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Seismic Risk of Inter-Urban Transportation Networks

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Abstract

The paper presents a holistic approach for assessing and managing the seismic risk and potential loss in inter-urban highway networks in earthquake-prone areas. The vulnerability of all elements of the intercity transportation system (i.e., roads, bridges, abutments, retaining walls, and tunnels) is assessed considering the interdependency among the structural, transportational and geotechnical components of the network under different seismic scenarios. Both the direct earthquake-induced damage, as well as the indirect socio-economic loss attributed to reduced network functionality are taken into account in an explicit and transparent formulation that is then displayed in space through an ad-hoc developed GIS-based software. The methodology and the decision-making tools developed are adequately modular, for them to be utilized after appropriate adaptation by local authorities in identifying, prior to a major earthquake event, those vulnerable components of their network whose failure may have a disproportional socio-economic impact. In this way, a rational and effective emergency plan can be deployed to minimize potential human, social and financial loss after a future earthquake. The outline of a foreseen application is also presented for the case of the road network of the Region of Western Macedonia in Greece. Through this pilot application, the methodology is to be optimized in real conditions before being cast in the form of a fully parameterised seismic risk tool, to be used in other earthquake prone areas as well.

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Keywords: Seismic risk; transportation networks; earthquake engineering

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1. Introduction

Given the high seismicity in South-Eastern Europe, and Greece in particular, which corresponds to more than 80% of the seismic energy released at the European level, and the significant direct and indirect cost of damage and loss associated with a major earthquake, the development of methods and tools for the mitigation of earthquake loss is of paramount importance. This is a complex, essentially stochastic problem, not only due to the inherent probabilistic nature of earthquake itself, but also due to the complexity of modern multi-layered economy and social life, facts that render it difficult to assess in advance, quantify, manage and finally minimize the potential earthquake-induced consequences. For this reason, during the last decade, significant research effort has been made worldwide towards the development of a methodology to predict the expected earthquake losses, inclusive of structural and non-structural damage, human loss, infrastructure service disruption and indirect socio-economic cost, as a means to minimize what is called *Seismic Risk*, i.e., the overall Risk to elements of given *Seismic Vulnerability* that are exposed to certain levels of *Seismic Hazard*. A large number of the so-called fragility curves relating the probabilistic vulnerability of specific structural systems to seismic intensity is currently available both in Europe and the US, primarily for buildings but also for bridges (Kwon and Elnashai, 2006; Moschonas et al., 2009), some of them additionally considering soil-structure interaction effects (Aygün et al., 2008), surface fault rupture and pre-earthquake strengthening (Kim and Shinozuka, 2004; Padgett and DesRoches, 2008). Numerous earthquake loss scenarios have also been developed for many European cities, all of them focusing solely on the expected loss due to building damage. In contrast to the research work on the vulnerability of buildings and bridges, significantly fewer developments have been achieved on (a) predicting the physical vulnerability of lifelines and infrastructures, including the roadway and railway networks, and (b) estimating the interdependent behaviour of buildings, lifelines and infrastructures at a system level. Given the fact that potential failure of lifelines and infrastructure may have a tremendous financial impact (i.e., Northridge, US 1994; Kobe, Japan, 1995; Kocaeli, Turkey, 1999; Chile (Maule) 2010; Christchurch, New Zealand, 2010; Fukushima, Japan, 2011), all developed societies are increasingly less tolerant to the large associated economic loss, especially during the particular period of economic instability.

1.1. Current methodologies for management of seismic risk for urban and interurban roadway networks

Roadway network components (i.e. roads, bridges, retaining walls, tunnels) cannot be studied independently, since their seismic damage (due to strong ground excitation or indirectly, due to earthquake-induced ground failure) can have a significant impact on the operation of the network as a whole, during both the crisis and the recovery period. Along these lines, a series of methodologies, software and special tools have been developed world-wide for the assessment of seismic risk, either within or beyond the urban limits, based on network analysis (Augusti et al., 1998), seismic hazard assessment, vulnerability assessment for each network component and estimation of the direct and indirect earthquake loss. Typically, due to the spatial distribution of the data available and the results obtained, a Geographical Information System is implemented (Ansal et al., 2008; Sextos et al., 2008). Pivotal in this respect was the FHWA-MCEER Motorway Project in the US, in funding two 6-year projects that were launched in 1992, wherein a new methodology for seismic risk analysis (SRA) of motorway systems nationwide has been developed. The methodology initially developed was applied to the case of the motorway system in Shelby County, Tennessee and led to a public-domain, GIS-based, software package named REDARS™ 2 (Risks from Earthquake Damage to Roadway Systems). Soon after, a demonstration application of the software to the Los Angeles, California motorway system was conducted (Werner et al., 2001). Features of the software included, inter alia, post-earthquake congestion-dependent trip demands analysis, and a "decision guidance" model to guide decision making related to seismic risk reduction. A parallel effort in the US has been the development of the widely used HAZUS methodology (HAZUS-MH, 2004) and the associated software, which includes a module dealing with Direct Physical Damage to Lifelines - Transportation Systems. HAZUS provides estimates of physical damage, as well as functionality, of the different components of the roadway network, but, unlike REDARS, does not address interdependence of components on overall system functionality and does not perform network analysis. In its latest version (2004), it supports consideration of multiple hazard sources (i.e., floods, tornados, earthquakes). Other probabilistic approaches have also been developed (Stergiou and Kiremidjian, 2008) that take into account the impact of the risk of individual network components on the overall post-earthquake system loss and functionality.

The most recent GIS-based tool for managing network risk is the open source code MAEViz (Elnashai et al., 2008). In terms of early warning systems, ShakeCast (Lin and Wald, 2008) is a post-earthquake situational awareness application that automatically retrieves earthquake shaking data from the USGS ShakeMap, compares intensity measures against users' facilities, and generates potential damage assessment notifications, facility damage maps, and other Web-based products for emergency managers and responders. Most of the above methodologies and tools, albeit valuable, do no cover in a fully comprehensive way all issues involved, and are tailored to US needs and characteristics, hence for them to be applied to European roadway systems several major assumptions are needed. In Europe, a systematic effort to assess seismic risk of public infrastructure, inclusive of transportation networks, was made within the framework of the EU-funded, research project RISK-UE (Vacareanu et al., 2004) while a component-based assessment of roadway network seismic risk has also been performed for the case of northern Italy (Franchin et al., 2006). In all cases, though, the lack of data pertinent to Europe has led to the development of methodologies that were essentially based on US typologies and conditions, while commercial (and essentially risk-irrelevant) GIS software has been used. In South-Eastern Europe, the only system available for the management and monitoring of bridges along a major motorway is the one developed in Greece by Egnatia Odos S.A. within the research project ASPROGE (Kappos, 2009). The system supports the GIS presentation of data related to motorway service and maintenance but does not consider the potential impact of seismic failure on other motorway components. It should be also noted that in Greece, seismic risk has been primarily studied at urban level, regarding either buildings (Kappos et al., 2010, 2007), or lifelines (Pitilakis et al., 2006).

Along these lines, this research effort aims at developing a systematic and comprehensive approach for the assessment and management of seismic risk to urban and interurban roadway networks in Greece. More specifically, a holistic methodology is developed for the assessment of losses in the various components of the urban and interurban roadway network (inclusive of roads, motorways, bridges, overpasses, embankments and abutments, tunnels, retaining walls, slopes) exposed to the risk associated with a strong earthquake. The methodology includes the development of earthquake scenarios and maps indicating the distribution of seismic action in the areas under consideration, assessment of the vulnerability of all structural and geotechnical components of the network and final assessment of the (urban and interurban) direct and indirect losses: damage to structures/infrastructures, socio-economic consequences due to network operation disruptions (road and tunnel closures, bridge serviceability and downtime etc). Once the methodology is developed, it will be implemented through a freely distributable, multi-level software for management of the data and their visualization in space within a GIS system, which will permit, among others, the identification, at a time prior to the occurrence of the earthquake, of the most vulnerable components of the network exposed to seismic risk and/or of the components whose failure is associated with a very high loss. The methodology and software to be developed will be utilised for assessing seismic risk to the urban and interurban roadway networks of the Western Macedonia Region in Greece, an area which has been previously struck by strong earthquakes, the most recent one being that in 1995 (Ms=6.5).

2. Proposed methodology

Given the social and economic risks involved, the foreseen systemic approach for seismic risk assessment of urban and interurban roadway networks calls for a comprehensive treatment, which constitutes the basis of the overall strategy put forward herein. A major task is related to the need for assessing the physical seismic vulnerability of roadway networks, with emphasis on bridges and the relevant geotechnical structures (abutments, embankments) and tunnels, duly accounting for the effect of specific ground characteristics and geohazards (liquefaction potential, dynamic properties, non-linear soil behaviour and induced permanent ground movements), and its effect on the local and global vulnerability of the system (network); this requires information on structures and materials, as well as analytical models and experimental evidence. Moreover, a proper management of seismic risk cannot be achieved without quantification of the impact of structural and geotechnical component damage on the traffic flow, and the estimation of the subsequent social and economic consequences, the latter often graver than the direct ones. Thus, once the physical vulnerability results are obtained, a comprehensive probabilistic seismic risk model is developed and indicators for the evaluation of direct (physical effects) and indirect (socio-economic) impact on the urban and interurban roadway system is defined, using appropriate risk metrics. Once this risk assessment is completed, a systemic approach for seismic risk evaluation is developed taking into consideration all related interdependence models. With such a model available, new risk management software is being developed for assessment of Seismic Risk and Resilience, to be used in any region of Greece. It is envisaged that, subject to a relatively limited adjustment and tailoring, such a system may also by used by the European engineering community at large.

2.1. Seismic Hazard Assessment

At first, fundamental seismic hazard parameters are determined for the study area, such as seismotectonic environment, location and directivity of faults, spatial variation of soil properties, intensity and frequency content of earthquake ground motion, as well as the corresponding free-field accelerations, velocities, and displacements. Despite the fact that the state-of-the-art in this field is already highly advanced, the incorporation of near-fault motion in the framework of a risk/loss estimation of transportation components is a significant contribution. Emphasis is placed on establishing velocity content and duration of near-fault pulses, as a function of magnitude and orientation with respect to the particular fault. This new knowledge is also directly used for the computation of the above parameters for the earthquake scenario to be developed specifically for the pilot study in the Region of Western Macedonia, Greece.

2.2. Seismic Vulnerability of Motorway Bridges with emphasis on the Region of Western Macedonia

Bridge types within a transportation network may vary in general, regarding the structural system and geometry. Since the assessment and management of seismic risk in a transportation network is directly dependent on the fragility of the bridge inventory, the need for bridge classification becomes essential, in order to systematically produce fragility curves for a variety of bridges and eventually link the structural system configuration (and geometry) to the seismic performance of the transportation network in general.

After compiling an inventory of typical structural configurations and existing fragility curves already proposed in the literature, new fragility curves are proposed, explicitly tailored to the Greek bridge typologies; some preliminary results are presented in Section 3.1. Different classification schemes are comparatively assessed based on ATC-13, FHWA 2006 and HAZUS. An important contribution of this research is that the effect of strengthening on the vulnerability of existing bridges is also studied, and new fragility curves are developed for the initial, as well as the strengthened structures. Other phenomena that are commonly neglected are also taken into consideration, such as spatial variability of earthquake ground motion and soil-structure interaction.

2.3. Seismic Vulnerability of Geotechnical Network Components

There is currently a paucity of information on seismic fragility of geotechnical components of a roadway network; hence a new methodology and a set of fragility curves are being produced for critical geotechnical components of the system (i.e. retaining walls, slopes, tunnels, bridge embankments and abutments). The effect of specific soil characteristics (liquefaction potential, dynamic soil properties and non-linear soil-structure interaction, and earthquake induced permanent ground movements) on the local and global vulnerability of the system is studied together, while coupling between structural and geotechnical damage (for instance, the effect of abutment failure on the inelastic response of the bridge as a whole) is also investigated. The resulting fragility curves will finally be used for the purposes of the pilot study.

2.4. Transport Network Analysis

This step envisages the development of an integrated methodology for the urban and rural network analysis and management in the case of closure of road sections or nodes - due to earthquake damage - through the implementation of the appropriate models. The existing models are mainly traffic assignment applications, which distribute the traffic flows to the road network under the prevailing network constraints, with time optimization as the main objective. These mathematical models are extended/adjusted with a view to better capturing user behaviour in the presence of network disruptions and re-routing, including as exogenous parameters the estimated impacts of traffic redistribution –due to damage of road links and critical nodes (i.e. bridges and tunnels) on the socio-economic and environmental conditions of the adjacent areas. Digital maps will be developed illustrating the loads of the study network for the different seismic scenarios and the implementation of appropriate traffic management measures in order to alleviate the negative impacts caused by traffic redistribution.

2.5. A comprehensive methodology for the assessment of seismic risk of urban and interurban roadway networks

The first step is the establishment of the individual components of an urban and interurban roadway network. Subsequent steps include the study on the correlation between fragility and functionality, during the crisis and recovery period that follows a major earthquake, and the development of a holistic methodology for the assessment of seismic risk of urban and interurban roadway networks, with a view to studying the influence of different earthquake scenarios on network performance and obtaining an estimate of the overall direct and indirect socio-economic consequences on both the human and structural capital. These are followed by prediction of all financial, social, cultural and political assets related to the seismic risk of a roadway network in normal and crisis conditions, development of correlated models for various elements at risk and computation of both their individual vulnerability and its effect on the risk of the system as a whole. A methodology to quantify the 'total value' of an urban and interurban roadway network is also being developed considering the cost of repair or reconstruction of the structural and geotechnical components of the system, human loss and injuries, indirect costs related to traffic re-direction, as well as the mid- and long-term cost for restoring social and financial life.

2.6. Software development for the assessment of seismic risk of urban & interurban roadway networks

An interactive, freely available GIS-based software of open architecture, is developed, to be used for the management of seismic risk of roadway networks. The seismic hazard scenarios, structural and geotechnical fragility functions, and traffic analysis algorithms, are being implemented, along with the holistic methodology developed within a comprehensive, modular, easily parameterized package that can be used by both the regional authorities and the central government. The software will essentially be used as a decision-making system that is able to retrieve digital data and process them through an expert system. All results are presented in a multi-layered GIS environment, in the form of digital maps.

2.7. Monitoring of critical roadway network components

A novel concept is introduced, consisting in integrating data from a vibration monitoring system on the ground and the transportation network components as a means to provide important information for the actual condition of representative bridges, and improve the seismic vulnerability assessment and seismic risk management of the network as a system. This is achieved by analysing the information contained in vibration measurements collected from representative structures of the bridge network during the various operation phases (normal ambient-operational vibrations before and after a seismic action/event and moderate to strong earthquake-induced vibrations) for the calibration of linear and nonlinear numerical (finite element) models developed and the associated fragility curves. Novel techniques are also being developed for drastically reducing the high computational effort involved in model updating of high-fidelity large-scale finite element models of bridges, while model updating tools exploit monitored data from moderate and strong earthquakes to validate and/or improve nonlinear (hysteretic) models of localized bridge components, improving the understanding of nonlinear behaviour, soil-structure interaction effects and effectiveness of isolators (e.g. bearings and dampers). Finally, Web-based tools are developed for the automated acquisition and analysis of vibration measurements in real time within the seismic risk management software.

2.8. Pilot study: Assessment and management of seismic risk for the urban and interurban roadway network of Western Macedonia

The area for the pilot study for the assessment of seismic risk of the urban and interurban road network is Western Macedonia, Greece. It has to be noted that the Prefecture of Western Macedonia was until recently (1996) in the 21st place, between the less developed areas in the European Union, with a GPO equal to 62% of the European average. It was also hit by a major (Ms=6.5) earthquake in 1995. Nowadays it is connected to the rest of Greece through the modern Egnatia Motorway. As a result, this area is deemed optimal in terms of the variety of its urban and interurban characteristics (newly-constructed motorways, with numerous bridges and tunnels, are connected to existing old roads), logistical importance, the overall seismotectonic environment and their potential for future development. Along these lines, the implementation of the data already available for the city of Grevena, as derived by a previous AUTh project (Kappos et al., 2010) and the digital maps and structural data produced by Egnatia Motorway for this section of the motorway as part of the software to be developed. Having updated the data related to seismic hazard, structural vulnerability, geotechnical vulnerability, actual traffic re-direction plans (Section 2.4) and monitoring of representative bridges all specifically tailored to the region of Western Macedonia, a comprehensive seismic risk management strategy will be developed for the study area.

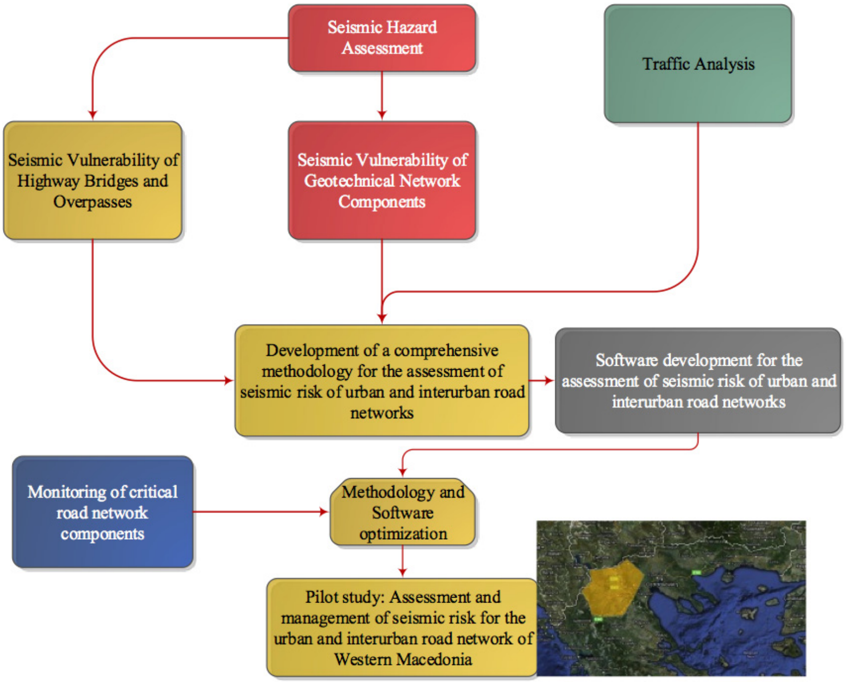

Fig. 1. Overview of the proposed methodology for assessing seismic risk of intercity transportation networks.

3. Preliminary results for the prefecture of Western Macedonia

3.1. Classification of bridges

The methodology presented herein is based on the one developed within the framework of 'Seismic Protection of Bridges' research programme (Moschonas et al. 2009), duly tailored to include all bridge categories of the inventory studied (Western Macedonia). The basis of the adopted taxonomy is to classify bridges according to their features that are more significant regarding the seismic response, namely pier type, deck type, and pier-to-deck connection type (Table 1). Combination of the subclasses relating to each feature results in a total of 45 different possible classes; each one expressed using a 3-number code. However, when a bridge inventory was compiled for Western Macedonia only 14 from the potential 45 classes were actually found in it.

Table 1. Bridge Classification / Classification Scheme of Western Macedonia, Greece.

	Piers		**Deck**		**Pier-deck connection**
Code #	Description	Code #	Description	Code #	Description
1	Single column / Solid section	1	Slab (solid or with voids)	1	Monolithic
2	Single column / Hollow section	2	Box girder (single-cell section)	2	Through bearings (with or without seismic isolation)
3	Multi-column bent	3	Simply-supported precast-prestressed beams connected through continuous R/C top slab	3	Combination of monolithic and bearing connections
4	Wall-type				
5	V-shaped				

Bridge stock in the region of Western Macedonia, Greece.													
Code # (based on Table 1)	232	221	422	431	121	111	223	112	311	421	432	522	1-span
Number of Bridges	14	16	4	2	4	5	2	2	6	6	2	1	14
Percentage (%)	18%	21%	5%	3%	5%	6%	3%	3%	8%	8%	3%	1%	18%

3.2 Fragility curves

In order to assess the seismic performance of bridges as a component of the transportation network, fragility curves, representing the conditional probability of reaching or exceeding a limit state (performance criterion) for different levels of seismic intensity is calculated for every bridge type.

$$P[(\mathrm{D} \geq \mathrm{DS}_i \big| I_M) \tag{1}$$

The methodology adopted is easily applicable to bridges having different structural systems and geometries, while the vulnerability of multiple critical components and the possibility of different failure modes are additionally considered. Threshold limit state values (capacity) are explicitly defined for every component, taking into consideration the effect of variability in structural properties and geometry on component capacity, while the uncertainty in capacity is considered as well. For the demand calculation an elastic response spectrum, or inelastic (pushover), analysis is performed for the calculation of the control point displacement of the component (measured at the level of the deck). Demand uncertainty ($\beta_{,demand}$) values for different bridge structural systems are used, based on the results of Probabilistic Seismic Demand Model (PSDM) and analysis results of one representative bridge in each category.

$$P[(\mathrm{D} \geq \mathrm{LS} \big| I_M) = \int_{-\infty}^{I_M} \frac{1}{I_M \cdot \sqrt{2\pi \cdot \hat{\beta}}} \cdot e^{\left\{-\frac{[\ln(I_M)\hat{\mu}]}{2 \cdot \hat{\beta}^2}\right\}} d(\mathrm{I}_M) \tag{2}$$

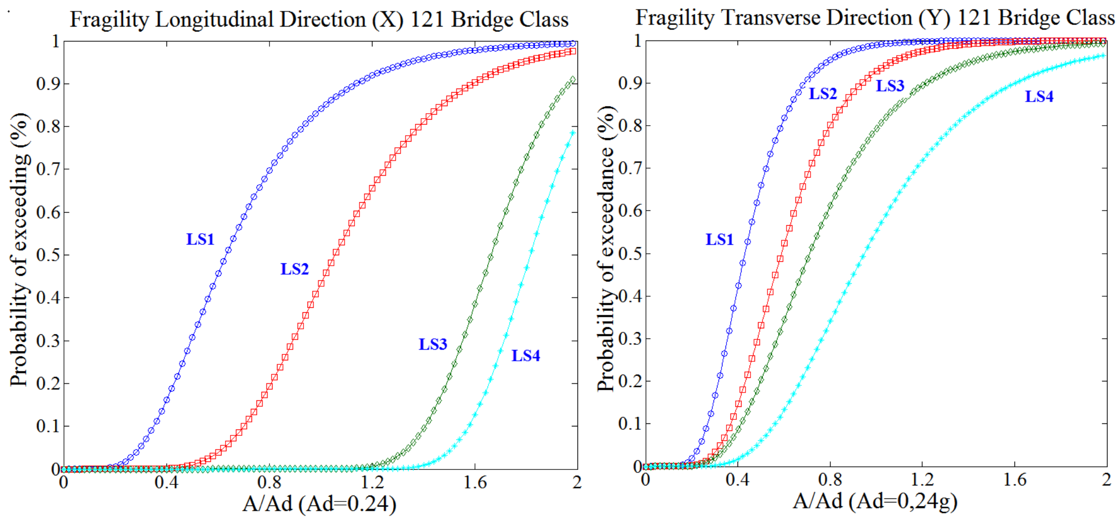

Fig. 2: Fragility Curves for 121 Bridge Class.

Fragility curves, calculated for bridge class 121 (single column piers monolithically connected to box girder deck) are presented in Fig. 2, for both the longitudinal and transverse direction. Seismic fragility curves are represented by a log-normal cumulative distribution function, and are normalized to a_d (the design PGA) in order to become independent of the design seismic action (Dymiotis et al., 2001). It should be noted that in the specific case, series connection between the components was considered (conservative assumption).

4. Conclusions

This paper presents a comprehensive approach on the assessment, management and mitigation of earthquake induced risk and potential loss in inter-urban highway networks. The network is considered as a system comprising of all elements of the intercity transportation system at risk (i.e., roads, bridges, abutments, retaining walls and tunnels) and is assessed considering the interdependency among its structural, transportational and geotechnical components. Emphasis is given on the direct seismic damage and the indirect socio-economic loss whose distribution in space is displayed on an ad-hoc developed GIS-based software. The proposed methodology is a valuable tool for the local authorities in identifying, prior to a major earthquake event, those vulnerable components of their network whose failure may have a disproportional socio-economic impact. For validation and optimization purposes, it is also applied for the road network of the Region of Western Macedonia in Greece. Detailed inventories of the bridge stock and the relevant fragilities are produced. The research effort is currently under process, however, it is deemed the proposed methodology is modular, easily adaptive and applicable in other European areas as well.

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