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Road Protection Against Climate Threats: Risk Assessment and Priorities

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Abstract

During the last decades, the frequency and the intensity of extreme weather events marked a net increase worldwide. Aggressive events, such as, storm surges, wildfires, floods, snowstorms and hurricanes, constitute a big threat to the integrity of the road transport system, since they can severely harm the infrastructure and road assets. The threat can become even more severe to passengers, unexpectedly driven to face harsh weather events. In the field of road adaptation to climate hazards, multiple scientific approaches and protective measures taken have not produced yet the expected results. The road transport sector is still suffering from climatic hazards and undergoes severe deterioration in case of extreme events turning into disasters. The need for a method of reliable risk assessment leading to proactive measures to reinforce the road infrastructure and increase its resilience to climate threats still remains.

The risk assessment method herewith presented introduces a realistic approach for identifying and quantifying the climate related risk for the road traffic and infrastructure. The risk assessment examines four couples of stressors-hazards, namely, rainstorm/floods, long and heavy rainfall/landslides, high temperature/wildfires and snowfall/blizzard conditions. The method defines, for each couple, a generating factor, a contextual factor and two amplifying factors. The Risk Factor, for each stressor/hazard couple, is derived from an algorithm that interconnects these factors in a comprehensive way. Moreover, the issue of priorities to set in the frame of a policy of road adaptation to climate change, with regard to individuals (real-time road-users, potential road-users, neighboring inhabitants) and the infrastructure (failures generating risks for road-users or, merely, traffic closures) is addressed to provide insight on a subject which may turn out to be crucial in case of disaster.

Keywords: Road, Infrastructure, Climate Change, Hazard, Protection, Engineering, Measures

Scientific and Engineering Background

Climate change and extreme weather events present a significant challenge to the safety, reliability, effectiveness and sustainability of every transportation system. Extreme weather events such as cyclones, wildfires, floods and ice/frost effects can severely harm the road infrastructure [4] and create enormous impediments to traffic. Far more disastrous is the eventual direct impact on passengers, vehicles and goods, suddenly and unforeseeably hit by the weather event while moving on the roadway [7].

It seems that, during the last decades, weather threats have become more severe and extreme events are nowadays more frequent, a phenomenon probably associated with climate change. With regard to road traffic and infrastructure, climate threats constitute a major concern. Roads are levers of economic growth and of social welfare in every country, under ordinary conditions, but they become much more important and crucial, at a state of emergency. Ambulances, fire-brigade and emergency vehicles must be able to move freely and safely on the road network so as to help citizens and restore assets and activities to prior-to-event condition. Climatologists and engineers, searching for realistic strategies in this field, focused on operations and safety of individuals moving on the transportation networks, at a first stage, and maintenance of the infrastructure at a second stage. Researchers in the USA [7] managed to design a software to quantify the economic impact of extreme events on road infrastructure.

In 2011, the findings and the outcome of the RIMAROCC project [1] created one of the most analytical and comprehensive methods of risk assessment to face natural hazards. The framework consists of seven steps, namely, Context analysis, Risk identification, Risk analysis, Risk evaluation, Risk mitigation, Implementation of action plans, Monitor/re-plan/capitalize. Risk is considered as a function of Threat, Vulnerabilities and Consequences. For each specific risk, the framework aims to evaluate its probability and the consequences to traffic and to the infrastructure. The respective action plan consists of engineering operations, financing options, socio-economic analysis and time schedule. The list of probable measures includes actions to address threats to the traffic and to the infrastructure. The framework is exhaustive and well-structured, though, probably, too complicated for application to national and secondary road networks.

A PIARC group of experts developed a report on "Climate Change Adaptation Framework for Road Infrastructure" [12] and the World Bank issued a report on "Integrating Climate Change in Road Asset Management" [15]. The PIARC framework consists of four stages, namely, Identifying scope, variables, risks and data (Stage 1), Assessing and prioritizing risks (Stage 2), Developing and selecting adaptation responses and strategies (Stage 3), Integrating findings into decision making processes (Stage 4). The risk assessment is performed in terms of likelihood of the climatic event and the probable impact on the infrastructure. With regard to potential hazards, the framework considers sea level rise, increase in precipitation, increased drought, increased wind strength, increased temperatures, changes to snowfall, permafrost, ice coverage and suggests, accordingly, suitable adaptation measures. The PIARC framework is explicit and complete but it is extensive and, probably, difficult to handle, in the frame of management of 2-lane road networks.

In spite of their completeness, these methods of road adaptation to climate change and many other in this field [3, 6, 8,14], as well as several engineering projects for road adaptation [5, 9, 10, 13] have not produced yet the expected results: the road transport sector still suffers from extreme weather events. Roads and transport infrastructure are often hit by climate hazards: big landslides on main roads in Japan (2021), devastating wildfires in California, Spain, Portugal and Greece (2017-2021), heavy snowfall in Central Europe generating road and airport closures (2018). The reasons of failure, in the fight against climate hazards and disasters, are explicitly presented in former studies [11]. The need for a rational method of risk assessment of road stretches and for a guide to set priorities in the protection of individuals and the infrastructure remains.

The present research paper aims to respond to this challenge by presenting a realistic method to identify and quantify the risk of each hazard for the road traffic and infrastructure. The method accordingly introduces an alternative perspective of facing natural hazards by setting priorities for measures to be taken. The comprehensive method presented herewith, is simple, innovative and easily applicable. In this regard, it may constitute a useful tool to road operators, public administration and private firms aiming to preserve the road infrastructure by effective engineering and non-engineering measures and to keep the transport system open and safe at adverse weather conditions.

Climate Stressors, Hazards and Risk Assessment

Climate stressors are climatic factors of very high or very low values. Long and heavy precipitation, rainstorms, snowstorms, high temperature, drought, hurricanes and other, are climate stressors generating hazards of harmful impact on the road infrastructure. Hazards associated with climate stressors are floods, landslides, slope erosion, wildfires, water shortage, wild life destruction, storm surges and other, which have multiple impacts on roads, traffic and the environment [6].

There is a variety of methods to identify potential climate threats and subsequent impact on roads. A quite extensive description of risk assessment methods has been presented by Axelsen et al [2]. Most methods use input from climate projection models to assess climate threats and define contextual factors from actual site conditions. They may also process road and traffic characteristics to estimate potential impacts on road serviceability.

In most existing methods, the risk assessment by road stretch is performed for each natural hazard separately. The road engineer must, at a preliminary stage, identify potential hazards that may cause damage to the examined infrastructure. Before performing a risk assessment, it is necessary to accurately define the climate stressor-hazard relevance, that is, the process which turns an extreme climatic event into a threat to networks, properties and individuals. Subsequently, the potential impact on the road traffic and infrastructure must be identified and this will lead to the adequate measures for the protection of assets and individuals,

The Risk Assessment Algorithm

The risk assessment method of the Aristotle University of Thessaloniki (AUTH) has been elaborated through back-analysis of serious climate incidents, taken place over roads and motorways, in recent years. The risk assessment, in its present form, examines four couples of stressors-hazards, namely, rainstorm/floods, long and heavy rainfall/landslides, high temperature/wildfires and snowfall/blizzard conditions. The method suggests, for each couple, one generating factor (the climate stressor), one contextual factor and two amplifying variables. This main concept of the risk assessment was derived from thorough study and investigation of hazards. In all examined cases, the climate stressor combined with a decisive contextual feature turned an extreme event into a hazard. The climate stressor and the contextual factor are the generating variables of the hazard, while the amplifying variables, climatic or contextual, may intensify the hazard and worsen the situation. The Risk Factor for each stressor/hazard couple is derived from an algorithm associating the generating factor with the contextual factor and the amplifying factors. The mathematical algorithm conceived to estimate the Risk Factor, for each stressor/hazard couple, attributes a rating value to each factor. The mathematical algorithm has a form:

$$\textbf{Risk Factor: } R = (A^n \times B)^{c(1+s)}$$

where A is the generating factor, B is the contextual factor, n, c are constants and s is derived from the amplifying factors S1 and S2. A and B range from 1 to 10, n, c are stressor- dependent parameters (n>1, c<1), and s ranges from 0 to 0,1

The Risk Factor ranges from 1 to 10, the highest values designating major risk. The form of the algorithm was determined from findings of back-analysis of previous hazards and their respective effects to the road infrastructure. In every case of climate hazard and, much more, in case of disasters, the multiplying effect of the synergy of factors/variables of different origin was clear and this led to the abovementioned form of the mathematical algorithm. Specifically, with regard to the generating factor and the contextual factor, the analysis of past events demonstrated that their combination had a net multiplying effect and not an additive one.

The specific structure of the algorithm, for each one of the four stressor/hazard couples, is still under development.
The mathematical algorithm combines climatic variables with contextual variables, in terms of aggressiveness to roads. Components of the road network (alternative roads, escape routes, warning appliances), as well as the quality of the infrastructure (bridge piers, bridge decks, pavement performance, road structural strength) are crucial in case of all natural hazards. Generating and amplifying factors for the 4 couples of "stressors/hazards" and the impact on the traffic and the infrastructure were defined as follows:

High temperature+ rainless period/ wildfire
generating factor: A= mean max. seasonal temperature (30 days) + rainless period (days)
contextual factor: B= road context: tree groves, forests, conifers surrounding the road
amplifying factors: S1 = fire triggering activities, properties, agriculture, flammable assets
S2= strong winds

Impact on traffic / infrastructure: **risk of accidents/fatalities, distress of infrastructure**
- Rainstorm/ Plain flood- immersed road structure
generating factor: A= max. rainstorm intensity/ duration
contextual factor : B= discharge potential of watercourses, bridges and culverts
amplifying factors : S1 = likelihood of debris flow/blockage of watercourses
S2 = vegetation and gradient of catchment area

Impact on traffic / infrastructure: **risk of accidents+ fatalities/ road closure**
- Long and heavy rainfall/Floods
generating factor : A = rainfall height (48h)
contextual factor : B = potential for rainwater infiltration, flat and bare surfaces uphill
amplifying factors : S1= landslides record, unstable engineered slopes, insufficient drainage
S2 = (lack of) road serviceability, monitoring, early warning and intervention Impact on traffic **/ infrastructure: landslide-slope erosion/ road closures**

- Snowstorm, Long and heavy snowfall/ blizzard, low visibility
generating factor: A = snowstorm, strong winds, snowfall intensity
contextual factor: B = (lack of) road serviceability, snowplow, snow fences, hazard lights
amplifying factors: S1 = snowfall cover depth, prolonged low temperatures
S2 = road vulnerability, bridges and viaducts, risk of avalanche

Impact on traffic / **infrastructure: pavement slipperiness, road closure, accidents, fatalities**

At the occurrence of some climate events, the effect of the generating factor/stressor is decisive in the process which turns the event into a hazard. This is the case of rainstorms and snowstorms, events difficult to fight by engineering measures. By contrast, the effect of the generating factor is less important in the case of high temperatures. Reasonably, extreme high temperatures do not cause wildfires under any conditions and neighboring activities.

The 5 Steps to Safety and Integrity

Generally, there are five steps to be taken in a frame of concerted efforts for protection of road networks against climate threats, as follows:

A. Forecast the likelihood and the intensity of probable weather events. Climatic models introducing a long return period should be used to accurately predict extreme events.
B. Restore initial balance in the broader area of the road. Increase discharge capacity of watercourses uphill. Remove flow blockages due to debris. Restore abandoned quarries. Eventually, in hot climates, remove evergreen trees from the roadside
C. Prevent by measures impeding hazard aggression to the road infrastructure. They are mostly engineering measures, applied, probably, in the broader area of the road. They play the role of a shield barring the way of the climate threat to the road infrastructure (Fig. 1).
D. Monitor and detect: provide suitable and continuous monitoring of vulnerable areas, establish early warning and alert services, in case of emergency. Monitoring may extend beyond the road but must cover, at least, the right-of-way. It is very important in case of roads in forestry areas.
E. Protect, reinforce the road structure by engineering measures to withstand the event and alleviate its consequences. Dense placement of fire hydrant pumps, snow fences, roadside and bench ditches, rip-rap on embankment slopes [Fig. 2], soil nailing and rock anchoring on cut slopes, lateral waterproof barriers along roadway edge line.

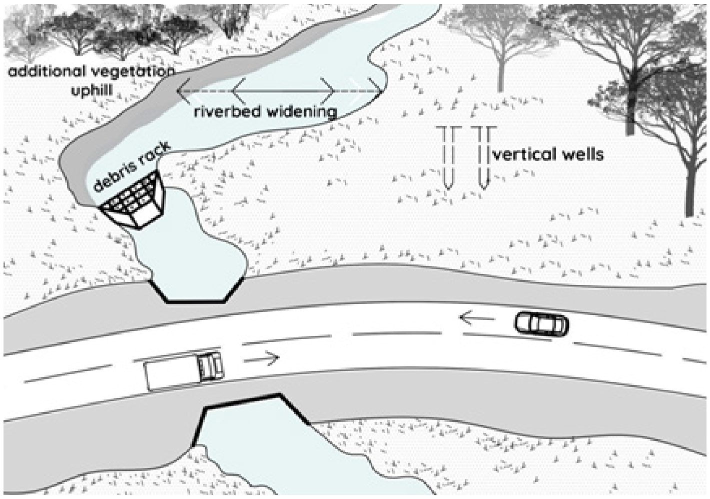

Figure 1: Preventive Measures Against Flooding

The risk assessment is, in fact, an algorithmic evaluation of the probability of occurrence and the consequences of a specific hazard. The risk assessment is conducted following the estimates of the forecast step and introducing real data from the actual condition of the road and its context. Findings of the risk assessment reasonably lead to suitable adaptation and protection measures. By contrast, restoration and prevention measures are useful in any case and must be taken, regardless of the risk assessment findings [11].


Figure 2: Protective Measure Against Flooding: Rip Rap on Embankment Slope

Priorities of A Protection Plan

In the case of new construction projects, correctness and completeness of the road design is a prerequisite for the operational integrity of the infrastructure. The Road Designer must first consider all options of alignment with respect to eventual climate threats and hazards. Low embankments in flood-prone plains are inadequate and can hardly prevent inundation of the roadway. Roads crossing deep forestry areas must have proper fire-resistant clearance (Fig.3). Providing for safety along the coastline, roads need to be adequately constructed on embankments bearing a concrete wall at the exterior front to withstand storm surges. A smart and preventive road design is the very decisive step to adaptation of roads to climate threats.

In order to ensure uninterrupted availability of existing road networks, measures need to be taken to increase the resilience of road transport infrastructure to weather extremes and climate change. These measures may be applied to road assets, such as, pavements, drainage networks, safety equipment, culverts and bridges, berms and slopes, but also to the broader road area.

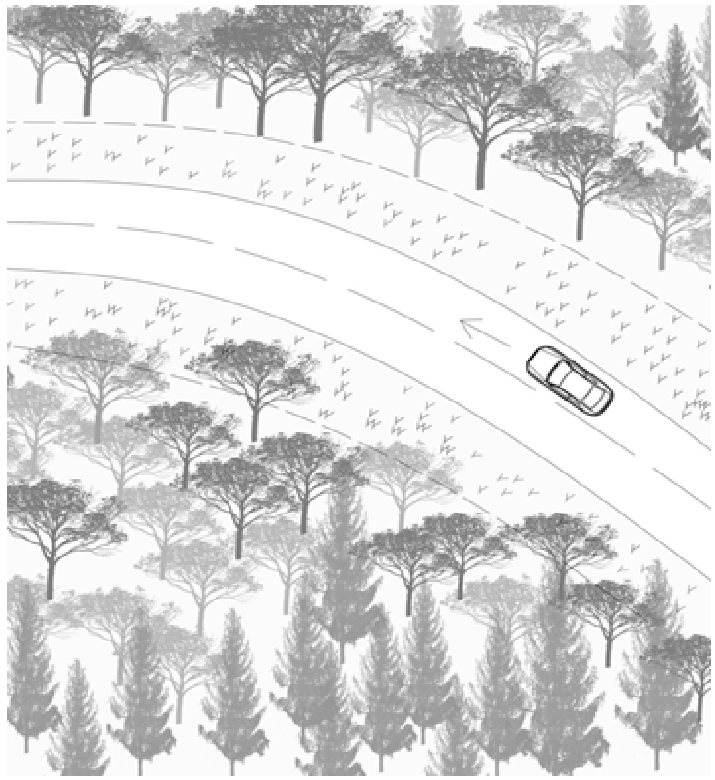
Figure 3 : Clear Zone on Roadside In Forestry Area

All measures must be realistic and cost-effective. They must be adapted to each specific case but also to the potential and resources of the Road Operator. A Road Designer, processing prospective measures to protect the traffic and the infrastructure against aggressive weather events, has to set distinct priorities about the objectives of all engineering interventions. These priorities are as follows:

- **The utmost priority is human life, specifically,** of real-time road-users, inhabitants of neighboring settlements, citizens of urban centres served by the road
- **With regard to protection of road-users,** it is essential to keep the road structure safe but, also, to adequately adapt the broader road area. For instance, in case of a snowstorm, the road structure will probably remain intact, nevertheless, road-users will encounter major problems due to low visibility and to pavement slipperiness. Snow fences, guardrails instead of N. Jersey barriers, may prove beneficial, while snowplow services are mandatory to provide uninterrupted traffic.
- **Neighboring settlements,** uphill and downhill the road, must

be protected against flooding. Insufficient flow capacity of culverts will create problems uphill, while deactivated secondary watercourses downhill may provoke overflow of the main stream, receiving bigger flow discharge than its capacity (Fig.4).

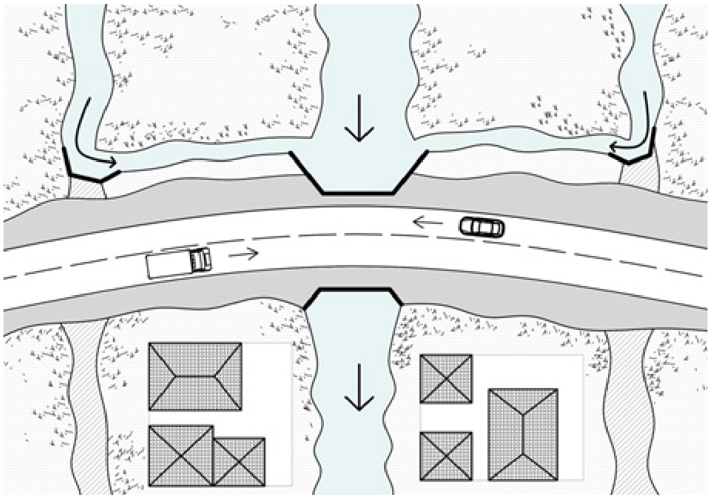

Figure 4 : Diversion of streams creates risk of overflow

- Roads leading to and intersecting at urban centers must remain open to traffic for many reasons. In case of hazardous events, these roads will provide access to emergency services and will play a significant role in the safeguard of human life.

Conclusions

Dealing with the advent of harsh weather events and their probable impact on roads and traffic, it is important to establish the relevance between generating climate stressors and resulting hazards. In case of probable heavy precipitation in the broader road area, it is essential to differentiate a rainstorm from a heavy rainfall, since they cause different problems.

The risk assessment algorithm was developed in a formula requiring input through 4 variables in each case of a stressor/hazard couple. This assessment requires a realistic analysis by consecutive steps and constitutes a critical issue in the decision-making chain. It is believed that this process enables most road engineers to identify and quantify the risk of climate hazards quite accurately. Equally critical is the establishment of priorities. Road designers, constrained by budget limitations, must identify and suggest engineering measures by order of importance to human life. The hereby presented method aims to assess risks associated with climate hazards and prescribes priorities in establishment of measures. A decisive criterion for setting up the main structure of the method was the simplicity and the applicability, so as to provide Road Authorities, even those managing 2-lane roads, the means to suitably adapt the existing infrastructure to future challenges and threats. It seems that, all over Europe, climate hazards, such as floods, blizzards and wildfires, are becoming more frequent and more intense and affect all road infrastructure systems. Consequently, the need to react concerns not only motorway operators but also regional and local authorities managing road infrastructure. These authorities are obliged to ensure smooth traffic flow, under all weather conditions, following a simple and effective risk assessment process, like the one herewith presented, which will indicate the adequate measures for protection of the road-users and the infrastructure.

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