Improving Resilience of Transport Instrastructure to Climate Change and other natural and Manmande events based on the combined use of Terrestrial and Airbone Sensors and Advanced Modelling Tools

Irène Sevilla, Philippe Chrobocinski, Fotios Barmpas, Franziska Schmidt, Norman Kerle, Antonis Kostaridis, Anastasios Doulamis, Rémy Russotto

IMPROVING RESILIENCE OF TRANSPORT INSTRASTRUCTURE TO CLIMATE CHANGE AND OTHER NATURAL AND MANMADE EVENTS BASED ON THE COMBINED USE OF TERRESTRIAL AND AIRBORNE SENSORS AND ADVANCED MODELLING TOOLS

Irene Sevilla (1), Philippe Chrobocinski (2), Fotios Barmpas (3) Franziska Schmidt (4), Norman Kerle (5), Antonis Kostaridis (6), Anastasios Doulamis (7), Rémy Russotto(8)

(1) ACCIONA Ingeniería

(2) Airbus Defense and Space

(3) Aristotle University of Thessaloniki

(4) IFSTTAR Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux

(5) Universiteit TWENTE

(6) C4Controls Ltd

(7) National Technical University of Athens

(8) Confederation of Organisations in Road Transport Enforcement (CORTE)

Autor de Contacto: Irene Sevilla irsevilla@acciona.com

Summary:

The project PANOPTIS, funded by the European Commission under the H2020 Programme, aims at increasing the resilience of the transport infrastructures (focusing on roads) and ensuring reliable network availability under unfavourable conditions, such as extreme weather, landslides, and earthquakes. The main target is to combine downscaled climate change scenarios (applied to road infrastructures) with structural and geotechnical simulation tools and with actual data from a multi-sensor network (terrestrial and airborne-based), so as to provide the operators with an integrated tool able to support more effective management of their infrastructures at planning, maintenance and operation level.

During the first stage of the project, the consortium will develop advanced technologies to monitor and control transport infrastructures, such as a Geotechnical and Structural Simulation Tool (SGSA) to predict structural and geotechnical risks in road infrastructures; drone-technologies applied to road upkeep and incident management; improved computer vision and machine learning techniques for damage diagnosis of infrastructure, and early warning systems to help operators identify and communicate emerging systemic risks. At the same time, experts in climate modelling, will analyse the possible short and long term effects of climate change on transport infrastructure (e.g. flooding, heavier snows).

All the information from the different sensors, models and applications will be integrated and processed through a unique *Resilience Assessment Platform* that will support operators in the introduction of adaptation and mitigation strategies based on multi-risk scenarios.

During the second stage of the project, ACCIONA Engineering will implement the developed technologies and methodologies in a section of the Spanish A-2 motorway, in the province of Guadalajara. PANOPTIS integrated Platform will help optimize the management and maintenance of the Ministry of Public Works' concession for a 77.5-km section, all in collaboration with ACCIONA Infrastructure Maintenance (AMISA) and ACCIONA Concessions. In parallel, PANOPTIS platform will also be implemented in a section of 62

Km of a Greek motorway, renowned for its seismic activity. The trials in Greece hosted by the operator *Egnatia Odos* will integrate the motorway that serves the Airport of Thessaloniki. So the scenario will integrate a modal transfer segment.

Key words: Road Infrastructure (RI), Transport Infrastructure (TI), resilience, Decision Support System (DSS), adaptation, Climate Change (CC), sensors, unmanned aerial vehicle (UAV), Machine Learning (ML), Computer Vision (CV), Holistic Resilience Assessment Platform (HRAP)

1. INTRODUCTION

The EU has more than 4.5 million km of paved roads, 212,500 km of railway lines and 41,000 km of navigable inland waterways[1]. In particular, road transport carries more freight and more passengers than all other modes combined[2]. Transport activity across Europe is expected to continue growing. From 2010 to 2050, it is estimated that passenger transport will grow by about 42 percent. Freight transport is expected to grow by 60 percent[3]. The cost of EU infrastructure development to match transport demand has been estimated at over € 1.5 trillion for 2010-2030[4].

One of the greatest challenges facing transport operators and engineers today is the fast and efficient inspection, assessment, maintenance and safe operation of existing infrastructures, including highways and the overall Road Infrastructure (RI) network. Due to factors such as ageing, Climate Change (CC), extreme weather conditions or other natural and manmade hazards, increased traffic demands, change in use, inadequate maintenance and deferred repairs, the Transport Infrastructures (TI) –including also railways, marine infrastructure, etc.- are progressively deteriorating and become more vulnerable, urgently needing inspection, assessment and repair work. According to the EC, the weather stresses alone represent from 30% to 50% of current road maintenance costs in the EU (8 to 13 billon €/year). More frequent extreme precipitations and floods (river floods and pluvial floods) as expected in different regions in Europe are projected to result in an extra annual cost for TI of 50-192 million €/year, for the period 2040-2100[5]. At the same time, while routine monitoring can have a focus that is limited to the actual corridor and its immediate surroundings, the complexity of any critical incident necessitates a more synoptic coverage, whereby air- and space-borne instruments work in synergy with ground-based sensors. The UN Sendai Framework for Disaster Risk Reduction 2015-2030[6], by taking into account the experience gained from the implementation of the Hyogo Framework for Action[7], the lessons learnt, gaps identified and future challenges, highlights certain priorities for action at local, national and global scale. Current preparedness plans hardly take into consideration regional CC predictions, while other disaster risk governance and operational tools for the end-to-end management (preparedness, protection, early warning, response and recovery) are quite fragmented, leading to a non-unified and inconsistent crisis confrontation. Hence, the resilience of RI/TI based on risk understanding and multi-modal data analysis falls short.

PANOPTIS aims to leverage existing tools and services (e.g., climate models, modelling of extreme events and their impacts, Early Warning Systems (EWS), Structural Health (SH) / environmental monitoring sensors and EU services, such as Copernicus) as well as novel technologies (terrestrial and satellite imaging for RI inspection, advanced machine learning and data fusion techniques, etc.) in view of delivering an integrated platform that can be applied to RI, addressing multi-hazard risk understanding, smart prevention and preparedness, faster, adapted and efficient response. PANOPTIS new integrated system to support operational and strategic decisions, by better absorbing and efficiently recovering from damages respectively[8], aims to increase the resilience of RI/TI[i].

2. OBJECTIVES & TECHNOLOGIES OF THE PROJECT

The general objective of the project is to develop a Decision Support System (DSS) providing a comprehensive set of functionalities to help transport agencies to make faster and more effective decisions to detect and respond to recurring and non-recurring conditions in the transportation network. PANOPTIS system aims to be an integrated platform covering three segments: 1.Prevention/prediction of natural and manmade risks 2. Damage assessment during/post event and 3. Situational awareness between all the motorway actors (owners of the infrastructure, inspectors, maintenance teams, road police, firemen, etc.).

PANOPTIS DSS tool builds on the following technologies:

2.1 Climate, Atmospheric Forcing and Multi-Hazard Modelling

Currently available climatic and atmospheric indicators for Climate Change scenarios are not directly applicable for impact assessment on transport/road infrastructure. PANOPTIS will provide quality-assessed numerical indicators quantifying the climatic, hydrological and atmospheric stresses on the RI elements covering processes and interactions from the short-term timescale (days) to periods assessed through long-term (10-60 years) climatic scenarios. A Land Surface model will be used to account for the impact of present and future climate on soil surface parameters (e.g., the presence of liquid water), and hence quantify the structural and thermo-physical impacts of the atmosphere and topsoil parameters on RI elements and operation[9].

The high-resolution modelling effort will exploit existing sources of climate data enriched with data from the micro-climate stations and enhance their added value of derivative risk indicators for selected risk “hot-spots” (e.g., bridges and tunnels), introducing a risk modelling interface with the proposed resilience assessment platform. PANOPTIS aims to provide input for the relevant regulatory framework, e.g., Eurocode 1 that is now under revision, on the load models for climatic actions. Data-based calibration of these load models will be done, and methodologies for evolution of these load models to take into account Climate Change will be proposed.

2.2 Networked micro-climate and smart tags

PANOPTIS proposes to utilize edge network devices like smart tags and micro-climate/ weather stations installed along RI. The proposed distributed sensor network is based on small, autonomous, unattended, reliable and long life wireless tags that will be deployed in certain selected part of the RI (Figure 1) that will continuously monitor for weather change.

---

[i] In the project PANOPTIS, we have focused our case studies on road/highways infrastructures, mostly due to budget constraints; however, the field of our work can be expanded and adjusted to the great majority of transport infrastructures, such as railways, marine docks, etc.

Figure 1 Topology of Network Smart Tags, Micro-climate stations and connected components in RI hot-spot

2.3 Fore-Now/Casting Weather Predictions methods and tools

PANOPTIS will apply weather fore- and now-casting methods at such high resolution to allow for an accurate assessment of the impact of the models on the RI, supporting reliable decisions and appropriate mitigation strategies. PANOPTIS will use Early Warning Systems (EWS) to anticipate extreme weather events and their impact on the road networks. The EWS will use all available local weather information (rain gauges, stream gauges, automatic weather stations (AWS) weather radars observations, etc.) and forecasts (short-term forecasts –*Now-casts*–, Numerical Weather Prediction (NWP)[10] forecast). The various observations will be blended (see Figure 2) using geo-statistical techniques[11].

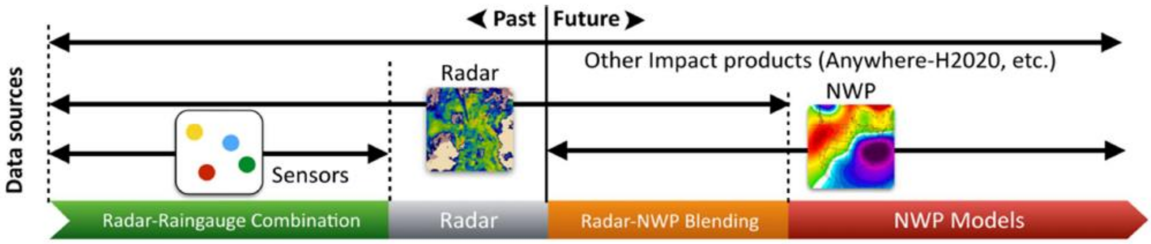

Figure 2 Weather observations and forecasts /impact products to be used

2.4 Geotechnical and Structural Simulation Tool (SGSA)

PANOPTIS will exploit an advanced SGSA simulator to assess the vulnerability of specific structural or geotechnical elements of the RI (bridges, slopes, tunnels, etc.). The structural analysis tools are based on the finite element method and can be used for the static or dynamic analysis (including material and/or geometric nonlinearities) and design of any kind of Civil Engineering structures. The main geotechnical analysis tool is an application for calculation of the stability of structures, their foundations and of slopes and retaining structures, based on the Kinematic Element Analysis (KEA) method, which is a general numerical multiple body failure mechanism method to investigate solid body continua in fracture condition[12]. The stability calculation by the KEA is combined with the computation of ground water flow, pore water pressure distribution and the underground free water surface (ground water table). Steady state conditions can be solved as well as non-steady time step calculations. The structural simulator will exploit monitoring data from various traditional sensors (ground sensors) as well as data from new technologically advanced sensors (UAVs, satellite) in order to assess the current condition of specific (identified) elements of the RI (i.e. a bridge), while updating/calibrating the numerical models of these elements used in the simulator.

2.5 Multi-Hazard Vulnerability Modules and Assessment Toolkit for RI (Geo)Structures

A Multi-Hazard Vulnerability Assessment Toolkit (MHVAT) software suite will be developed to offer integrated analytical assessment of the vulnerability of ageing RI under natural and man-made hazards. It will leverage the SGSA tool to assess the performance of RI under scenarios of single, cotemporaneous and cascading events, integrating information from hazard to structural response and risk/vulnerability assessment. The MHVAT will be employed to produce Multi-Hazard Vulnerability Modules (MHVM) of software that characterize both RI elements (bridge, drainage, slope, overpass) and influential non-RI ones (e.g., transmission power lines, communication towers). Each MHVM will also incorporate a surrogate (geo)structural model for rapidly updating and re-assessing the vulnerability and functionality of an RI or non-RI component as an event evolves, employing actual local measurements to remove uncertainty. The modules will be fully linkable in any configuration, representing physical or functional connections, to model the entire RI system and its interconnectivity with power and communication networks.

2.6 Quick Assessment Damage Maps

In case of a significant disaster event, damage maps are generated through Copernicus EMS, based on high-resolution satellite images. Those maps, but also actual satellite images where available, will be used to carry out a fast and synoptic wide-area assessment and identify extensive damage, flooding, landslide blockage etc. (Figure 3 and Figure 4). As shown, the map gives a valuable synoptic overview (water origin and extent, overall landslide size etc.), but lacks local detail, which the PANOPTIS system can provide. In such situations the fixed sensors may be compromised, and maintenance vehicles cannot access all sites, hence locally controlled remote sensing is needed.

Figure 3 Satellite-based damage map following the 2013 flooding in Germany

Figure 4 Pre- and post-disaster satellite image showing extensive road damage (from Hurricane Irene in 2011)

2.7 Improved multi-temporal, multi-sensor observations with robust spectral analysis, computer vision and Machine Learning (ML) damage diagnostic for diverse RI

PANOPTIS aims to use advanced sensors, such as RGB (visible spectrum cameras), multispectral cameras, thermal infrared, Light-Detection-and-Ranging (LIDAR), and remote sensing platforms (drones, satellite imaging) that will be supported by novel computer vision techniques and Machine Learning (ML) algorithms. In terms of data processing PANOPTIS will advance methodologies for 3D analysis using photogrammetric means and ML, mainly focusing on deep learning methodologies and tensor Algebra decomposition. Information fusion will be employed to exploit the redundancies and complementarities among the different data modalities (RGB, thermal, LIDAR, etc.). The monitoring mechanisms will also include outlier and anomaly detection techniques, which will provide warnings for unusual or potentially suspicious activity. Finally, 3D modelling and analysis techniques over different time instances will be explored, so as to create 4D representations of important infrastructures. Applying change detection approaches such as Change History Maps in the context of the derived 4D models will allow for detection of structural deformations and other types of alterations. The deep learning will allow users to detect flaws and defects on the infrastructure by analysing the data received and extracting a set of suitable descriptors.

2.8 Detailed and wide area transport asset mapping, integrating state-of-the-art mobile mapping and making use of Unmanned Aerial Vehicles (UAV) technology

The UAVs will be operated both in regular maintenance operations for faster and more efficient detection of flaws in the RI; and during/after crisis situations, to get a quicker overall assessment of the surroundings of the affected event area (along with the satellite-based quick damage assessment maps). PANOPTIS will determine an optimal surveillance scheme that is either based on newly emerging hybrid drones or multi-rotor based UAV employing multi-hop routines, where the Mobile Mapping System (MMS) base hosting the UAV will be moved in a calculated manner to allow extensive coverage.

2.9 Holistic Resilience Assessment Platform – *HRAP*

PANOPTIS will provide an advanced simulation environment for assessing the resilience of RI and assess potential impacts due to various hazards and to support the identification of cost-efficient adaptation measures. This environment will permit the integration of various analysis, modelling tools and damage/ vulnerability functions previously described. All these tools along with additional traffic modelling and socioeconomic impact analysis tools, will be chained in order to develop an end-to-end simulation environment enabling to run different hazard “what-if” scenarios and:

- Estimate the intensity of various hazards on RI elements (inundation maps for floods, extreme weather parameters spatial destitution, earthquake shake-maps ground motion fields, etc.);
- Test various risk management approaches, plans and strategies, countermeasures and adaptations for the studied RIs by assessing their overall impact/cost;
- Understand the sensitivity of system assets, infrastructure, and services to the selected types of hazards/events towards a performance based planning;
- Understand interdependencies due to cascading failures in interconnected elements i.e., failure in energy or telecommunication network;

- Set up risk-based response strategies adapted to scenarios and define efficient standard response procedures;
- Assess and quantify the overall resilience of the RI with a holistic quantitative approach.

2.10 Enhanced Visualisation Common Operational Picture (COP), Incident Management System (IMS) and Decision Support System (DSS)

The COP will be generated by integrating all the information that will be provided by the various tools (e.g., multi-hazard models, SGSA models and HRAP), the sensor data, the maintenance planning, etc. as different layers in a unified enhanced visualisation user interface to enable enhanced situational awareness capabilities to the RI operators.

The IMS provides the integration of facilities, equipment, personnel, procedures, and communications for managing all incidents and emergencies[13]. The IMS will permit the collaborative response of all involved relevant local and regional partners to efficiently implement response strategies in order to stabilize the incident and accelerate the transition to recovery. The infrastructure owner (or manager) has the responsibility of the data and information. The decision flow comes from their operational centre(s). Depending on the nature of the decisions or recommendations, they can be addressed to different units/organisations:

- Early warning (hazard predicted): sent to the display unit (warning panels), intervention teams to be placed on a higher readiness level (or mitigation actions (e.g. salt on the road for predicted snow event).
- Damages: sent to 1. Intervention teams – first responders such as firemen for the users and maintenance team for repair: for action (response, repair and/or re-routing of the traffic and 2. To road police for re-routing and for users protection.

The COP is shared between the road owner/manager, the response units, the maintenance units and the law enforcement agencies so all the actors can share the same vision and understanding of the situation.

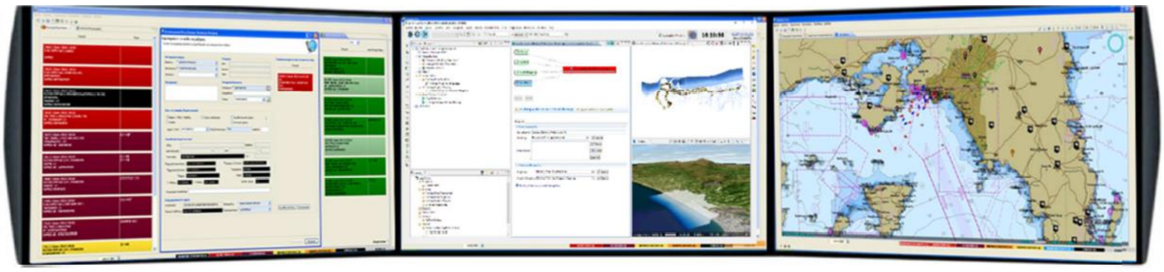

Figure 5 IMS, risk/impact assessment simulation and 3D COP representation in a unified environment

The PANOPTIS DSS aims to assist RI/TI managers/operators in the decision-making process connected with unstructured and semi-structured problems that cannot be solved through simple reasoning or through other information systems. The DSS will provide optimum information combining all the available data sources in the identified “hot spots”, translated into related impact and warnings when necessary.

3. DEMONSTRATION OF PANOPTIS PLATFORM IN THE FIELD OF ROAD

INFRASTRUCTURE

PANOPTIS platform will validated through two real case studies in the Greek and Spanish Road Network. PANOPTIS will perform extensive tests in both demo sites to proof the suitability of PANOPTIS platform for multiple hazard assessment and optimized operational and strategic decisions for management and maintenance of both highways in Greece and Spain. The demonstration will focus on the following main objectives:

- To improve multiple-hazard assessment and strategic management for protection of hotspots of the highway section,
- To improve strategic (smart maintenance and inspection) and operational (check the structural condition of the surveyed infrastructure after an incident) decision making,
- To test the various PANOPTIS outcomes and the overall integrated DSS tool with actuation technologies in real scale critical parts of the RIs

3.1 Spanish demo case in A2 Highway

The demo site in Spain is a section of the Spanish A2 Highway that connects Madrid with Barcelona. The highway is publicly owned, but the operation and the maintenance is done by the Concessions Division of ACCIONA. The selection has been done based on its criticality for the RI/TI system of Spain, as it connects the two largest Spanish cities and its potential affection by a broad range of (mostly weather-related) events having already caused important damages, such as a bridge collapse due to a flooding event[14].

The demonstration activities will be focused on the section managed by ACCIONA, which has a length of 77.5 km, in the province of Guadalajara. It has four lanes (two per traffic direction). The highway section crosses a region with Continental-Mediterranean climate, with long and severe winters, and long, dry and hot summers. Climate Change projections in this area generally foresee an increase in the maximum temperatures in summer (~5ºC by the end of the century) and a decrease of minimum temperatures in winter (~3ºC by the end of the century).

Figure 6 Section 2 – Highway A2 Spain.

The PANOPTIS system will be employed, among other activities, in the optimization of the winter road maintenance and deicing operations, very costly in this region due to the high frequency of frost and snow events; the monitoring and control of critical infrastructure (e.g. embankments) to ensure its stability and prevent certain failure events (e.g. landslides) intensified by extreme weather conditions (strong winds and precipitations); and the application of UAV-surveying and mapping in combination with computer vision techniques in routine maintenance of different road elements (road surface, slopes, drainage).

3.2 Greek demo case in Egnatia Motorway

A section of the Egnatia Motorway in the Northern part of Greece will be used as a test case, selected due to the high exposure of its structures - bridges and geotechnical works (high embankments, big cuts) - and their increased vulnerability to catastrophic seismic events, high annual precipitations that affect active landslide areas, traffic overloading, and geotechnical movements (landslide, settlements, rock-falls). Records with the evolution over time of the dynamic characteristics of some seismic prone bridges, based on continuous ambient vibration monitoring are available. The highway is publicly owned, and the operation and maintenance of this stretch is done by the PANOPTIS partner Egnatia Odos, a public body technical company that was also responsible for the design and construction of the motorway and outsources the operation, maintenance and exploitation of the motorway.

The demonstration activities will be focused on a mountain section of Egnatia Motorway, from the exit portal of Dodoni tunnel (Ch. 59+700) to the I/C Panagia (Ch. 121+940), with a length of 62.24 km, in the prefecture of Epirus, North West Greece. It has 2 separate branches, 2 lanes and an emergency lane per branch. In this section the motorway has 13 long bridges and 16 tunnels. The highway section crosses a region with Continental-Mediterranean climate, with cold winters, and hot summers.

Figure 7 Metsovo bridge. Egnatia Motorway.

Given the high seismic loads in this region, the demo trials will focus, among others, on structural/geotechnical assessment of bridges and geotechnical works under the combination of earthquake and landslide; application of the SGSA simulator on each one of the most representative hot-spots of the road infrastructure, namely: slopes, auxiliary bridges, tunnels, and drainage systems; and the validation of the Computer vision, machine learning and UAV technologies for improved inspection of the hot-spot elements mentioned.

4. EXPECTED RESULTS & IMPACT ANALYSIS

The implementation of PANOPTIS technologies into the Transport/Road Network is expected to lead to the following results, expressed in form of socio-economic and environmental impacts:

Socio-economic Impact:

- Improvement of smooth continuity of mobility of people and freight even in case of serious disruptions due to natural or man-made circumstances.
- Safer and more resilient roads and highways (RI/TI in general), and consequently better conditions for the users.
- Reduction of need for highly trained personnel, thanks to the use of an user-friendly DSS tool integrating and analysing multiple-sources information, and helping users to make decisions.
- Safer working environment for inspection/maintenance/first-response teams, who are most of the times required to execute their tasks in the harsh environments, and facing inconvenient and not safe conditions such as passing vehicles, noise, smoke, chemicals, risk of collapse, etc. The exposure to these conditions is expected to greatly reduce by the usage of “expert/smart” systems.
- Inspection and maintenance costs reduction through regular, structured and planned inspections. PANOPTIS system can monitor permanently the infrastructure and if needed use the satellite images or the UAV to perform damage assessment. As the (pre)inspections will be made easier, it will enable the RI owners to do more frequent inspections to detect possible earlier and thus to minimize the repair costs through a more preventive maintenance.
- Reduction of vehicle operating costs through structured inspection of the pavement and will in-turn result in decreased fuel consumption, tire repair costs, vehicle maintenance and depreciation[15].
- Reduce road/highway down-time for inspections, based on the implementation of remote sensing techniques allowing operation of the system without stopping the highway traffic.

Environmental Impact:

- It is expected that PANOPTIS will contribute to a greener environment. Thanks to the implementation of more regular and targeted roads and highways structures’ inspections, there will be significant reduction of accidents probabilities and thus higher environmental safety overall.
- Emissions in the highway networks are expected to reduce through their appropriate operation following proper inspection. This is also coupled with the expected reduced use of conventional manned inspection and maintenance techniques following the adoption of the PANOPTIS outputs.
- The use of PANOPTIS system and capabilities is expected to increase the average life-time of Road Infrastructure. The PANOPTIS system will provide quicker and targeted maintenance and inspections at identified hot-spots of RIs increasing the estimation of life, having in mind the impact of their hostile environment, enduring heavy stress, changing weather conditions and extreme stresses. Road elements with longer lifecycles will impose further environmental benefits.

5. Acknowledgments

Financial support has been provided by the Innovation and Networks Executive Agency (INEA) under the powers delegated by the European Commission through the Horizon 2020 program “PANOPTIS–Development of a decision support system for increasing the

resilience of transportation infrastructure based on combined use of terrestrial and airborne sensors and advanced modelling tools", Grant Agreement number 769129.

6. REFERENCES

[1] *EC estimations based on data from Eurostat, UIC and national sources*

[2] https://ec.europa.eu/transport/modes/road/road-initiatives_en

[3] http://nws.eurocities.eu/MediaShell/media/EuropeonthemoveBriefingnote.pdf

[4] *EC calculations based on TENtec Information System and the Impact Assessment accompanying the White Paper, SEC(2011) 358.*

[5] Towards climate resilient transportation infrastructures, Technical Report 1/2015, Smart Transportation Alliance

[6] https://www.unisdr.org/we/inform/publications/43291

[7] https://www.unisdr.org/we/coordinate/hfa

[8] https://en.wikipedia.org/wiki/Resilience_(engineering_and_construction)

[9] Heus T, et.al., 2010. Formulation of the dutch atmospheric large-eddy simulation (dales) and overview of its applications. Geosci. Model Dev. 3: 415–444

[10] Kober, K., G. C. Craig, C. Keil, A. Dörnbrack. 2012: Blending a probabilistic nowcasting method with a high resolution numerical weather prediction ensemble for convective precipitation forecasts., Q.J.R. Meteorol. Soc., 138: 755–768

[11] Berndt C., Rabiei E., Haberlandt U. 2014. Geostatistical merging of rain gauge and radar data for high temporal resolutions and various station density scenarios. Journal of Hydrology. 508: 88-101.

[12] Euringer T., "Objektorientierte Formulierung und Programmierung numerischer Starrkörperverfahren in der Geotechnik", PhD Thesis, July 1997, Lehrstuhl für Bauinformatik, Technical University of Munich.

[13] Fundamental Capabilities of Effective All-Hazards Infrastructure Protection, Resilience, and Emergency Management for State Departments of Transportation published by American Association of State Highway and Transportation Officials on Sept. 2015

[14] http://elpais.com/diario/2000/06/13/espana/960847215_850215.html

[15] EU Road Surfaces: Economic and Safety Impact of the Lack of Regular Road Maintenance - Directorate-General for internal policies, Policy Dept B – Structural and Cohesion Policies, - Transport and Tourism.