DECISION SUPPORT TOOL FOR ASSESSING THE VULNERABILITY OF A TRANSPORT NETWORK SECTION TO CLIMATE CHANGE IMPACTS

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ABSTRACT

The prospect of a changing climate raises critical questions with regard to how increasing temperatures, precipitation, rising sea levels, extreme storm events, and other impacts could affect any transportation system and its infrastructure . The majority of climate change related transport policies are focused on reducing the green house gas emissions, rather than addressing its key impacts on the sector. Work in this field has only recently been emerging strongly with most efforts concentrating on setting the framework for understanding climate change impacts to transportation. Adaptation measures are seen from a somewhat infrastructural engineering approach, rather than a strategic or systems performance level. Vulnerability is, however, inherently linked to the process of adaptation, and, hence, the analysis of vulnerability provides a sound basis for designing strategies to either provide remedial measures or increase adaptive capacity. In light of the above, the paper proposes the development of a practical and interactive Decision Support Tool (DST) to be used by transport authorities and operators in a preliminary vulnerability assessment of a particular network section with regard to climate change. The methodology employed as the basis of the DST's operation, aims at assessing the vulnerability of a specific section of a transport network to climate change effects, by estimating a ""Climate Change Vulnerability Index" by use of a Multi-Criteria Analysis. The DST has also the capability of assessing simultaneously different scenarios and prioritising resulting vulnerabilities. The main use of the proposed tool is to provide a preliminary decision framework to address impacts of climate change to transportation systems under conditions of uncertainty. Its results may contribute to policy-relevant conclusions and recommendations, guiding also future investments in transport infrastructure against adverse impacts from climate change.

Keywords: climate change, vulnerability, Decision Support Tool

INTRODUCTION

In a densely clustered worldwide economic environment, a similarly dense transport system is required to be operational and functional at all times. Reliability and efficiency in transport operations are essential for ensuring stable economic productivity and sustainability. However, extreme weather events and climate change interacting with exposed and vulnerable transport system components may lead from minor to severe disruptions to a transport network, or other hazards endangering social and economic welfare.

Global scientific consensus is that the world's climate is changing to an uncertain degree. The significant impacts of climate change are long-run and will be felt gradually over the next 50 to 100 years. Long term changes in climate have been observed at continental, regional, and ocean basin levels in temperatures, rainfall patterns, winds, extreme storm and other weather events. It is also widely known that transport systems perform worse under adverse and extreme weather conditions. Transport infrastructure comprises of many different systems, and each is vulnerable to a range of climatic threats. On the whole though, the climate affects directly the design, construction, safety, operations, and maintenance, and indirectly the demand for transport services. Consequently, changes will be required in the building and operating standards of the transport sector at a local, regional, and even national level.

Climate change projections are inherently uncertain due to the unknown course of future emissions, the limitations in modelling the climate accurately, and the effects of natural variability. Therefore, although extensive literature exists on climate change, projections do not always converge. For example, according to the UK climate projections science report (Defra, 2009), mean temperatures in the UK are expected to increase (particularly over summer periods), precipitation is expected to rise up to +70% during winter period and reduce up to 40% during summer period, humidity is expected to decrease up to 10% and summer-mean cloud amount is expected to decrease by up to 20%. The Defra report is, however, inconclusive in terms of extreme storm events, snow and sea levels.

The International Panel on Climate Change (IPCC) (2007a) claim that temperature in the US has increased and is projected to continue to do so. Temperatures have been rising over the last century, with more rapid increase since 1970 than earlier, while average global temperatures increased by 0,74ºC during the past 100 years.

Precipitation patterns are also changing, with more frequent intense events being expected. The sea level is rising, and the rate of change is likely to accelerate due to the glacier melting, and the thermal expansion of the oceans. According to the IPCC (2007a) report, over the 20th century, sea level rose by 0,17m, at a rate of 1,8mm annually, from 1961 to 2003. The intensity of severe storms is also expected to increase, while future tropical cyclones will become more intense, with larger peak wind speeds and heavier precipitation. The IPCC (2007a) report is also inconclusive in terms of changing trends for storm phenomena, such as tornados, hail, and lightning.

The Stern (2007) and Intergovernmental Panel on Climate Change (IPCC) (2007b) reports, that deal explicitly with damages on (among others) water, agricultural, health and insurance sections, pay little attention to climate change impacts on the transport sector. Nevertheless, a focus on dealing with the impact of climate changes on transport infrastructure systems has recently emerged, fully acknowledging that the complexity of projecting the potential impacts of climate change presents a considerable challenge for transportation decision makers, as will be presented in the next section. As these work to meet the challenges of congestion, safety and environmental sustainability, they must also address the risks posed by a changing climate to ensure that substantial investments in a region's infrastructure are protected in the future by effective adaptation strategies. The prohibitive cost of fully adapting transport networks to cater for increasingly severe weather could make it increasingly impractical to accommodate expectations that transport networks will function whatever the weather.

Transport decision-makers require, therefore, information regarding future changes in climate average and variability to better anticipate potential impacts of its change. According to the US climate change science program (2008) report, climatic factors need to be considered, not in isolation, but as part of a broader set of social and ecological factors that provide the context for better informed transportation decisions. Furthermore, uncertainty regarding climatic changes requires to be incorporated into transport systems design and operations.

BACKGROUND

A vast number of research articles are focused on the significant contribution of transport to climate change, with limited work on the exact opposite cause-effect relation. Koetse and Rietveld, (2009) carried out a survey of the empirical literature on the effects of climate change to transport systems, Youman (2007) discussed the implications of climate change on infrastructure planning, design and management, while Jonkeren *et al.* (2011) studied its likely effect on inland waterway transport. With regard to railway transport, the research project ARISCC performed and implemented a climate change adaptation strategy for the International Union of Railways (UIC) (Nolte *et al*., 2011), Baker *et al.* (2010) focused on the operation of U.K. railways and the adaptation measures that will be required, while Lindgren *et al.* (2009) studied the future vulnerability to climate change of the Swedish railway transport system and its adaptive capacity.

Furthermore, Taylor and Philp (2010) analysed the implications for transport infrastructure, transport systems and travel behaviour in Australia, outlining opportunities for adaptation responses based on existing governance structures, and Dewar and Wachs (2006) discussed the treatment of uncertainty related to climate change in the transportation planning sector. A novel approach is followed by the research project FUTURENET, which aims at assessing transport sector security in the face of climate change (Bouch *et al.*, 2012). Finally, Eisenack *et al.* (2011) reviewed the literature that considers explicitly adaptation to climate change in the transport sector and reached the general conclusion that research on adapting transport to climate change is at a stage of "infancy". Many proposed adaptations are only very general guiding principles, while the majority of the more specific adaptations are technical and address road and water transport.

The vast majority of the available literature on climate change effects to transport, nevertheless, originates from reports and studies (mainly governmental), which have begun to shed more light into the level of assets at risk from climate change focusing on a particular mode of transport. One such report is the US Gulf Coast Study (CCSP, 2008) providing a comprehensive assessment of how climate change will affect transport in the United States

Gulf Coast area. The Asian Development Bank (ADB), together with the Government of Timor-Leste, an island highly susceptible to climate change effects, undertook an innovative, cost-effective assessment of climate change vulnerability and impacts to be incorporated into the road project design, environmental management and road maintenance procedures for the island (2010).

In parallel to the above, a significant amount of work is already underway on a national governmental level of transport organisations, engaging on policy and adaptation strategies advocacy for road and rail networks. The Highways Agency in the UK, for example, published their Climate Change Adaptation Strategy and associated Framework (2009), while the UK rail industry has put in place an extensive research programme to analyse the possible impacts of climate change on its network (Local transport adaptation, 2009). Over in the US, the government completed a major new climate change assessment, the US Global Change Research Program's (USGCRP's) Global Climate Change Impacts in the United States (Karl et al., 2009). In addition, the United Nations Economic Commission for Europe (UNECE) has also set up a Group of Experts to work on Climate Change impacts and adaptation for international transport networks (www.unece.org).

It is rather evident from the above literature review that work in this field is currently emerging strongly with most efforts concentrating on setting the framework for understanding climate change impacts to transport, based on the assumption that current vulnerabilities and sensitivities can be extrapolated in a linear manner into the future. The majority of related studies are for selected transport modes and case/location specific, while very few focus specifically on international transport networks. Adaptation measures are seen from a rather infrastructural engineering approach, rather than a strategic or systems performance level. In addition, little attention is given to decision making practices under uncertainty.

Therefore, there is a need for adopting a strategic framework that can effectively consider climate inputs, through a systematic mapping of transport system related vulnerabilities and their consequences in order to take into consideration the inherent uncertainty of climate forecasts. In addition, climate change should be considered at the early stages of transport infrastructure planning and included in risk and vulnerability assessments. To this end, a more future-oriented decision support framework in which to interpret climate change forecasts to the transport system is required in order to guide the implementation of adaptation measures.

In light of the above, the paper proposes a practical Decision Support Tool (DST), targeted at transport infrastructure and operations stakeholders, with the scope to provide recommendations on how to identify critical infrastructure vulnerable to the potential impacts of climate change and incorporate this information into their decisions to ensure a reliable and robust future transportation network.

CLASSIFICATION OF THREATS AND IMPACTS

The published research provides information on several significant vulnerabilities within the transport sector to climate variability and change (DOT, 2002; Eichhorst, 2009; TRB , 2008; CCSP,2008). For simplification purposes, the present paper will only consider –based on related research and studies- four key factors with regard to climate projections that are most likely to occur over the near foreseeable future and are of higher relevance to most

components of the transport sector: (i) changes in mean temperature, (ii) changes in mean annual precipitation, (iii) resulting changes in sea level, and (iv) frequency and magnitude of extreme weather events.
In addition, there are three transportation vulnerabilities associated with climate change:

- Infrastructure: Planning and design, materials selection construction and maintenance;
- Operations: Efficiency, mobility, safety, and environment and social externalities;
- Demand: Location, timing, mode(s) and sector, behavioural responses.

The discussion on classification of impacts is indicative rather than broad in coverage of all aspects, highlighting major impacts, similarities and differences among transport modes that bear the most important implications for adaptation strategies. It also focuses on direct impacts, since indirect ones, of an economic, environmental and demographic context are beyond the scope of the current analysis.

Increasing temperature

Projected warming temperatures and heat extremes will affect all types of transport infrastructure, particularly that of land transport modes. The most common impacts are road pavement deformation (albeit not exclusively caused by increasing temperatures), softening and buckling and other structural material degradation, such as thermal expansion of bridge joints, buckling of railway track and track movement. Aquatic vegetation growth could also lead to clogging of inland waterways.
Roads, railways, and airstrips are all vulnerable to the thawing of permafrost. Increased frequencies of freeze-thaw cycles have been related to premature deterioration of road and airport runway pavements. Warming temperatures and melting sea ice are also likely to result in increased variability in year-to-year shipping conditions and higher costs due to requirements for stronger ships and support systems (TRB, 2008). With regard to aviation, temperature extremes will affect airport ground facilities and runways in similar ways they affect road infrastructure, while they could also cause reductions in aircraft lift and efficiency. Finally, inland waterways could experience lower water levels due to increased temperatures and evaporation with ships not being able to carry as much weight.

Increasing or decreasing precipitation

The frequency, intensity, and duration of intense precipitation events have been traditionally important factors in designing specifications for transport infrastructure. Increases in the frequency and intensity of the precipitation could cause flooding of roads, railbeds, airstrips, cycleways and walkways, as well as seaport facilities and airport runways. Increased precipitation may also cause decrease of structural integrity due to erosion, landslides and slope failures that could damage road and rail infrastructure and force greater levels of maintenance. In addition, precipitation is a key factor that contributes to the weathering and premature deterioration of transport infrastructure. Finally, it imposes safety risks, with increasing accident frequency.
On the other hand, decreased precipitation results in increased ground movement and changes in the water table, thus, causing high soil salinities, landslides and subsidence. This impact on soil structure might accelerate the material, structure and foundation degradation,

and hence, reduce the infrastructure lifespan, increase maintenance costs and might eventually lead to structural failure when aggravated by extreme weather events. In addition, dry periods in combination with floods could alter erosion and deposition patterns on river and canal banks, impacting on navigable waterways.

Rising sea level

The impact of sea level rise is mainly limited to coastal areas, and can damage or render inaccessible coastal infrastructure including road and railway beds, port and airport facilities, tunnels and underground rail/metro corridors. In addition, it can affect the port operations, with berths not having sufficient height to cope with rising sea levels. There is also the risk of inundation of road and rail infrastructure, as well as the degradation of roadway surface and base layers from salt penetration.

Extreme weather events

Extreme weather events, such as intense storms or increased wind speeds and hurricanes, cause severe impacts to infrastructure, mobility, accessibility and safety. Impacts include severe damage or even destruction of roads, infrastructure fabric, railways, and airports. In addition, extreme events reduce the navigability of rivers and channels, disrupt shipping routes and can even cause derailments or collisions. Other impacts include lightning strikes disrupting electronic signalling systems, obstruction of roads due to fallen trees, buildings or vehicles overturning because of strong winds, etc. Such impacts will sequentially increase the liability and insurance costs to transport authorities and related stakeholders.

Risks

The above climate change phenomena impose a variety of risks to transport networks. As an indication, the UK Highway Agency (2009) has summarized the high level climate change related risks that could impact a road network, together with their associated consequences, as presented in Table 1.

Table 1- Climate-related risks to road transport

Risks	**Examples**
Reduced asset condition and safety	Assets deteriorate more quickly due to changes in average climatic conditions; assets are more badly damaged as a result of more extreme climatic events.
Reduced network availability and/or functionality	Need for restrictions on the network to maintain safety; increased need for roadworks.
Increased costs to maintain a safe, serviceable network	Construction/maintenance/repairs/renewal required more often; new (more expensive) solutions required e.g. designs and materials/components/ construction costs.
Increased safety risk to road workers	Increased risk to construction and maintenance workers and Traffic Officers as a result of climatic change e.g. if need to work on the network more often; if required to work on the network during extreme climatic events or if climate change requires them to perform more 'risky' activities.
Increased programme and quality risks due to required changes in construction activities	More onerous design requirements; new technical solutions required with higher uncertainty, affecting project programmes and/or quality.
internal operational procedures not appropriate	Effects of climate change require new ways of working

	- changed or new business processes, new skills/competences.
Increased business management costs	Need for more staff; more frequent (expensive) incidents to pay for; need for more research into ways of coping with climate change.

DECISION SUPPORT TOOL

As discussed previously, the uncertainty of climate change acts as one of the barriers to any adaptation strategies under a long-term horizon. Decision support tools are designed to assist in planning decisions where future conditions are uncertain or can change rapidly. To this end, a Decision Support Tool (DST) is proposed, to be used by transport authorities and operators in a preliminary vulnerability assessment of a particular transport network section with regard to climate change. Vulnerability is based upon the sensitivity of infrastructure or systems to climate change as well as its resilience, or adaptive capacity for sustaining climate impacts with minimal cost or disruption in service (FHWA, 2009). From this perspective, the definition of vulnerability must be contingent on estimates of the potential climate change and adaptive responses (Kelly and Adger, 2000). To accomplish this, a vulnerability index is proposed, based on criteria which influence the vulnerability of transport network section to climate change.
In prioritizing vulnerabilities there is no “right” answer, and there will be a number of elements with regard to transportation systems and infrastructure that are considered to be more vulnerable to climate change impacts than others. This is to be expected, since different climate change phenomena may have very different effects, and it is not always possible to compare these in a precise manner. To this end, the diverse nature of climate change impacts and the variety of transport components that are affected arguably call for a (MCA)-type approach. Based on the above, a DST is proposed that involves four distinct phases, described in the following.

Phase 1-Case/Scenario Definition

The first phase involves the clear definition of the case study/scenario profile characteristics in terms of defining the type of transportation system, its modal characteristics and its physical location and natural environment. In addition, the DST will define the potential transport vulnerability elements related to (a) “Infrastructure” or (b) “Operation”, in order to distinguish among the key vulnerabilities associated with any transport network system (transport demand is not considered in the DST’s present form since it would require a different structure of DST). In this manner, the user will be allowed to assess at the next phases the vulnerability of each different component of the transport network section, and subsequently prioritise these. The following categories and related subcategories defining the profile of the case/scenario under study will be available for selection by the user:

1. Location/physical environment (l)
    a. Urban
    b. Rural
    c. Coastal
    d. Mountainous terrain
    e. Level terrain

    f. Lakes/rivers close by

2. Transport Mode (m)
    a. Road
    b. Railway
    c. Maritime
    d. Aviation
    e. Public Transport

3. Transport Component
    a. Infrastructure (i)
        i. Planning and design phase
        ii. Construction
        iii. Maintenance
    b. Operation (o)
        i. Continuous all weather
        ii. Efficiency
        iii. Mobility
        iv. Safety
        v. Environmental and social externalities

4. Climate Change Projections (C_j) and Uncertainty $P(C_j)$

The climate change condition and the corresponding uncertainty will also be available for selection for each specific scenario:

1. Temperature
    a. Increased temperature (i.e increase in no of degrees)
    b. Thawing of permafrost (% increase)
    c. Heat waves and milder winters (number of additional hot days)
    d. More frequent droughts and less soil moisture (number of additional days of dry season)
2. Increase precipitation (% increase)
3. Decrease precipitation/droughts (% decrease)
4. Sea level rise (increase in m)
5. Extreme events
    a. Intense Storms (frequency)
    b. Winds/Hurricanes (% of wind speed increase, frequency)

Based on the above, each specific case/scenario profile denoted by the element CASE $_{l,m,i,o,c}$ will be uniquely defined in the DST application by the following elements: Location (l), transport mode (m), transport infrastructure (i), transport operations (o), and climate change category (c_j). . In the case that more than one scenarios are analysed, a matrix will be created with elements CASE $_{k,l,m,i,o,c}$, where k is the number of each specific case. In addition, the probability of occurrence of a climatic change for a specific case is selected based on a range probabilities of occurrence under specific time horizons obtained from leading mathematical models of climate change, namely Change General Circulation models, or GCMs, such as the Atmosphere-Ocean General Circulation Models (AOGCMs). Therefore, a matrix with elements CLIMATE $_{k,P(Cj)}$ is also produced, where k is the specific case/scenario number, and C_j the climate change category, with each matrix element constituting the probability of occurrence for each climate change category $P(C_j)$.

It should be noted that the four categories used to define the scenarios, as well as the criteria and sub-criteria for the purpose of the MCA in the following section were selected by the authors, based on the background research documented in the paper, as well as the authors' individual expertise, knowledge and judgment.

Phase 2-Criteria Measurement

The estimation of the "Climate Change Vulnerability Index" for a transport network section will be carried out through the application of a Multi-Criteria Analysis (MCA), which is a structured approach of determining overall preferences among alternative options by reference to an explicit set of objectives that the decision making body has identified, and for which it has established measurable criteria to assess the extent to which the desirable objectives have been achieved (DTLR, 2000). The MCA appears well suited to deal with both the qualitative and quantitative factors that have been introduced and facilitates the prioritisation of vulnerabilities using commonly accepted and measurable data. This phase will, therefore, ask the user to provide values of measurement for the list of criteria selected for the purpose of the above MCA.

Criteria Selection

A set of criteria (with related sub-criteria) are introduced, considered by the authors to be the factors determining the vulnerability of a specific transport system/component to the effects of climate changes. Furthermore, weights are established for each of the criteria together with associated indicators for their measurement. Resulting criteria values are converted to a single unit via an artificial scale determined by the authors. To this end, an Analytical Hierarchy Process is introduced for the relation between criteria and sub-criteria for each criterion, in order to facilitate their weighting and measurement.

A significant proportion of the 'value-added' by a formal MCA process derives from establishing a sound set of criteria, directly and objectively measurable, against which to judge the different components. To this end, the criteria ($Cr_{z,j}$) selected for each climatic change occurrence j are presented in Table 2 together with their units of measurement and corresponding weights.

It should be noted that for the qualitative criteria (Cr_3, Cr_4, Cr_5) scores are derived by ranking the "verbal" physical performances from the "low impact" to the "high impact", and then assigning the values of artificial scale respectively from the lowest to the highest values.

1: extremely low
2: low
3; medium
4: high
5: extremely high

Criteria Weighting

For the purpose of the analysis, the simple Paired Comparison Approach is employed in order to derive criteria weights (W_z) using the question "is this criterion more important than the other?", offering a binary choice. For each respondent, the full set of choices yields a preference score for each criterion, that is, the degree to which a criterion is more important compared to all other criteria. For the purpose of this analysis, criteria weights were obtained from the standardization equation (1).

$$\text{Standardised score } w_i = \frac{'preference'\, score\ w_i}{\sum 'preference'\, scores} \qquad (1)$$

Average criteria weights are presented in Table 2 as an indication, obtained from a pool of experts of the road sector from different countries in Europe in order to ensure a geographical balance on the climate change factors that influence transport infrastructure.

Phase 3-Estimation of Vulnerability Index Score

The DST will use as input the measured values for all criteria requested in the previous phase to automatically estimate the "Climate Change Vulnerability Index" score for each case/ scenario in the third phase.

Estimation of criteria/impact levels in artificial scale

To make the various criterion scores compatible in order to facilitate their aggregation, it is necessary to transform these into one common measurement unit. There are two types of scores depending on the nature of criteria. For the set of criteria, for which the higher the value of the score, CI ,the better the "Climate Change Vulnerability Index". For the other set, denoted CII, the lower the value of the score, the better the "Climate Change Vulnerability Index". Moreover, each criterion score is forced to take values between [0,1], through the application of the following functions, depending on the nature of each criterion:

$$U_{CI,f}=P_{CI,f}/A_f, \qquad (2)$$

$$U_{CII,g}=A_j/P_{CII,g}$$

With: $P_{CI,f} \geq 0$ and $P_{CII,g} \geq 0$

$A_f \geq P_{CI,f}$

$A_g \leq P_{CII,g}$

where:

f, g: criterion number for criterion type C_I and C_{II}, respectively

$P_{CI,f}$ and $P_{CII,g}$: Physical (real) performance score of criterion i (of criterion type I) and criterion j (of criterion type II)

$U_{CI,f}$, $U_{CII,g}$: Artificial (after transformation) performance score for criterion i (of criterion type I) and criterion j (of criterion type II)

A_f: Constant variable, representing the max value of all scores for criterion i (of type I)

A_g: Constant variable, representing the min value of all scores for criterion j (of type II)

Table 2- Climate Change Vulnerability Criteria

Main Criteria Groups	**Criterion No**	**Description**	**Unit of measurement**	**Weight of Group (Wz)**	**Weight of Criterion Within Group (Wzx)**
Cr 1 Transport operations: Represents those elements of transport operations affected by climate change.	**Cr 1.1**	Percentage of time that the transport section does not meet safety and capacity levels after the weather event	%	0.4	0.1
	Cr 1.2	Percentage of time that the transport section does not meet safety and capacity levels after the weather event.	%		0.1
	Cr 1.3	Degree of infrastructure deterioration	%		0.2
	Cr 1.4	Increase of user operating costs	%		0.1
	Cr 1.5	Reduction in user costs due to improved weather advisory, control and treatment strategies	%		0.05
	Cr 1.6	Additional delay/travel time as % of normal time	%		0.05
	Cr 1.7	Additional traffic accidents	No of accidents/ veh-kms		0.15
	Cr 1.8	Increase in vehicle operating costs	%		0.05
	Cr 1.9	Increase in emissions	%		0.05
	Cr 1.10	Increase in vehicle damage (e.g due to salt)	%		0.05
	Cr1.11	Loss of property (vehicle)	No of vehicles		0.1
Cr 2 Transport assets: Represents those elements of transport assets affected by climate change.	**Cr 2.1**	Design and construction of new or replacement assets	euro/km	0.3	0.4
	Cr 2.2	Maintenance and Management of existing assets	euro/km		0.25
	Cr 2.3	Additional maintenance needed (e.g. snow removal, icebreakers)	euro/km		0.1
	Cr 2.4	Introduction of weather advisory, control and treatment strategies	euro/100kms		0.05
	Cr 2.5	Design and implement measures for resilient network	euro/100kms		0.2
Cr 3	**-**	Economic impacts: The economic importance of the different transport modes is defined as the total economic production quantity created from the regular function of each transport infrastructure.	Qualitative: 1-5	0,15	-
Cr 4	**-**	Exposure (non-economical): Assessing the time horizon for climate change effects to materialise.	Qualitative: 1-5	0,05	-
Cr 5	**-**	Severity of exposure: Assessing the magnitude of stress associated with a climatic change impact.	Qualitative: 1-5	0,1	-

Aggregation

The total score of the system's overall performance is obtained by the weighted summation of criterion scores applying Multiple Attribute Utility Theory (MAUT). Consequently, the "Climate Change Vulnerability Index" (VI_k) is computed by the following equation for each specific case/scenario k:

$$VI_k = \sum_L \sum_m \sum_i \sum_o \sum_j (CLIMATE_{k,j} * \sum (C_{jZ} * W_z * W_{zx}) \qquad (3)$$

Based on the above, the result of Phase 3 will be a matrix VI_k with k values of estimated vulnerability indices for k cases/scenarios.

Phase 4-Prioritization of Network Sections

Based on the estimated values of the "Climate Change Vulnerability Index" for each specific case k produced in the previous phase, this last phase ranks the estimated indices, and the DST automatically presents a prioritized list of vulnerabilities. To this end, the user is provided with a prioritised list of vulnerable network components/ sections, based on the criteria selected to represent their vulnerability to climate change and their potential to disrupt the operation of the network. This prioritisation provides a sound basis for identifying priority areas, related timescales and responsibilities for planning, setting up adaptation strategies and implementing appropriate measures.

The DST logic is depicted in Figure 1.

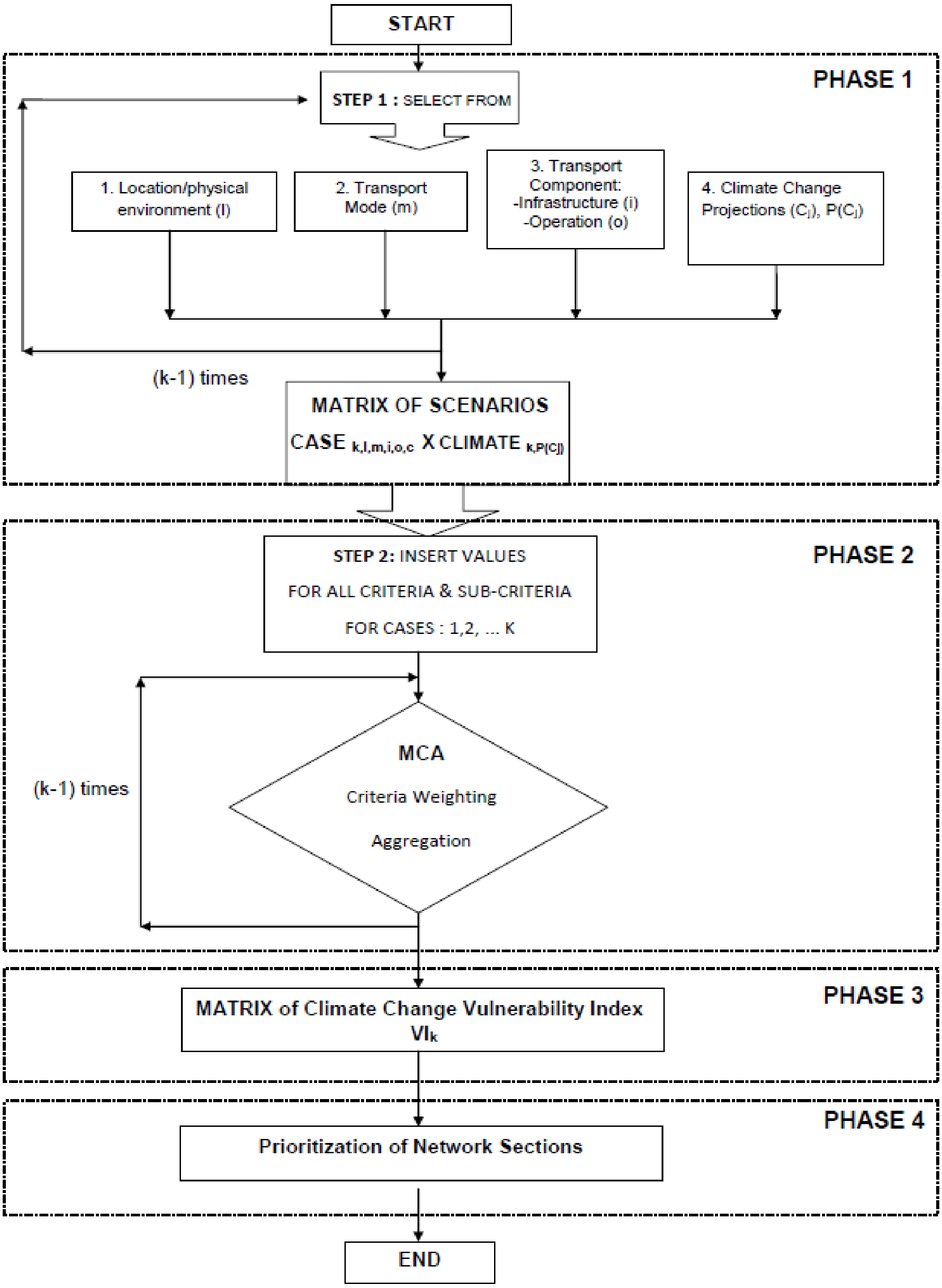

Figure 1-DST Flow Chart

DST APPLICATION

This section presents an example case of the DST application, in order to demonstrate the proposed tool's use and overall functionality. The application was carried out for two separate road sections of 200m of the Attiki Odos Motorway, a 65 km long, urban-peripheral motorway forming a ring road around the city of Athens, Greece. The first road segment (S_1) selected is located within the urban environment of the metropolitan capital, while the second within its rural periphery (S_2), and more specifically, on a mountainous terrain, in order to include diversity in terms of the physical environment. In addition, the operation (o) component was selected, as the motorway acts as a key artery relieving the congested city centre with average daily traffic volumes exceeding 280,000 vehicles.

Climate Change is already visible and perceptible in Greece, and even more in its capital city, which is expected to become hotter, drier and more variable. There is a clear warming in the country in recent years, with record-breaking hot summers being an increasingly regular occurrence. Furthermore, in total, the trend of precipitation in Greece is negative both on an annual, as well as on a seasonal basis, reaching particularly high reduction figures in certain locations. According to reports prepared by the National Observatory of Athens (Giannakopoulos *et al.* 2011), the following changes are predicted for the period 2021-2050 for the ATTIKA (Athens) climatic zone, which will act as input to the DST for this particular time horizon:

- summer maximum temperature increase by 1.7^{o}C
- 15 more days of heat waves
- 20 days of dry spell duration
- increase in total winter rain of up to 20%
- mean annual precipitation decrease by 6.5%.

The probability of occurrence is taken as 1 for simplification purposes.

Other climate change effects such as sea level rise and extreme events have not be considered in the application, since they are not considered to be affecting the Attika climate zone for the horizon under study.

The above input data were inserted in the DST tool (Phase 1) to define the scenarios for road sections S_1 and S_2, respectively. In addition, values for the measures of the criteria were provided (Phase 2), enabling the DST to estimate the "Climate Change Vulnerability Index" for the two road sections (Phase 3) and prioritise these (Phase 4). The results, presented in Table 3, indicated that the operation of the Attiki Odos Motorway's section located in the rural environment is more vulnerable to climate change effects than its urban counterpart.

Table 3- DST Application Results.

Group	Criterion No	Segment 1			Segment 2		
		Value	Conversion to Art scale	VI (S_1)	Value	Conversion to Art scale	VI (S_2)
Cr $_1$	Cr $_{1.1}$	30%	0,33	0,013	40%	0,40	0,016
	Cr $_{1.2}$	15%	0,15	0,006	20%	0,20	0,008
	Cr $_{1.3}$	20%	0,20	0,016	23%	0,23	0,018
	Cr $_{1.4}$	20%	0,10	0,004	20%	0,20	0,008
	Cr $_{1.5}$	5%	0,95	0,019	5%	0,95	0,019
	Cr $_{1.6}$	40%	0,40	0,008	47%	0,47	0,009
	Cr $_{1.7}$	0,02	0,40	0,024	0,04	0,80	0,048
	Cr $_{1.8}$	10%	0,01	0,000	10%	0,01	0,000
	Cr $_{1.9}$	15%	0,15	0,003	15%	0,15	0,003
	Cr $_{1.10}$	1%	0,01	0,000	1%	0,01	0,000
	Cr$_{1.11}$	1	0,10	0,004	**2**	0,20	0,008
Cr $_2$	Cr $_{2.1}$	1000000	0,10	0,012	140000	0,01	0,002
	Cr $_{2.2}$	300000	0,10	0,008	350000	0,12	0,009
	Cr $_{2.3}$	1000	0,10	0,003	1000	0,10	0,003
	Cr $_{2.4}$	10000	0,10	0,002	10000	0,10	0,002
	Cr $_{2.5}$	120000	0,10	0,006	150000	0,13	0,008
Cr $_3$	-	2	0,40	0,060	2	0,40	0,060
Cr $_4$	-	2	0,40	0,020	2	0,40	0,020
Cr $_5$	-	3	0,60	0,060	3	0,60	0,060
Climate Change Vulnerability Index				**0,268**			**0,301**

CONCLUSION

As the global climate continues to change, the difficulty in meeting the challenge of both building and maintaining a robust and reliable transport system increases. Research studies have recently begun to clarify the main threats and the level of risk imposed to transport components from climate change stressors, pointing out the need for effective and efficient adaptation measures at several levels. To this end, the industry is called to significantly reduce vulnerability of its assets and ensure that substantial investments in critical transport infrastructure are not going to be lost due to adverse climatic conditions' effects in the foreseeable future.

There are several approaches for assessing the vulnerability of a transport system to a threat as complex as the climate change. Nevertheless, vulnerability is inherently linked to the process of adaptation, and, hence the analysis of vulnerability provides a sound basis for designing strategies to either provide remedial measures or increase adaptive capacity. These qualitative differences in climate impacts and suitable adaptation strategies suggest that priorities for adaptation assistance should be determined separately for key climate-sensitive systems and sectors.

In light of the above, the paper proposed a practical and interactive Decision Support Tool, which, based on a conceptualisation of vulnerability of a specific section of a transport network to climate change effects, allows transport authorities and operators to carry out a preliminary vulnerability assessment of this particular section with regard to climate change. In addition, the proposed DST has the capability of assessing simultaneously different scenarios (defined by any potential combination of the following variables: location, transport mode, transport component/section, infrastructure or operation, climate change projection) and rank resulting vulnerabilities.

One reason for using vulnerability prioritization is that the choices/adaptive measures that need to be made to reduce the likely effects of climate change are often political decisions at a regional, national or even international level. These constitute in most cases decisions on adaptation funding with regard to what should be protected and to what degree. Hence, the proposed DST could be used as a tool to identify priority areas and targets, modified to suit the requirements of particular regions and systems, where policy intervention is most required. Additional policy implications of its use could be the identification of future policies that could make a difference to the impact of climate change events. The above demonstrate the tool's applicability, usefulness and relevance to policy decisions. In addition the tool provides for a rigorous yet flexible and less data intensive framework for incorporating climate forecasts in the design and maintenance of transport systems, where future climatic conditions are uncertain or can change rapidly.

The operation of the DST was successfully demonstrated through an application for a road network in Athens, the capital of Greece. As with any similar system, however, the DST has certain limitations and operational constraints, within which it could operate. These are mainly related to the accurate downscale of climate projections of leading global and regional mathematical models to local regions of each scenario under study. The latter is considered by the authors as part of potential enhancements to future versions, together with including an additional phase, where adaptation strategies would be recommended with regard to the magnitude and type of the vulnerability identified.

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