ITS in a Changing Climate – a Savior Tool or Another Vulnerable System?

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ABSTRACT

This paper describes a typology of components present in intelligent transport systems (ITS), or a physical architecture components of ITS and points out what type of weather phenomena are particularly harmful for ITS. The EWENT project's second work package studied what are the frequencies of extreme weather in different parts of Europe and how these frequencies are about to change. The means of six different regional climate models are presented. When looking at climate model projections the overall pattern in Europe is clear: the climate is getting warmer with more heat waves and fewer winter phenomena. Precipitation seems to turn from snow to water ever more often, but the change is of course still very uncertain. Warming causes increased risks of thunder storms which are associated with increased probability of heat waves. If heat waves increase significantly, as seems to be the case especially in Mediterranean, also sand storms may become more frequent and severe since heat waves could loosen the soil. All air-lifted sub-systems and outdoor equipment, such as path-side systems, are in principle at risk. The more intelligence and control can be shifted to in-vehicle systems, the lighter will the public sector cost burden probably be, thinking of the mitigation costs.

INTRODUCTION AND SCOPE

Our climate might be changing and this poses a risk on our technical systems, such as transportation system. Intelligent transport systems (ITS) will also face the same risks as extreme weather phenomena can cause malfunctioning of any technical system. ITS is not only vulnerable as an infrastructure component of its own, but also because it is relying on other infrastructures, telecommunications and power supply being the first obvious ones.

This paper describes a typology of components present in ITS, or a physical architecture components of ITS and points out what type of weather phenomena are particularly harmful for ITS. The results are based on first findings of the 7^{th} Framework Programme project of the European Union, EWENT, Extreme Weather impacts on European Networks of Transport. http://ewent.vtt.fi/.

In the first part of this paper, the typical physical aggregate components of different ITS applications are defined and described. Then the critical weather phenomena impacting the reliable functioning of ITS are listed based on the first step results of EWENT project. Thirdly, the climate scenarios derived by EWENT partner meteorological institutes are briefly shown. Following this, the critical weather phenomena and risk scenarios of extreme weather occurrence probabilities in the future are combined with vulnerable components of ITS in order to demonstrate the potential risks that ITS is facing if climate change seriously starts to play a role – some ITS components or infrastructures might require new standards if their resilience to weather phenomena poses a risk on reliability. For example, in the future heavy snow precipitation can more often cut telecommunication links and power lines making ITS crippled and preventing it from fulfilling its task. However, this paper does not go into technical details of ITS components, but stays on a strategic level of analysis.

The last section of the paper summarizes the findings and discusses the different roles ITS could have in helping the transport system to adapt to climate change and extreme weather impacts. The analysis on extreme weather probabilities shows where weather-related intelligent services could serve best in the future. This will also help to strategically target ITS research in areas that could be of increasing relevance in the future.

Surprisingly little has been written and reported about weather resilience of ITS. This paper makes the first statements on this issue which will inevitably receive much more attention in the future. It also addresses the question where ITS will serve as weather-impact-eliminating tool and where it is just another system exposed to weather.

BACKROUND, EWENT PROJECT

The European project EWENT (Extreme Weather impacts on European Networks of Transport, http://ewent.vtt.fi/) issued recently its first work package results. The report (1) introduces a review of extreme weather phenomena and identifies their impacts and consequences on European transport system. First, there is an extensive literature review on extreme weather events and their impacts and consequences. About 150 articles, reports and books were reviewed. This is followed by a review of media reported cases, almost 200 of them. With the help of these two methods and material they provide, critical threshold values for most relevant weather phenomena that affect different transport modes are listed. The phenomena have impacts and consequences which result in deterioration in the service level of transportation system. A dozen different impact mechanisms are charted and annexed to this report. Precipitation in all its forms (water, snow, hail) seems to dominate the harmful impacts. Road transport system seems to be the most vulnerable of modes, but a great deal of this conclusion is resulted by the fact road is the dominant mode, and hence most affected.

Weather phenomena are followed by certain impacts, which then cause certain consequences, as illustrated in Figure 1. This is the base structure of the whole EWENT project. This paper looks on the impacts and not the final consequences.

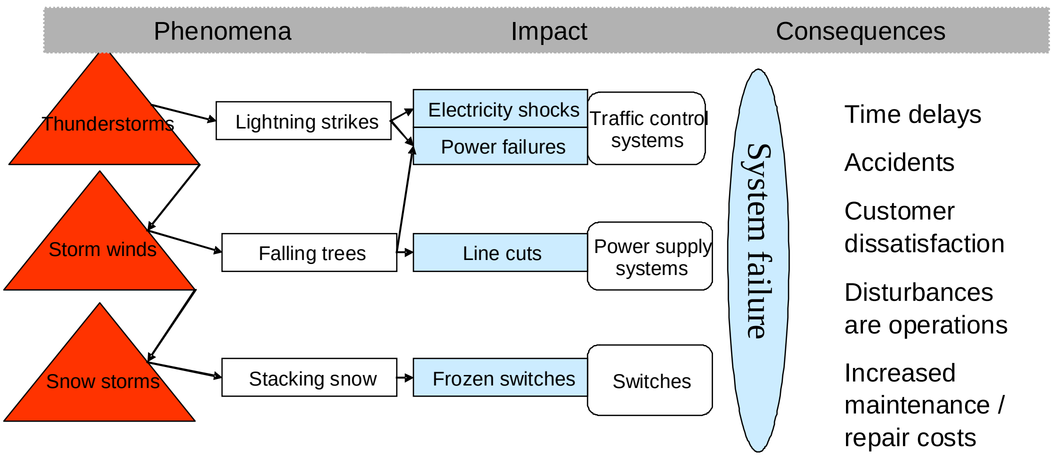

Figure 1. Simplified impacts and consequences of harmful weather in rail transport (1)

The extreme weather map (Figure 2) shows the most common extremes with identifiable consequences, i.e. heavy rain, heavy snowfall, extreme winds, extreme heat, drought, and visibility. The map is of course a crude simplification that simply points out what the most urgent problems seem to be in different parts of Europe.

All aspects and functions of the transport system are affected, but in different ways in different parts of Europe and on different time scales when impacts are distinguished between operations and infrastructure. Operations can always be more or less flexibly adapted to a changed situation, but infrastructure requires long-term planning if modifications concerning weather resilience are to be achieved.

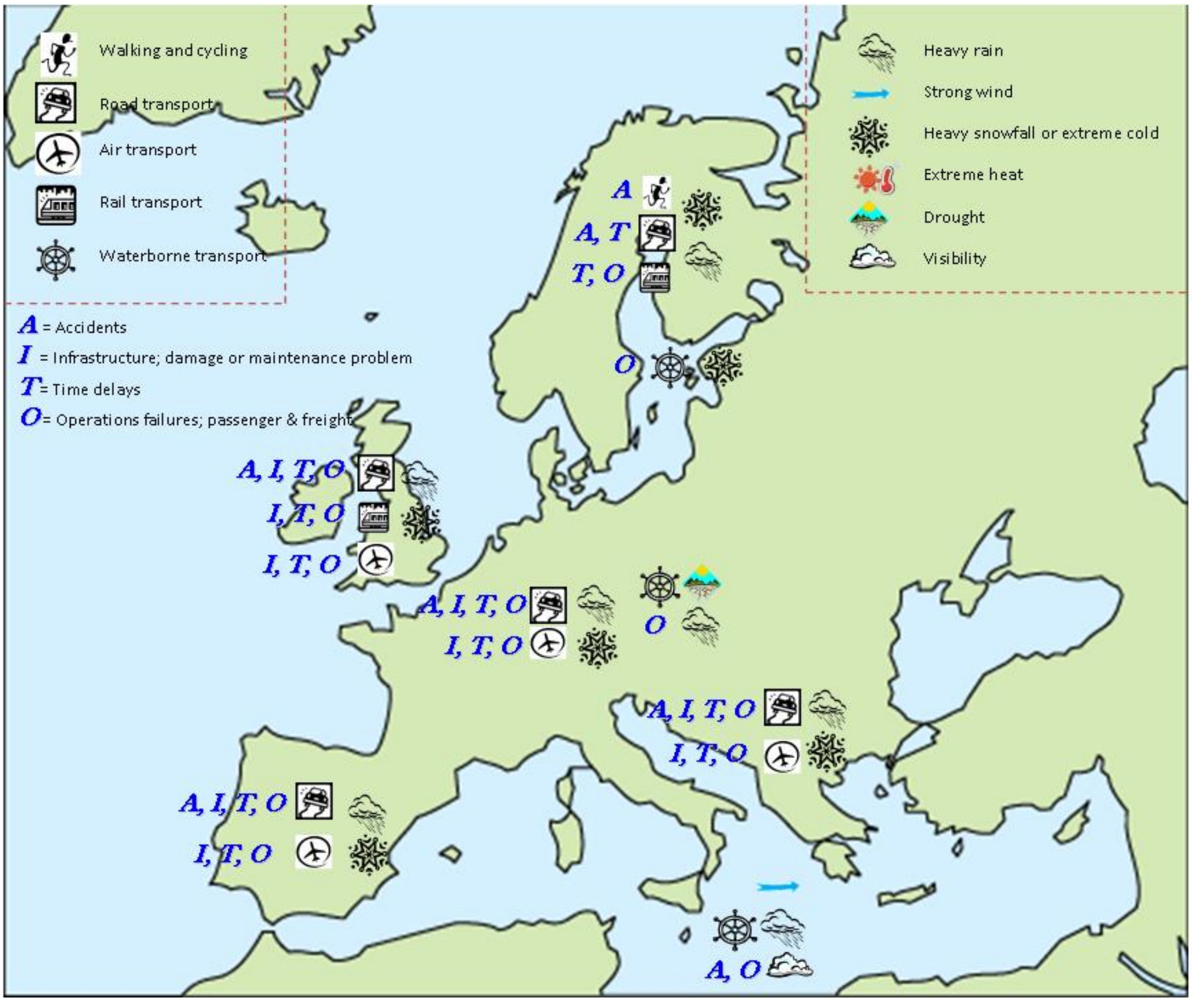

Figure 2. Sum-up of critical weather phenomena, their occurrence by region where effects are the most severe, with the most affected modes of transport and the consequences (1)

For ITS, such an analysis has not been done, as far as the author knows. To understand what type of weather phenomena can be critical for ITS we need to have an overall, holistic picture on ITS itself and identify its most vulnerable components and how extreme weather might impact them. Assessing impacts is not as straightforward question as it might appear, at least when looking at the majority of impact assessments done in the field of ITS. In fact, we use different 'impact models' in our assessments. Sometimes the choice of these models is arbitrary and not a conscious choice. We can identify and classify these models, however, as shown in Table 1.

It goes without saying that this paper relies mostly on the models with least analytical and empirical elements within, that is in logical-descriptive and heuristic impact assessment models.

Model type	*Characteristics*	*Data need examples*
Analytical	Empirically validated, widely accepted model; produces results in "what-if" scenarios	Known input variables
Empirical, validated	Empirically validated, but the model validity is discussed or criticised; not widely accepted; can be used for ex ante scenario work	Suggested input variables
Empirical, unvalidated	Continuation of empirical experience, e.g. trend models; not valid if the underlying dependencies or mechanisms change	Historical data, time series
Logical-descriptive	The dependencies can be illustrated or described but not analytically quantified	No explicit or immediate data needs, some historical data or prior studies may back the argumentation; data serving deduction and induction; interviews and gathering of insights and experiences and other qualitative data usually utilised extensively
Heuristic	The model appeals to perception of the reality and included associations between associated phenomena	

Table 1. Impact assessment model types. (2)

THE PHYSICAL META STRUCTURE OF ITS AND SUPPORTIVE SYSTEMS

The physical main components of ITS are of course multiple and technological changes will bring in new components and some older ones will slowly disappear. But taking a holistic view to the whole system including supporting systems without which ITS would not function, our scene will get very wide. There are two major systems that are essential for ITS to function. There needs to be a *power supply system* that makes ITS subsystems run. Power supply lines need to be lifted in the air or buried underground to separate them from the outreach of people for safety and security reasons.

Then there needs to be a *communications system* which can be divided into wireless (GPS, GSM, GPRS, etc.) and wired systems. We can further distinguish the *positioning systems* (GPS or cell-based) which seem to be evermore important for ITS and services delivered by ITS. Positioning and wireless communications systems seem to be merging, if not already done so. Then there is finally a variety of near-field communication systems that convey data between units within ITS.

There is always a pathway, which we call here the *path*. For land transport modes this means a physical infrastructure network. For waterways the path is partly physical (buoys on path and the harbors), and for flight paths it is purely based on three-dimensional positioning of the vehicle, except for the airport infrastructure itself. In paths, there are *embedded units*, typically sensors for traffic flow or road surface conditions. Most of the technology of ITS is however, on the side of the paths, such as automatic vehicle identification units, variable message and control displays, access control equipment, etc. The *pathside equipment* is usually highly dependent on both power supply and communications systems. If either of those systems fails, the pathside systems will not be able to fulfill their tasks.

For all transport modes there is a *traffic management center*, either a centralized or a decentralized one. Again, the power and communications systems are vital for the carry out of the centers' tasks. Traffic management centers have essentially the same functions across the modes, and today they start to have almost the same basic capabilities to manage and control traffic flow and vehicle movements. They are a critical node point especially in terms of communications.

Finally we can identify *vehicles* on paths and *mobile / floating sensors, transmitters* and *receivers* as well as *in-vehicle systems* that seem to be very much in focus when considering ITS in general.

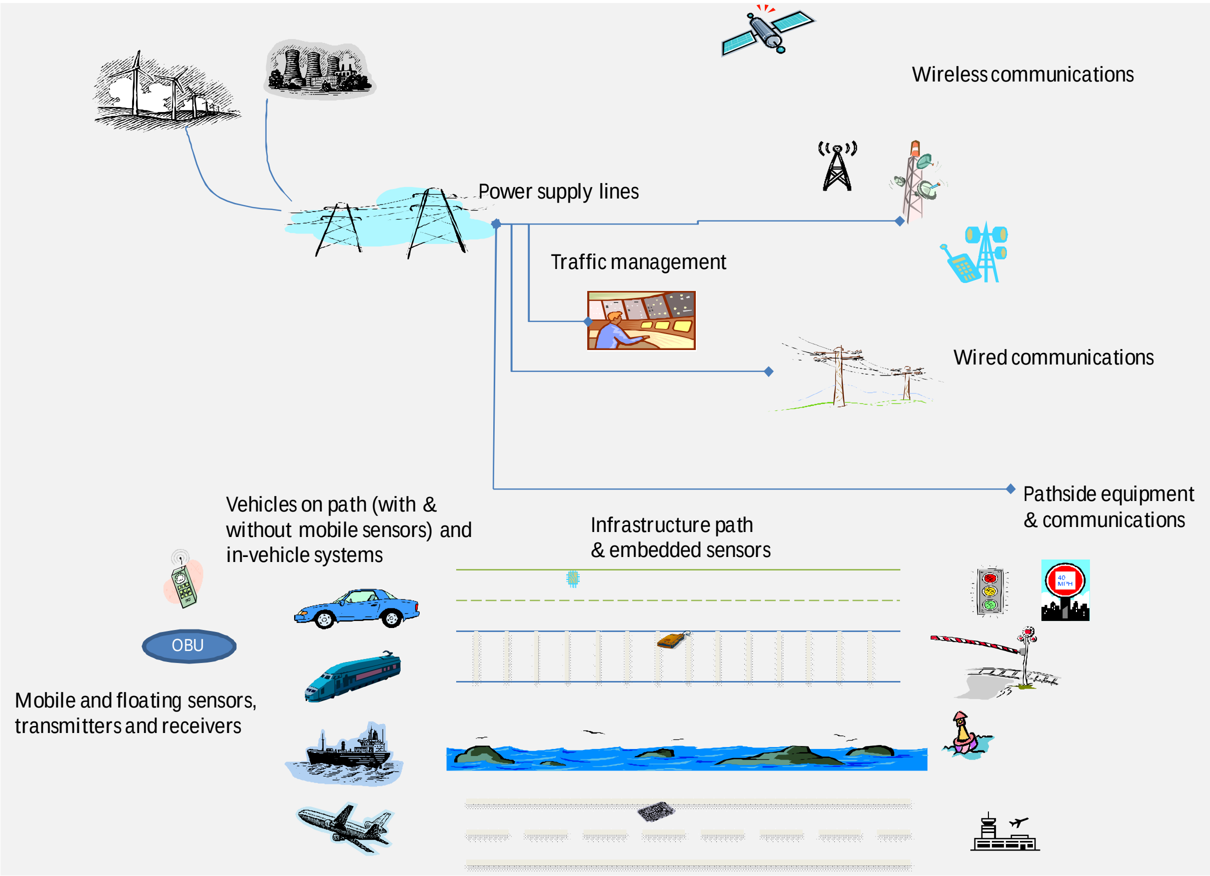

Figure 3. ITS meta-system

Of these meta-system components, the most exposed to weather are naturally those standing outside. In-vehicle systems and traffic management centers are well protected, as are most mobile and floating sensors which typically are located inside vehicles too. This simple fact should be noted more carefully than what one is tempted to do at first glance.

What are then the weather phenomena for the rest of the systems that are critical for their reliability and why? These questions are answered next.

EXTREME WEATHER PHENOMENA IMPACTING ITS METASYSTEM COMPONENTS

The media reports and published scientific articles gathered and analyzed in (1) showed that for different European regions there are different critical weather phenomena. The following sections summarize the results.

VERY LOW TEMPERATURES – WINTER CONDITIONS

Very low temperatures have a great impact on physical infrastructures but surprisingly not so much than temperatures around the freezing point. The latter creates slippery surfaces and deteriorates surfaces and land structures faster than very low temperatures. For ITS meta-system low temperatures seem not to pose any significant threats except for in-vehicle systems that might prove malfunctioning when the actual vehicle is refusing to start! However, the threat can be considered non-considerable for land transport modes and most effects are mechanical in nature. For waterborne ITS, instead, low temperatures pose slightly greater risk as some equipment (mainly buoys) as packing ice together with strong winds might remove them or they might not have efficient enough batteries to withstand extra long-term cold.

The contrary case, i.e. very high temperatures have multiple harmful impacts on transportation system, but most of them are affecting the physical structures – pavements, rails, etc. High temperatures do not count as seriously or even moderately harmful phenomena unless equipment or systems are truly poorly designed and engineered.

HEAVY PRECIPITATION

Extreme rainfall in the form of water is the most serious of events when considering the harm caused for transportation system, especially when it turns into flooding. Land structures might get washed away, infrastructure sections cut away. Not only do the structures damage, but so do the power supply and data communication lines hence eliminating ITS systems totally in the worst case. Heavy rains with more than 150 mm/24 h are almost sure to cripple most ITS systems in their vicinity. 100 mm/24 h is the amount which will have direct impacts on traffic flow but not yet on systems on a wider scale. (1)

When precipitation comes down as snow, the impact is less serious with exception when heavy snowfall is combined with low temperatures and strong winds building a blizzard. Blizzards are in fact one of the least studied weather phenomena, but they have a nasty habit of combining several unpleasant impacts: snow is stacked, ice covers are built and the cold effect is multiplied. All outdoor technical systems are vulnerable to blizzards.

Hail downfall has a direct physical impact on outside systems literally battering them to if not pieces at least breaking the weakest parts of them. When hail diameter exceeds about 2 cm, ground damage begins clearly to occur. (1)

STRONG WINDS

Strong winds take many forms: gusts, tornadoes, or pure fast blowing storms. All these are equally damaging and only 17 m/s or above start to have impacts. When wind speeds exceed 32 m/s, the impacts are almost unpreventable. Structures such as gantries are usually designed to withstand strong and even extreme winds but when trees start to fall and heavy objects float in the air the damage is unavoidable. Air lifted power lines and communications systems are particularly vulnerable in these situations.

One special case of strong winds is a sand storm, again a phenomena not yet studied very thoroughly. For aviation fleet, the amounts of 0.2-2 mg/m^3 are eroding but for ITS this phenomena is still an open question. It is obvious, that e.g. in southern parts of Europe and in the Mediterranean sand storms are not that uncommon.

THUNDER STORMS, LIGHTNING

Lightning represents an extreme electric burst and whenever any electric system or component is hit by it, there is a high risk of damage. Communications links, power supply and all pathside equipment are exposed to thunder. Lightning strikes are usually identified as particularly harmful events for railways and aviation, but damages occur also at sea. What thunderstorms do to road ITS we have little empirical knowledge. It is certain, however, that damages do take place. How much, to what extent and how severe is still quite an open issue. For railways of Finland, thunderstorms and lightning strikes are the most common reason for system failure resulting in delays together with snow-related events.

Thunderstorms are very hard to predict but there is a certain positive correlation with heat spells. The exact form and strength of the correlation requires further research, however.

OTHER PHENOMENA

The EWENT study lists far more weather phenomena, such as drought, low visibility, volcanic ash, turbulence, water devils, funnels, etc., but none of these seem to present any significant threat to ITS meta-system.

EXTREME WEATHER IMPACTS ON ITS

In Table 2, the above discussion is summarized. For weather extreme impacts in general, the empirical data is more or less given in (1) and (3), but as to extreme weather impacts on ITS, we still have to rely on less empirical and less quantitative impact assessment.

Clearly the severest impacts are experienced when power or communications systems fail. These basic systems are essential for the ITS too. For pathside equipment and units embedded in the infrastructure path the impact assessment is more difficult, but obviously thunder and hail pose an identifiable threat to those systems.

Meta-system component	*Extreme weather phenomena*	*Impact*
Power supply lines, underground	Heavy precipitation	Flooding may cause power breaks and short-circuits
Power supply lines, air-lifted	Blizzards, strong winds, thunder storms	Ice formation, fallen trees on lines, lightning damages
Wireless communications systems	Thunder storms, blizzards, strong winds, (sand storms?)	Lightning damages, ice formation, fallen trees or flying objects damaging equipment
Wired communications systems, underground	Heavy precipitation	Flooding may cause communications breaks
Wired communications systems, air-lifted	Blizzards, strong winds, thunder storms	Ice formation, fallen trees on lines, lightning damages
Traffic management centers	Secondary impacts via power and communications systems	In case of communications or power supply meltdown the center is invalidated (if back-up systems fail too)
Infrastructure path and embedded units	Heavy precipitation and temperatures around freezing point	Melting and icing will deteriorate units faster
Pathside equipment	Thunder, hail, blizzards, strong winds	Electric damages, physical damages
Vehicles	None or unknown	None or unknown
Mobile and floating units	None or unknown	None or unknown

Table 2. Extreme weather impacts on ITS systems

THERE IS A CHANGE IN THE WEATHER…

The EWENT project's second work package studied what are the frequencies of extreme weather in different parts of Europe and how these frequencies are about to change (4). Six different regional climate models were used and each of them produced different results. In the following the average results of the climate projections are presented. All the projections indicate results around year 2050.

Six different climatological regions were identified for the analysis:

- Northern European (sub-arctic) region NE
- Maritime (oceanic) region: O
- Mediterranean region: M
- Temperate Central European region: Tc
- Temperate Eastern European region: Te
- Alpine region: A

All the European 27 Union member states plus a few more were characterized by one or more of these climatological regions. Figure 3 shows the first exercise – and note: not the final! – of the European country characteristics.

Country	Climatological Regions					
	NE	O	Tc	Te	M	A
Austria			X			X
Finland	X					
France		X			X	X
Greece					X	
Italy					X	X
Poland			X	X		
UK		X				

Table 3, Figure 4. Climatological regions in Europe (overview) and specifically in some selected countries (4)

The Northern European region (NE) is currently typically dominated by extreme winter phenomena. Cold spells, heavy snowfall and blizzards are the phenomena causing most impacts. Heavy rainfalls occur especially along Norway's coastline. The future projections around year 2050 indicate strong decline of most extreme winter phenomena due to global warming, but heavy snowfalls (over 10 cm/24 h) could even get more common. Projected rainfall extremes show slight intensification as well.

Maritime region (O) suffer moderately from winter phenomena today, but again, these phenomena show a decrease in the future. These countries do not, however, possess a very good preparedness to tackle e.g. heavy snow precipitation, so they will continue to suffer from extreme winter-type phenomena once they do occur. The probability of heat waves will probably increase in the coming decades. The model projections on wind gusts is mixed, there is a decrease of more than 17 m/s gusts but an increase of 25 m/s gusts.

Mediterranean region (M) is naturally the area where most heat waves are experienced. These waves are about to increase in the future according to the regional climate models. These heat extremes seem to develop even faster than in the rest of Europe. Annually the region could expect 5-10 days of more than 43°C. Cold events will get rarer.

The temperate Central European region (Tc) is less affected by weather extremes, but population and traffic densities make it vulnerable nevertheless. The projections show that an increase in heat waves and decrease in cold waves could take place. Extreme winds show mixed patterns and nothing certain, even in the light of model results, can be said about them. Even heavy rainfalls seem to decrease in the future.

The temperate Eastern European region (Te) experience currently more often cold spells and winter storms. These phenomena might decrease significantly by 2050. On the other side, extreme heat will be witnessed more often.

Alpine region (A) typically witness severe winter storms with blizzards and heavy snowfalls. These phenomena seem to be turning into extreme precipitation due to warming, hence affecting for example inland waterways transports.

Looking at climate model projections the overall pattern in Europe is clear: the climate is getting warmer with more heat waves and fewer winter phenomena. Precipitation seems to turn from snow to water ever more often, but the change is of course still very uncertain. Table 4 shows the change patterns until about 2050 (2041-2070 to be exact) in selected European cities, with selected critical weather parameter thresholds, based on the six regional climate models. It should noted that there is uncertainty related to these projections. The presented values are means the outputs of the climate models. Decimals are not show and figures are rounded. -0% means that there is a slight, less than 1% decrease in the probability. Correspondingly, +0% means a slight, but less than 1% increase. 0% means that there is not a distinguishable change.

EWENT D1 (1) identified three levels of impacts and the level 2 impacts (i.e. some adverse impacts are likely) are assumed here.

City	*Extreme weather phenomena; change in the probability of occurring*					
	Wind gusts >25 m/s	Snowfall >10 cm/d	Blizzard*	Heavy rain >100mm/d	Heat >32°C	Cold <-7°C
Bergen	-1%	-1%	-0%	0%	0%	-6%
Bucharest	0%	-0%	-0%	0%	+24%	-3%
Cork	-1%	0%	0%	0%	0%	-0%
Düsseldorf	-0%	-0%	0%	0%	+2%	-2%
Helsinki	-1%	-0%	+0%	0%	0%	-14%
Limassol	-0%	0%	0%	0%	+39%	0%
Madrid	0%	0%	0%	0%	+29%	0%
Thessaloniki	0%	0%	0%	0%	+33%	-0%
Vienna	0%	-0%	0%	0%	+8%	-4%

*Blizzard is defined here as snowfall exceeding 10cm/d + wind gusts >17 m/s + daily mean temperature below 0°C.

Table 4. Change in the probabilities of some extreme weather phenomena in selected European cities around year 2050 compared to the situation of today (2009) (4)

From ITS perspective the news is good. Winter storms in all its forms will affect less and less in the future and heat waves do not in themselves present a significant threat to ITS. However, there is one significant conclusion to be drawn: warming and as its byproduct the increased probability of thunder storms. Heat waves and thunder storms have a definite positive correlation, although the form and exact nature of the correlation calls for more thorough research (5).

Already today, most electric failures for railway system are due to thunderstorms, be the impact direct (damaging the rail subsystems) or indirect (damaging the power supply systems). Also communications systems are vulnerable to lightning strikes. Moreover, thunderstorms are associated with hail storms, which are equally harmful on the outdoor equipment, when occurring in their extreme form.

DISCUSSION AND CONCLUSION

As the patterns of changing weather are more or less clear, depending on the reliability of the climate projections of course, it is possible to envision the likely impacts on ITS. Warming causes increased risks of thunder storms which are associated with increased probability of heat waves. If heat waves increase significantly, as seems to be the case especially in Mediterranean, also sand storms may become more frequent and severe. Heat waves loosen the soil and southern Mediterranean may start to have similar features in climate as North Africa in some respects. It goes without saying that this projection is still highly uncertain, but this is what most climate models imply.

All air-lifted sub-systems and outdoor equipment, such as path-side systems, are in the line of fire. Most other systems seem to be less affected by extreme weather phenomena – at least if we compare the change from present to the future. However, even today our systems face extreme weather risks and there is no reason to assume that we will not experience phenomena which will paralyze some systems no matter what the climate projections indicate. The question rather falls down to our preferences regarding the reliability of these systems. The higher the traffic densities and the closer to the limits of the mobility capacity we are, the more vulnerable will the whole system become. It may well be, that seeking the extra capacity through ITS will make us face another type of problems, e.g. associated with ITS system weather resilience in the changing climate if ITS starts to play an increasingly important role in transport system management, as one is inclined to assume.

Most ITS sub-systems have a relatively short life cycle and they can easily be replaced and improved to withstand climate strain. Some meta-system components, such as power supply lines and communications systems have a longer life cycle and their resilience is perhaps more critical thinking of the reliability and robustness of the whole system. We should take good care of the basics, in other words. ITS does not in itself lack extreme weather resilience.

As to different modes, railways and aviation are most vulnerable to thunderstorms. Their traffic management systems are well protected but also highly centralized and a failure in critical places may paralyze or at least seriously reduce the capacity of railway and aviation systems. Yet at the same time, by investing in their resilience their reliability could be significantly increased. It is more difficult to do the same for road transport system which is much less centralized in terms of traffic management, less automated in all respects, and most autonomous and flexible in adapting to any changing situations. Furthermore, ITS components inside vehicles and intelligent vehicle-to-vehicle systems might well be the least vulnerable systems with respect to extreme weather.

It seems that we have at least two optional strategies – if we prefer it that way – at our disposal: 1) to rely on autonomous and flexible road transport where smarter vehicles are able to cope with some adverse weather impacts, such as increased slipperiness (temperatures around zero celcius) and sudden traffic interruptions; 2) to ensure that highly centralized and controlled public transport systems (railways, aviation) perform in most conditions. For the first options, the vehicle manufacturers and ultimately the consumers can cover most of the cost. For the other option, public sector probably needs to invest more, or at least more directly.

Due to global warming, which is manifested by the climate models, the winter extremes are decreasing, but that does not imply that winter extremes – heavy snowfall, blizzards, cold spells – would be easier to handle in the future. Recent experiences in Europe testify another story. The warming presents another type and partly unknown risk which inevitably time will show to be either a false alarm or a fact of life to be dealt with. For example, having more temperatures around 0°C instead of colder and drier weather, could build heavier ice covers on outdoor equipment and structures. For road traffic safety this change can be extremely harmful especially in the Northern European region, as reported in (6).

The following steps of EWENT project will look into the likely and expected consequences of the extreme weather phenomena and use the climate projections to identify risky regions and nodes of the European transport system. EWENT will also assess the costs resulted by extreme weather and draft tentative strategy options how to tackle the risks and reduce the socio-economic consequences of extreme weather.

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REFERENCES

(1)Leviäkangas, P (ed.) & Tuominen, A (ed.) & Molarius, R (ed.) & Kojo, H (ed.), Extreme Weather Impacts on Transport Systems. EWENT Deliverable D1. *VTT Working Papers 168*. 2011, VTT. Available from: http://www.vtt.fi/inf/pdf/workingpapers/2011/W168.pdf

(2)Leviäkangas, P & Hautala, R, Benefits and value of meteorological information services – the case of the Finnish Meteorological Institute, *Meteorological Applications* 16, pp. 369–379, 2009.

(3)Leviäkangas, P & Tuominen, A & Molarius, R & Schabel, J & Toivonen, S & Keränen, J & Törnqvist, L & Makkonen, L & Vajda, A & Tuomenvirta, H & Juga, I & Nurmi, P & Rauhala, J & Rehm, F & Gerz, T & Schweighofer, J & Michaelides, S & Papadakis, M & Dotzek, N & Groenemeijer, P & Ludvigsen, J, EWENT D1 Review on extreme weather impacts on transport systems, *EWENT project deliverable D1*. July 30, 2010. Available from: http://ewent.vtt.fi/.

(4)Vajda, A & Tuomenvirta, H & Jokinen, P & Saarikivi, P & Makkonen, L & Tikanmäki, M & Groenemeijer, P & Tymvios, F & Athanasatos, S, Probabilities of adverse weather affecting transport in Europe: climatology and scenarios up to the 2050s, *EWENT project deliverable D2.1*, draft 12.4.2011. Will be available at: http://ewent.vtt.fi/.

(5)Direct discussion with Mr Pertti Nurmi, Head of Meteorological Applications Group at Finnish Meteorological Institute, 21.7.2011.

(6)Andersson, A, Winter Road Conditions and Traffic Accidents in Sweden and UK – Present and Future Climate Scenarios. PhD thesis, Dept. of Earth Sciences, University of Gothenburg, 2010.