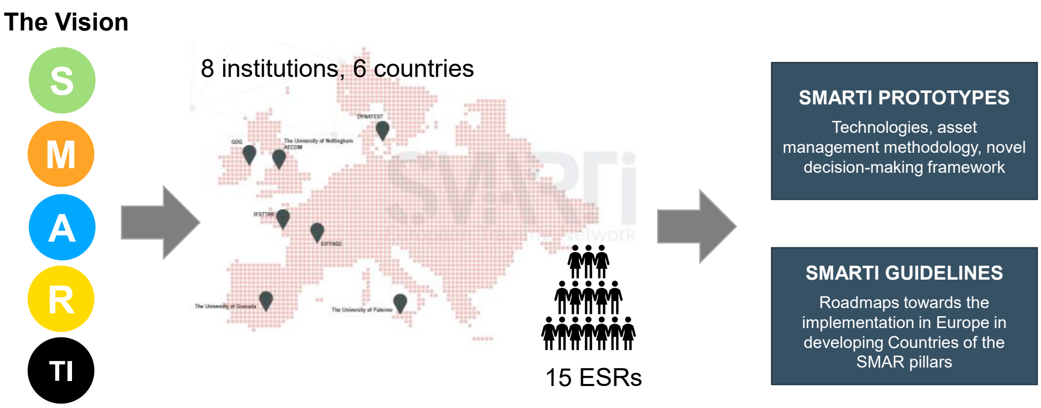

Fig. 1. SMARTI ETN methodology

3. Roadmaps towards SMARTI in Europe

3.1. Towards Sustainable TI

The environmental concerns that arose in the last decade led to the urgent need for a greener transport sector, both in mobility solutions and infrastructures. As the transport sector is one of the primary sources of environmental pollution, the EU commission set the goals of achieving at least a 55% reduction of transport-related greenhouse gas emissions by 2030 and a 90% reduction and climate neutrality by 2050 (European Commission, 2020a). For doing that, clean transport solutions must be fostered, and the life-cycle of the infrastructures has to be optimized. Much progress has been made using alternative fuels (electricity, hydrogen, biofuels and natural gas), especially for what concerns road and railway mobility (Holden & HØyer, 2005). This would lead to a reduction in the production of emissions and the dependence on carbon fossils. However, this is not enough to meet the goal. Actions are also needed to develop greener sustainable transport infrastructure. An infrastructure can be considered as such only if it provides environmental, economic and social benefits. These can be obtained through the maximization of recycling and the minimization of the impacts. However, to be actually effective, the sustainability benefits are confirmed only if the durability is not compromised and infrastructures are designed and managed to last. Fig. 2 reports the SMARTI roadmap which indicates the steps needed to implement sustainable TI by 2030. Implementing these steps will lead to a greener TI network in Europe in the next ten years. A future vision in which, with the view of maximizing recycling, specifications will limit the use of virgin materials instead of limiting the adoption of recycled materials as currently happens. Besides, skilled local management will guarantee the sustainable use and effective exploitation of land and natural resources. This will favor the establishment of circular systems to ensure that waste is prevented and the resources are re-used for as long as possible. The future design and management of TI will be based on decision-making systems, including routinely sustainability assessment techniques and sustainable procurement. The delivery of Sustainable Product Declarations will be the standard, and the Industry will be equipped by default to deliver them. A high-quality design and maintenance plan of the infrastructure must be set as a conventional standard to reduce the total costs and guarantee safety without compromising the service to users. This will be reached by adopting modular design and guaranteed service life of infrastructure components. The aim is to promote life-cycle thinking, considering all the environmental impacts arising during the whole life of the infrastructure (Mantalovas et al., 2020), to achieve a circular economy with governments planning TI' financing beyond duration of their political life.

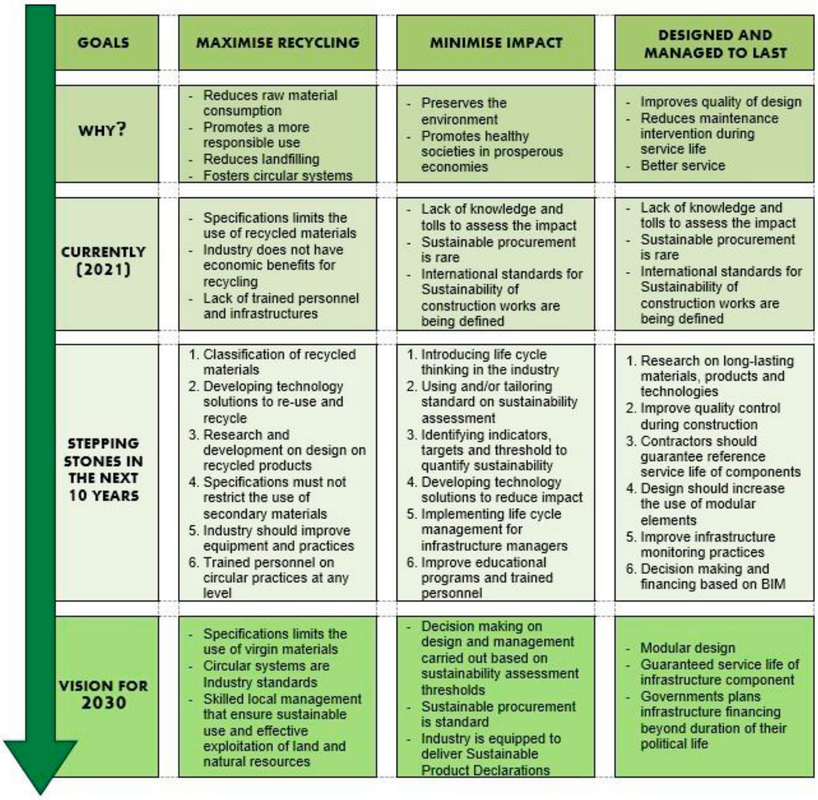

Fig. 2 Sustainable Transport Infrastructure – SMARTI Roadmap 2030

3.2. Towards Multifunctional TI

The future of TI lies in the optimization of the energy consumption passing from positive energy infrastructures to energy integrated transport infrastructures (EITI), which are conceived beyond transport and optimize the use of the land. In addition to recharging electric vehicles, transport infrastructures must be integrated into the energy to decarbonize the transport to meet the challenges of cities and regions.. Fig. 3 depicts the SMARTI roadmap toward multifunctional TI by 2030 in Europe. The principle is that roadways, runways, railways and waterways harvest the energies available in the TI' environment (Vizzari et al., 2021). This will be re-used to provide energy to the surrounding structure and infrastructures, and to the means of transport, allowing an optimisation of the land use and promoting the decarbonization of the transport sector. Implementing SMARTI's ambitious vision in the European TI network, in 2030 generalised eco-district life cycle assessment (LCA) tools, procurement and guidelines will be widespread, taking into account energy integrated system designs and EITI as industry standards. Besides, the opportunity of using transport infrastructures for monitoring the evolution occurring in the land will become a common practice. The movement and changes occurring at the infrastructure level will then represent a useful tool to understand and predict the changes on the planet, like those related to climate change. Transport infrastructure will be considered as a common good to reach decarbonization societal objectives: infrastructures networks will be equipped with Electric Systems (ES) to meet the decarbonization objectives set by the European Commission and single and interoperable technology will be selected by European countries in the mid-2020s.

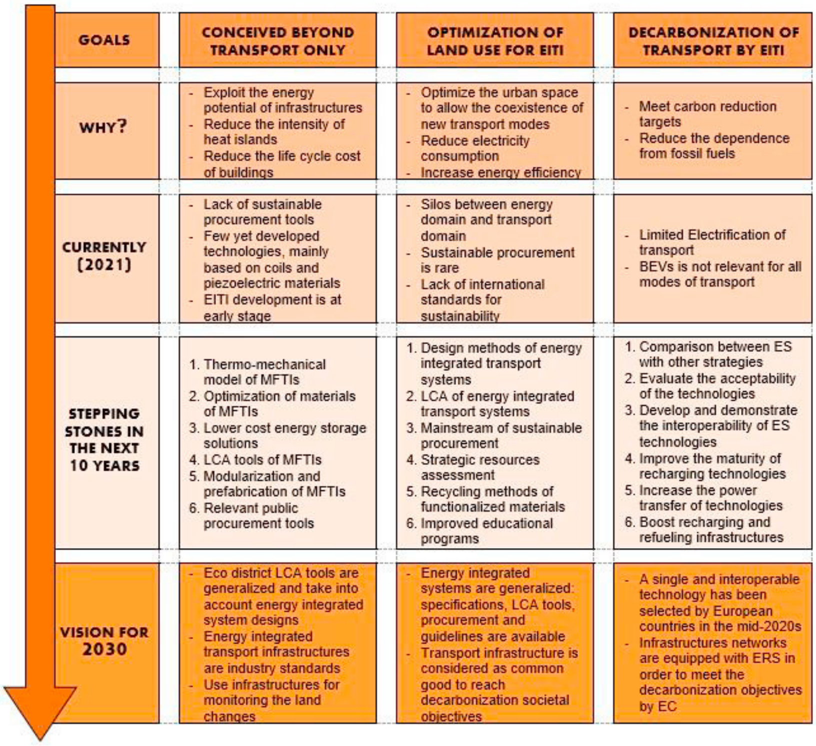

Fig. 3 Multifunctional Transport Infrastructure – SMARTI Roadmap 2030

3.3. Towards Automated TI

The rapid development of intelligent transport systems (ITS) technologies provides more and more possibilities to develop new types of sensors for monitoring traffic, weather conditions or pavement conditions, and wireless communication between vehicles and between the vehicles and the infrastructure (Meyer et al., 2019). These technologies can provide information to drivers and open the way to partially or fully automated driving, thus making travel and movements easier, safer and more intuitive. ITS technologies can also be used to collect data on traffic and pavement characteristics and deterioration and thus improve and automate the infrastructures asset management, permitting preventive maintenance actions (Barriera et al., 2020; Manosalvas-Paredes, Lajnef, et al., 2019; Manosalvas-Paredes, Roberts, et al., 2019; Roberts et al., 2020). Fig. 4 reports the SMARTI roadmap defining the steps to follow to achieve automated TI by 2030 in Europe. The adoption of the guidelines will lead to TI conceived to communicate with connected vehicles and provide the drivers with comprehensive driver information systems. This may help reduce congestion thanks to real-time traffic management and improve traffic safety through incident and accident detection and management systems. The effective deployment and use of real cooperative, connected, and automated mobility (CCAM) will be then finally obtained. TI will also be capable of ensuring their own structural health monitoring and asset management will be carried out through redundant multisource sensing systems. Asset management of all transportation networks will be commonly linked with Building Information Modelling (BIM) approaches. Such an implementation will translate into the optimization of maintenance costs, a better quality of service, and better maintenance planning.

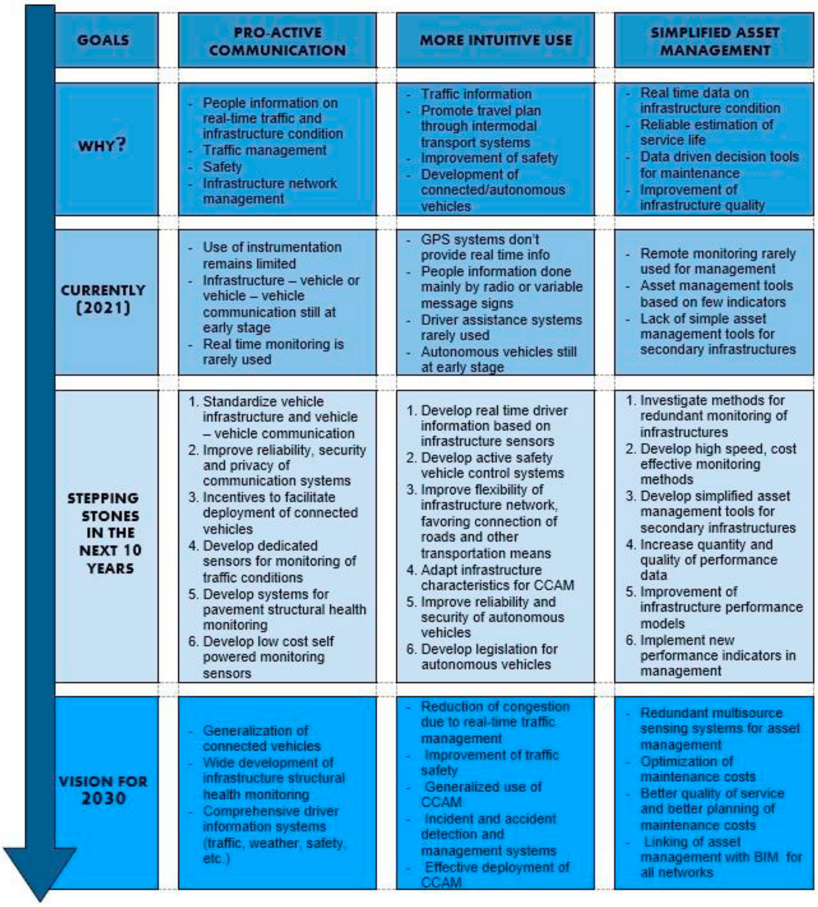

Fig. 4 Automated Transport Infrastructure – SMARTI Roadmap 2030

3.4. Towards Resilient TI

The need for efficient and effective transportation systems continues to be highly attributed to local, regional, national and international demand. At the local end of the scale, an increase in population and the complexity of the built environment require advanced transportation systems to enable the undertaking of social and economic activities. At the international end of the scale, globalization requires complex multi-national transportation systems to move people and goods. Meanwhile, transportation systems continue to be over-stressed in their everyday use, having to bear capacities greater than designed for and, in some cases operating beyond their design life. The situation is exacerbated by their potential exposure to a wide range of natural and human-induced hazards, including the effects of climate change. Therefore, providing reliable transportation systems requires them to be resilient (Sohouenou & Neves, 2021; Tamvakis & Xenidis, 2012). Fig. 5 depicts the SMARTI roadmap for resilient TI by 2030 in Europe. Following the identified steps will allow investment decisions about TI design and management, based on reliable data and less dictated by economic status or social factors, improving, therefore, their efficiency and effectivity. The so obtained healthy transportation system will contribute to the well-being of social, economic and environmental systems. The impact of natural and human-induced hazards will be reduced by including their risks in the planning, design, build, management and maintenance of TI, also thanks to the ready availability of data and information on them. TI will be characterized by an increased absorptive, restorative and adaptive capacity to shocks and stresses. By

2030, European TI need to be climate change resilient also by planning the land use to be responsive to its impacts. Multi-modal transport systems will be the standard, and they will be optimized to face not only normal conditions but also abnormal situations which are becoming more frequent.

GOALS	INFRASTRUCTURES PROVIDING A PERPETUAL SERVICE	REDUCED IMPACT OF NATURAL AND HUMAN-INDUCED HAZARDS	INCREASED RESILIENCE TO CLIMATE CHANGE-RELATED STRESSES
WHY?	- Support access to critical services for all users - Contribute to social, economic and environmental systems - Support the development objectives linked to sustainability	- Improve the wellbeing of communities particularly in vulnerable locations - Support provision of an effective transport network - Maximize benefits of the transport system	- Smooth and safe functioning of infrastructure - Minimize the risk to reliability and capacity of existing transport systems - Minimize the impact of climatic stresses on transport – dependent systems
CURRENTLY (2021)	- Infrastructures exceeded their service lives - The demand is higher than the planned and designed - Functionality is facing challenges difficult to integrate in resilient efforts - A system to characterize resilience is needed	- Capacity of systems to respond to abnormal conditions/hazards rarely measured - The range and impact of hazards is too wide making difficult their management coordination - Insufficient investment towards mitigating exposure to risks beyond natural hazards	- Disruptions affect transport operations, economy, safety - Infrastructure designed for different climate conditions - Costly infrastructure investments, maintenance and repairs - Higher vulnerability due to impacts on dependent systems
STEPPING STONES IN THE NEXT 10 YEARS	1. Integrate resilience criteria with standardized metrics 2. Use communication technology and systems to collect and disseminate transportation data 3. Measure capacity of systems and restructure them to respond to increased demands 4. Standard definition of transportation main characteristics, expected hazards, and capacity needed to address them 5. Prioritize investments in intelligent transport systems 6. Invest in equipment and train personnel for emergency response and research innovative solutions	1. Institutionalize adaptation practices as part of design guides 2. Develop capability to generate risk data in the location of existing and planned infrastructure 3. Invest in increasing capacity of network to absorb and adapt to changes 4. Embedment of resilience risk-based management in the policy of implementing organizations 5. Establish disaster and hazard mapping, management and decision-making systems 6. Establish disaster and hazard mapping, management and decision-making systems	1. Establish policies to reduce Green House Gas emissions 2. Identify existing vulnerable assets and the expected consequences 3. Update design guidelines for abnormal climate conditions 4. Consider future climate conditions in the planning and decision-making process 5. Develop adaptive strategies to reduce impact of climatic stresses 6. Research for design and testing innovative mitigation solutions
VISION FOR 2030	- Investment decisions based on reliable data and less dictated by economic status or social factors - Infrastructures are efficient and effective - A healthy transportation system contributes to the well-being of social, economic and environmental systems	- Hazard risks incorporated in planning, design, build, management and maintenance - Data and information about hazards is readily available - Infrastructure increased absorptive, restorative and adaptive capacity to shocks and stresses	- Land use planning that is responsive to climate change impacts - Multi-modal transport systems optimized for reliability and capacity in normal and abnormal situations

Fig. 5 Automated Transport Infrastructure – SMARTI Roadmap 2030

4. Conclusions

SMARTI European Training Network (ETN) carried out research, training and dissemination to contribute towards the achievement of the paradigm shift to SMARTI: Sustainable Multi-Functional Automated and Resilient Transport Infrastructures. SMARTI ETN developed a series of technology prototypes as well as guidelines to guide the implementation of SMARTI in Europe within 2030. The main part of the guidelines are the roadmaps presented in this paper and from which it is possible to learn the following take-home messages:

- The current transport infrastructure systems are not designed and managed to cope with the main challenges of our times. Therefore, concepts such as “Sustainability”, “Multi-Functionality”, “Automation”, and “Resilience” should be engineered and implemented into the design, construction and management of transport infrastructure.
- SMARTI ETN developed roadmaps for each of the pillars mentioned above, identifying aims, current practices and stepping stones, and steps that infrastructure managers, policymakers and governors should include in their planning.

- The steps needed to revolutionize the European transportation network are ambitious but still not impossible. The expectation is that industry and academia will collaborate and coordinate efforts to develop and implement smart solutions to reach the highlighted stepping stones toward the new "smart" transportation system. On the other hand, the SMARTI vision can be implemented and become a standard only if supported by laws and appropriate national policies.
- The establishment of this system in industrialized countries can represent an example to allow low-income countries to use the SMARTI vision and roadmaps as a technological leap toward implementing sustainable transport infrastructure globally as a standard.

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