LIFE+11 ENV/IT/000002

CLEAN-ROADS

Action A1
Experimental data collection campaign during a winter season

D.A1.3

Experimental data collection campaign

Project Coordinating Beneficiary	Provincia di Trento (PAT)
Project Associated Beneficiary n.1	Famas System (FAM)
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Document history

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31/05/2013	Merler Giacomo (PAT), Ilaria Pretto (PAT), Stefano Seppi (TIS), Roberto Cavaliere (TIS)	First report version. It presents the results of the initial data analysis carried out on top of the dataset collected during the winter season 2012/2013.
31/05/2015	Claudia Di Napoli (PAT), Ilaria Pretto (PAT), Stefano Seppi (TIS), Roberto Cavaliere (TIS)	Second report version. It presents the results of the more comprehesive data analysis carried out on top of the dataset collected during the winter season 2013/2014.

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[1] **PU** = Public.
CO = Confidential (accessible only by project partners and European Commission).
RE = Restricted Access, i.e. confidential but with a special access to a specific target of stakeholders defined by the project consortium and approved by the European Commission.

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1. Introduction

The second version of the report D.A1.3 presents the results of the data analysis and correlation activities carried out in the scope of the preparatory action A1 and targeting in particular the datasets collected during the winter season 2013/2014. In light of the recovery plan defined in the first stage of the project, and illustrated in detail in the deliverable D.A1.2 [1] and in the Inception Report [2] which were submitted to the European Commission in May 2013, this additional campaign represents the conclusion of the initial empirical assessment of the targeted environmental problem (Table 1). This final assessment has been carried out mainly on top of (i) the data of the first roadside road weather station and (ii) the first thermal mapping surveys performed by the initial mobile RWIS station prototype, which are directly related to other data sets that are already available (i.e. winter road maintenance activities recording data, traffic levels, other meteorological data and weather bulletins). For more details on the modalities with which this final assessment campaign has been carried out, please also refer to the updated versions of D.A1.1 [3] and again of D.A1.2.

Winter season	Revised activity set	Original activity set

2012/2013	• the winter road maintenance procedures are empirically evaluated;
	• a comparison with a first reference dataset is performed, consisting of:
	  ○ traffic data measured in correspondence of the test site;
	  ○ meteorological data and forecasts;
		• a first complete data collection campaign is carried out, availing of:
		  ○ the full set of roadside road weather stations;

2013/2014	• a first complete data collection campaign is carried out, availing of:
	  ○ the first roadside road weather station;
	  ○ the mobile RWIS station;
	• first test sessions of the CLEAN-ROADS components are performed;
		• a first complete demo of the CLEAN-ROADS is installed on site;
		• the road operators start to consider the data and the information provided by the system prototype, but in a unstandardized way;

2014/2015	• the whole CLEAN-ROADS system is tested, calibrated and technically validated; • the road operators start to consider the data and the information provided by the advanced RWIS system, but in a unstandardized way;	• the final version of the CLEAN-ROADS system is tested, calibrated and technically validated; • the CLEAN-ROADS system is finally evaluated and demonstrated through the introduction of optimized and standardized winter maintenance procedures.
2015	• the CLEAN-ROADS system is finally evaluated and demonstrated through	• the CLEAN-ROADS system starts to enter fully in

	the introduction of optimized and standardized winter maintenance procedures.	operation in the test site area, eventually evolved by means of the experience gathered in the winter season 2014/2015.

Table 1: The re-allocation of empirical project activities during the different winter seasons of the project.

This second version of the deliverable is structured as follows. Chapters 2 and 3 give an overview of the observed meteorological conditions and salt usage statistics during the winter season under analysis, respectively. Chapter 4 presents the results of the correlation analysis that has been carried out by comparing the effective treatment data with the estimates of salt need which have been automatically computed on top of the road weather dataset collected by the RWIS station in Cadino. This analysis gives a first, solid quantification of the theoretical maximum optimization margin that one could imagine to achieve if compared to the current winter road management state-of-art. The deliverable is finally completed with an analysis of the traffic flows in correspondence of the monitoring site, which includes an investigation of the relationship with the road conditions. The aim of this analysis is not only to have an initial understanding on the impact of traffic levels on road surface temperature (RST) and conditions (RSC), but also to get a deeper overview of the potential risk associated to critical meteorological conditions.

2. Meteorological analysis

2.1. Climate overview during the winter season 2013-2014

The winter season 2013-2014 (considered in the time interval between December 2013 and February 2014) was particularly anomalous both in Trentino region and in the rest of Italy as well as in most of Europe. In particular, for the regions of central and northern Italy it had been one of hottest and wettest seasons ever observed in the last century, characterized by temperatures well above the average and frequent and abundant rainfall, with exceptional contributions on alpine areas and heavy snowfall in mountain.

Europe

The synoptic analysis shows for Europe that winter 2013-2014 had been affected by positive thermal anomaly predominant over most of the continent (Fig. 1a).

Compared to the reference period 1981-2010, the season 2013-2014 had been characterized by the predominance of depression situations on western Europe, as shown by the maps of geopotential anomaly at 500 hPa (about 5500 m) (Fig. 1b), which determined frequent flows on the southern Alps related to situations of bad weather.

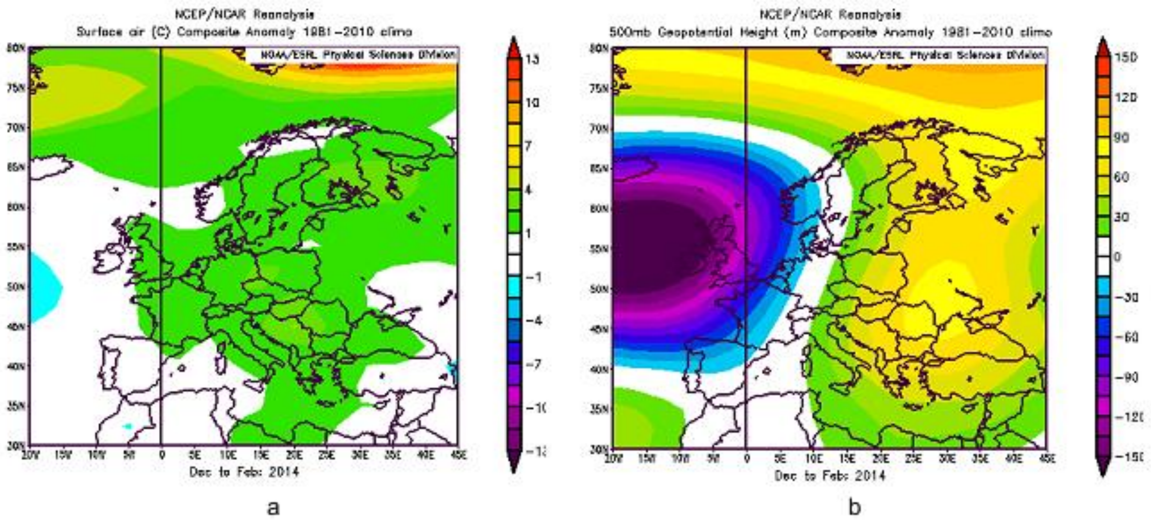

Figure 1: Surface temperature anomaly (a) and geopotential anomaly at 500 hPa, (approximately 5500m) compared to the period 1981 to 2010 for the winter 2013 - '14 (December 2013-February 2014) - Data provided by Oceanic and Atmospheric Administration - Earth System Research Laboratory - USA

This average configuration, however, reveals differences in individual months (Fig. 2)

In December anomalies towards more high-pressure situations prevailed on most of Europe with positive anomalies of temperature species north-eastern Europe.

In January and February anomalies related to situations of depressions on Western Europe prevailed, promoting most frequent precipitation in the Alps. In January temperatures were higher than average over much of central and southern Europe but lower on the north-eastern areas where anomalies prevailed at high pressures. In February, instead, warm anomalies dominated the entire European continent.

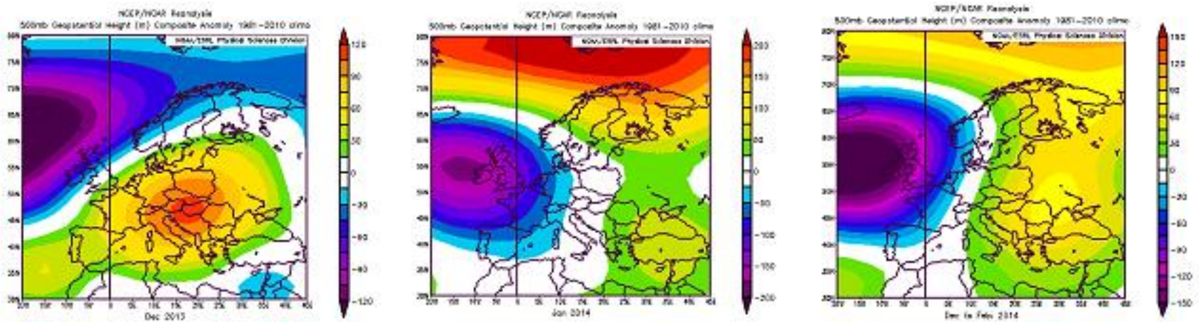

Figure 2: Geopotential height anomaly at 500 [hPa] (approximately 5500 m) registered in December 2012 (left picture), January 2013 (central picture) and February 2013 (right picture) respect to the period 1981-2010 [4].

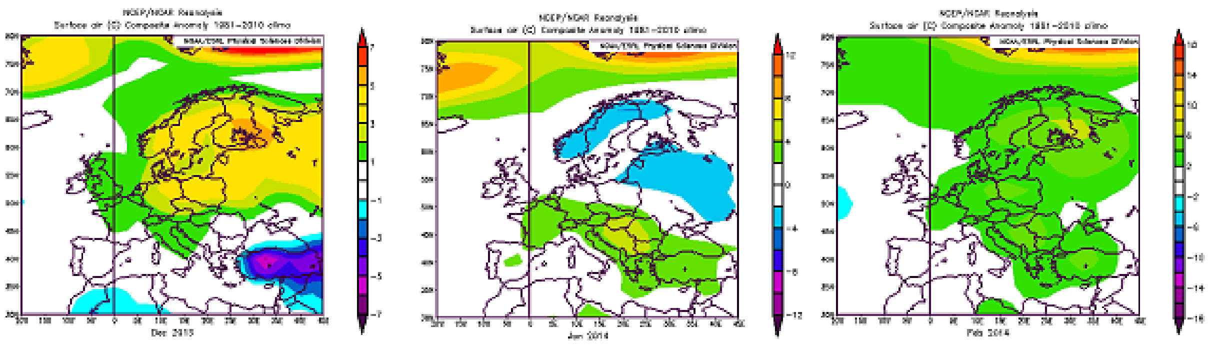

Figure 3: Superficial temperature anomaly registered in March 2013 (left picture), April 2013 (central picture) and May 2013 (right picture) respect to the period 1981-2010 [5].

Italy

The analysis conducted from the Institute of Atmospheric Sciences and Climate (ISAC-CNR) put in evidence that in Italy the winter 2013 - 2014 was the second warmest since 1800 with an average temperature higher than +1.80 °C above the average for the reference period 1971-2000. The total rainfall was above the average of 62% more than the reference period 1971-2000, with regional differences well above the average in the northern regions.

All months were warmer than average, in particular January was the third warmest since 1880, and February the second warmest ever since 1880.

As far as precipitations are concerned, higher anomalies were also highlighted in January and February when in the north-east regions contributions had been definitely above average with exceptional values.

Trentino Region

As stated in the introduction, also in Trentino region the winter season 2013-2014 had been one of the hottest and wettest seasons ever observed in the last century, with contributions of exceptional snow in the mountains.

The observed data for Trentino region (Fig.4 and 5) shows that **the temperature** of winter 2013 - 2014 was significantly higher than both the average for the period 1978 to 2005 (from +1.3 °C in Tione to +2.4 °C in Trento Laste) and the average for the period of reference in climatology, i.e. 1961-1990 (about +2 / +2.5 ° C).

Inverno	2014		Temperatura [°C]			Rank	Eventi estremi MAX [°C]		Rank	Eventi estremi MIN [°C]	
Nome	Quota m	Anno inizio	Media stagionale	Anomalia 1961-1990	Anomalia 1978-2005	Superiore	Tmax	Anno	Inferiore	Tmin	Anno
Pieve Tesino[1]	775	1955	2.7	2.2	1.8	3/60	3.5	2007	58/60	-3.1	1963
Lavarone	1155	1925	1.7	2.1	2.1	4/89	2.9	2007	86/89	-4.0	1963
Trento (Laste)	312	1920	4.7	2.5	2.4	2/92	5.4	2007	91/92	-1.3	1929
Cavalese	1000	1935	1.7	2.1	1.4	8/74	2.8	2007	67/74	-3.8	1963
Tione	575	1975	2.6	--	1.3	4/37	3.4	2007	34/37	-1.3	1991

Figure 4: Average winter temperature observed for some reference stations with reference to climate anomalies and rank

Nome	Quota m	Anno inizio	Valore	Dicembre °C	Gennaio °C	Febbraio °C	Inverno °C
Pieve Tesino[1]	775	1955	Temperatura media	3.2	1.9	3.1	2.7
			Anomalia 1961 - 1990	2.6	2.1	2.2	2.2
			Anomalia 1978 - 2005	2.2	1.4	1.8	1.8
Lavarone	1155	1925	Temperatura media	2.7	0.9	1.5	1.7
			Anomalia 1961 - 1990	2.6	2.1	1.9	2.1
			Anomalia 1978 - 2005	2.8	1.6	1.9	2.1
Trento (Laste)	312	1920	Temperatura media	4.5	3.9	5.7	4.7
			Anomalia 1961 - 1990	3.1	2.9	1.6	2.5
			Anomalia 1978 - 2005	3.0	2.7	1.5	2.4
Cavalese	1000	1935	Temperatura media	2.3	0.9	2.0	1.7
			Anomalia 1961 - 1990	2.6	2.0	1.7	2.1
			Anomalia 1978 - 2005	2.0	1.1	1.2	1.4
Tione	575	1975	Temperatura media	2.1	1.9	3.7	2.6
			Anomalia 1961 - 1990	--	--	--	--
			Anomalia 1978 - 2005	1.4	1.7	1.1	1.3

Figure 5: Seasonal average temperature for individual winter months observed for some reference stations with related climate anomalies.

All the winter months were warmer than average. The greatest anomaly was recorded in December (about +2.5 / +3 ° C above the average for the period 1961-1990). For the Trento Laste meteorological station, which is not so far from the test route, December was the warmest month since 1920. As you can see by daily temperature observed in this station (Fig. 6), expressed as a deviation from the average of reference, the values were higher than average for most of the winter season, especially in December and January, when they frequently were higher even than the average of the maximum values of reference.

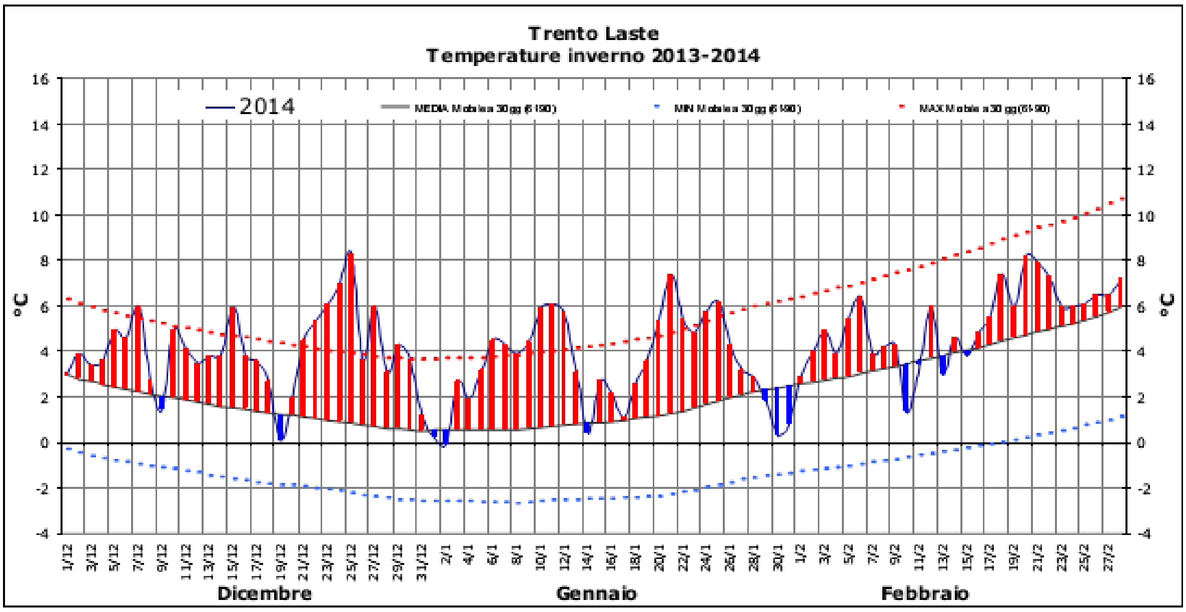

Figure 6: Air temperature measurements taken by Trento Laste station during the winter season 2013-2014.

Furthermore, winter 2013 - 2014 was characterized by exceptional contributions of **precipitation**, which had been well above the average for the period 1978-2005 and the average for the reference period for the reference 1961-1990 (Figure 7). Considering specifically Trento Laste, it had been the wettest ever since 1921.

Also the frequency of days characterized by precipitation (> 1mm/day). This had been higher than the average of about 10-15 days. Every single month (Figure 8) was characterized by rainfall higher than average, with higher deviations from the average in January and February. The most significant difference is detectable in the frequency of days with precipitation. In fact, in December, the rainy days are deviating slightly from the mean and were concentrated in two intense events that have occurred just in Christmas and St. Stephen days (December 25 and 26), while in the months of January and February rainy days had been frequent and well above average.

In the analyzed case of Trento Laste (Figure 9) it had been observed 12 rainy days in January and 18 days in February.

Tabelle di precipitazione

Inverno 2014			Precipitazione [mm]			Rank	Eventi estremi MAX [mm]		Rank	Eventi estremi MIN [mm]	
Nome	Quota m	Anno inizio	Cumulata stagionale	Anomalia 1961-1990	Anomalia 1978-2005	Superiore	P max	Anno	Inferiore	P min	Anno
Pieve Tesino[1]	775	1942	828.8	310%	359%	1/69			69/69	29.4	2012
Lavarone	1155	1921	687.8	183%	235%	2/94	732.5	1951	93/94	35.0	1981
Male'	735	1921	501.8	230%	252%	1/94			94/94	16.1	1932
Trento (Laste)	312	1921	531.4	236%	282%	1/94			94/94	8.2	1981
Tione	575	1921	731.6	248%	279%	1/94			94/94	14.4	1981
Cavalese	1000	1921	339.2	213%	255%	2/94	374.7	1951	93/94	20.3	1932

Figure 7: Average winter precipitation observed for some reference stations with reference to climate anomalies and rank.

Tabelle di precipitazione

Nome	Valore	Dic	Gen	Feb	Inverno	Valore	Dic	Gen	Feb	Inverno
Pieve Tesino[1]	Cumulata	205.2	295.6	328.0	828.8	Cumulata	205.2	295.6	328.0	828.8
	Valore medio 1961 - 1990	67.1	65.2	67.2	202.4	Anomalia 1961 - 1990	206%	353%	388%	310%
	Valore medio 1978 - 2005	80.3	54.8	48.5	180.5	Anomalia 1978 - 2005	155%	440%	576%	359%
Lavarone	Cumulata	127.4	280.2	280.2	687.8	Cumulata	127.4	280.2	280.2	687.8
	Valore medio 1961 - 1990	78.6	82.3	76.9	242.9	Anomalia 1961 - 1990	62%	240%	265%	183%
	Valore medio 1978 - 2005	78.2	66.4	53.8	205.5	Anomalia 1978 - 2005	63%	322%	420%	235%
Male'	Cumulata	116.8	201.6	183.4	501.8	Cumulata	116.8	201.6	183.4	501.8
	Valore medio 1961 - 1990	49.8	49.2	50.5	151.8	Anomalia 1961 - 1990	134%	309%	263%	230%
	Valore medio 1978 - 2005	55.0	46.8	37.2	142.6	Anomalia 1978 - 2005	112%	331%	393%	252%
Trento (Laste)	Cumulata	101.8	188.2	241.4	531.4	Cumulata	101.8	188.2	241.4	531.4
	Valore medio 1961 - 1990	54.6	53.5	47.5	158.0	Anomalia 1961 - 1990	86%	252%	408%	236%
	Valore medio 1978 - 2005	57.0	46.7	34.8	139.3	Anomalia 1978 - 2005	78%	303%	594%	282%
Tione	Cumulata	137.0	286.4	308.2	731.6	Cumulata	137.0	286.4	308.2	731.6
	Valore medio 1961 - 1990	74.6	72.8	60.2	210.4	Anomalia 1961 - 1990	84%	293%	412%	248%
	Valore medio 1978 - 2005	76.2	66.6	46.4	193.1	Anomalia 1978 - 2005	80%	330%	565%	279%
Cavalese	Cumulata	74.8	117.0	147.4	339.2	Cumulata	74.8	117.0	147.4	339.2
	Valore medio 1961 - 1990	35.9	35.4	36.2	108.3	Anomalia 1961 - 1990	108%	231%	307%	213%
	Valore medio 1978 - 2005	39.2	29.3	27.1	95.5	Anomalia 1978 - 2005	91%	300%	445%	255%

Figure 8: Cumulated precipitation for individual months and winter season (mm), with related climate anomalies (%), for some reference stations.

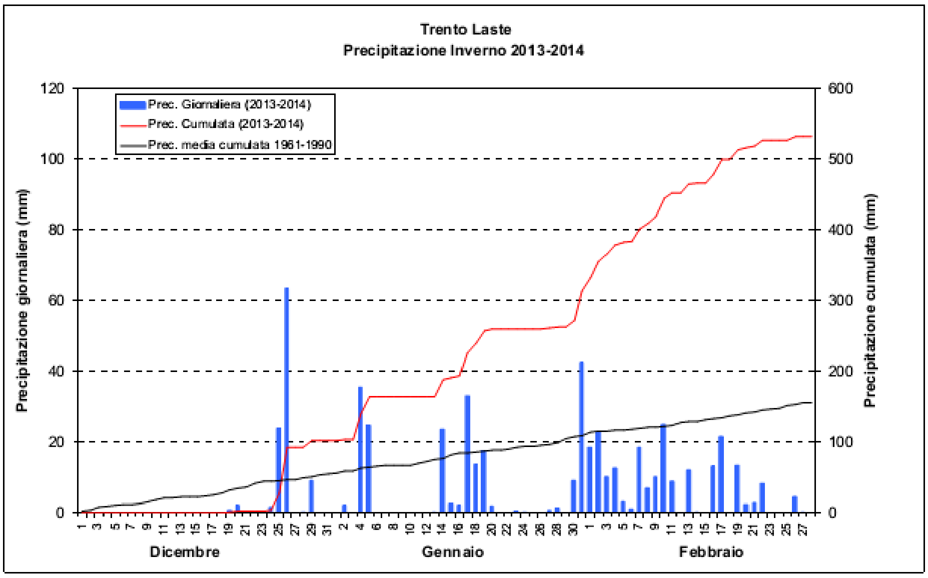

Figure 9: Daily precipitation, accumulated rainfall and average rainfall during winter season 2013-2014 registered by the meteorological station of Trento Laste [4].

The exceptional rainfall is reflected on the contributions of snow. Because of the high winter temperatures, observed values have been taken from records in the mountains (on average more than about 1500-1700 m), while episodes of snow at low altitudes were infrequent and mostly concentrated in the January.

2.2. Meteorology of the case study road: the Cadino station data evaluation

Last winter was exceptionally rainy and warm. As explained above, and as reported in many weather bulletin, no such behavior has been detected in the last century. Winter 2013-2014 was characterized by many precipitation days, cloudy sky and temperature well above the average; in the study road stretch, as explained below, only a couple of days of road freezing were detected. January and February are generally dry and cold months, but winter 2013-2014 showed the highest frequency of rainy days with mild temperatures instead.

The exceptional conditions of winter 2013-2014, with intense precipitations and mild temperatures, made the winter season more similar to the autumn season.

Figure 10 shows an historical analysis on the number of hours observed with a temperature below -4°C for San Michele all'Adige meteorological station. In the whole winter 2013-2014 (November, December, January and February) it had been observed only 10 hours with temperature below -4°C. As you can see from the Figure 10 such a conditions never happened since 1983.

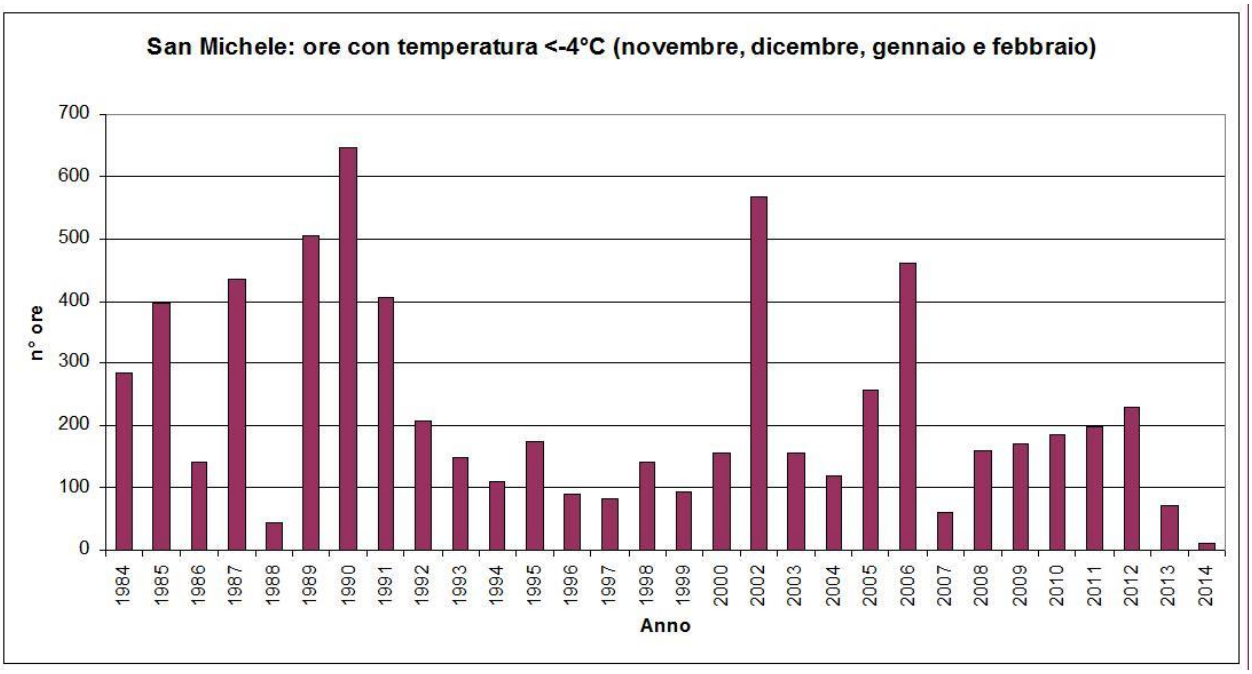

Figure 10: Historical analysis for San Michele all'Adige meteorological stations: hours registered with temperature < -4°C.

A comparison between San Michele all'Adige minimum temperatures and Cadino minimum temperatures detected for winter 2013-2014 shows that the two stations are very similar. On average, San Michele is about 1°C colder and the standard deviation is 1°C. For the purposes of the forecast for the next few days they are not so distinguishable because the mean absolute error is greater than 2°C.

In other words, the historical analysis conducted for San Michele all'Adige station is absolutely valid also for Cadino station, for which historical data are not available.

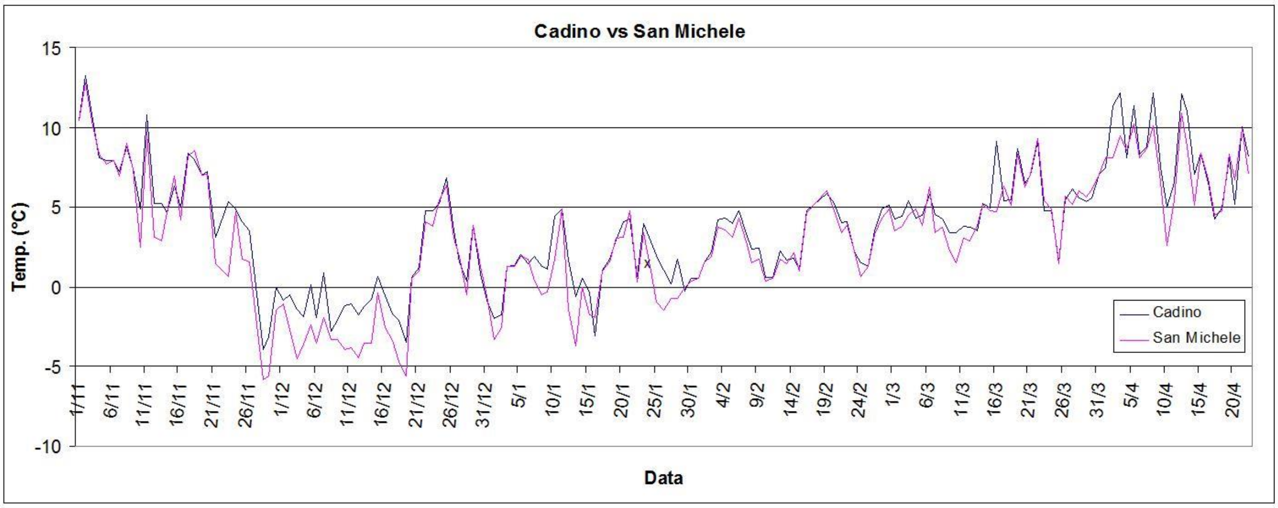

Figure 11: Comparison between San Michele all'Adige minimum temperature and Cadino minimum tempreraturedetected for winter 2013-2014.

The graph below shows the minimum temperature detected in Cadino station for winter 2013-2014. Measured minimum temperatures were never below -4°C.

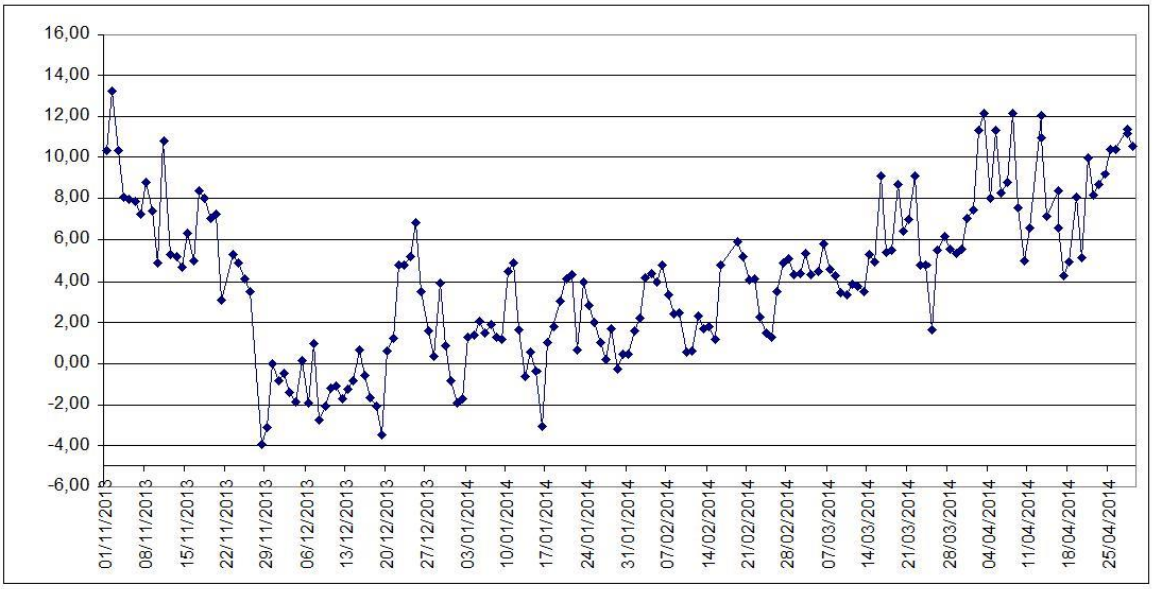

Figure 12: Minimum temperature detected in Cadino station for winter 2013-2014.

The conditions for frost formation are that the dew point temperature is below zero and that the temperature of the soil is lower than the dew point temperature. Based on these constraints, the analysis of hourly data detected in Cadino station during winter 2013-2014 showed that in only five days there were registered few consecutive hours with these conditions. It is well known that the formation of frost is not a very frequent phenomenon;

moreover the temperature well above the average of the ground has further reduced the possibility of formation of such a phenomenon. The frequent rains have also kept the soil wet by increasing both the heat capacity and the specific heat, and thus a high heat flux.

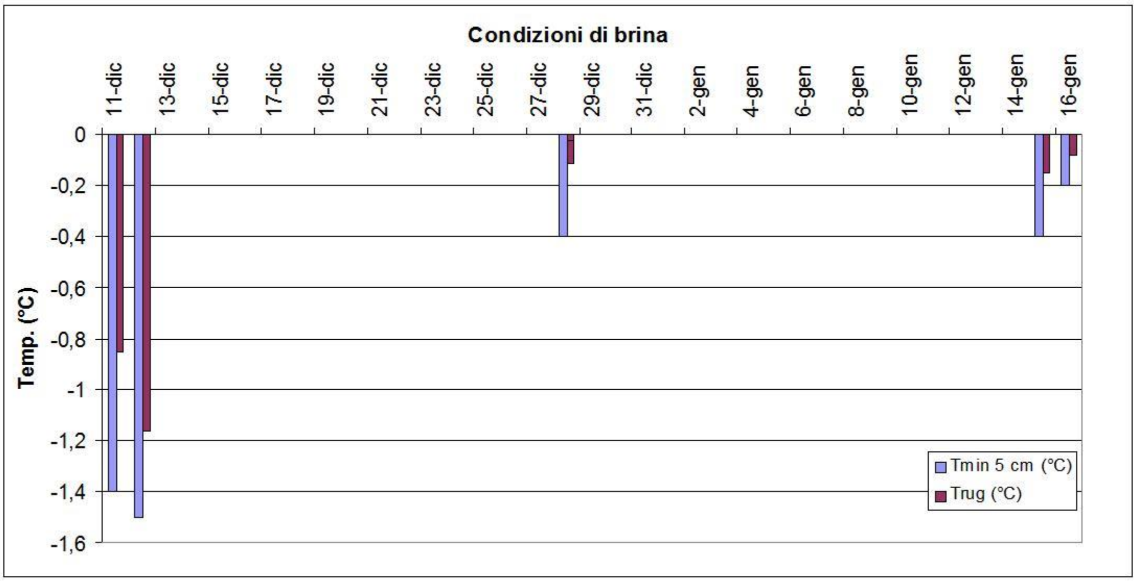

Figure 13: Frost conditions detected in Cadino station for winter 2013-2014.

3. Salt consumption analysis

3.1. Salt consumption analysis in Province of Trento

The overall quantities of salt purchased in the Autonomous Province of Trento during years 2010, 2011, 2012, 2013 and 2014 is presented in Figure 14. It is important to point out that the results reported below are referred to the quantities used during the solar years, and are therefore not directly linked with the different winter seasons. Please note that <u>the data related to year 2014 are incomplete</u>, since they do not take into account the winter season 2014-2015.

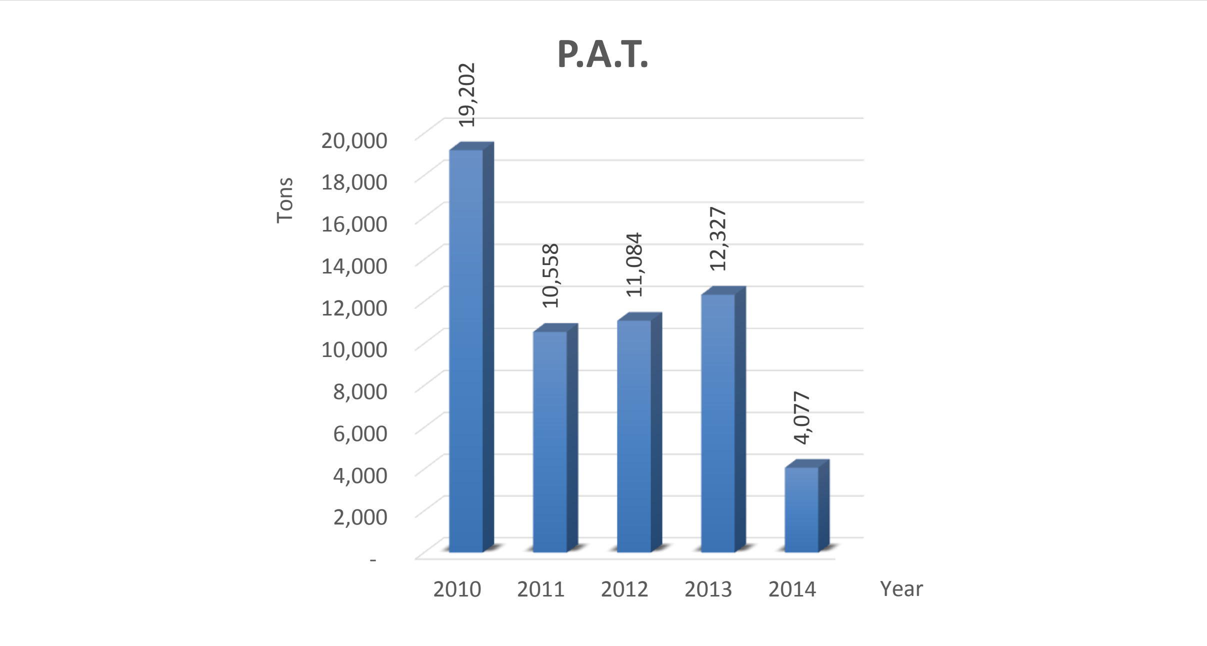

Figure 14: Overall road salt orders in the Autonomous Province of Trento during years 2010-2014.

The details of salt purchase in the reference sector of the project (sector nr. 4) is given in Figure 15. The patterns are similar to the total ones, apart for the usages in 2011 and 2012 (in this sector the consumption in 2012 has been lower than in 2011, differently from the overall road salt orders).

3.2. Salt usage data for the SS12 during winter season 2013/2014

Thanks to the active recording work of the road operators done during the winter season since the start of the CLEAN-ROADS project it has been possible to keep specific trace of the winter road treatments carried out on the case study route. In winter 2013/2014 road operators have automatically recorded the following information using a specific mobile application developed for the CLEAN-ROADS project [4]:

- **date and time of the treatments**;

- **type of the treatments** (*preventive anti-icing, preventive before a snowfall, during a snowfall, after a snowfall*);
- **quantity of salt spread** (expressed in [g/m^2]).

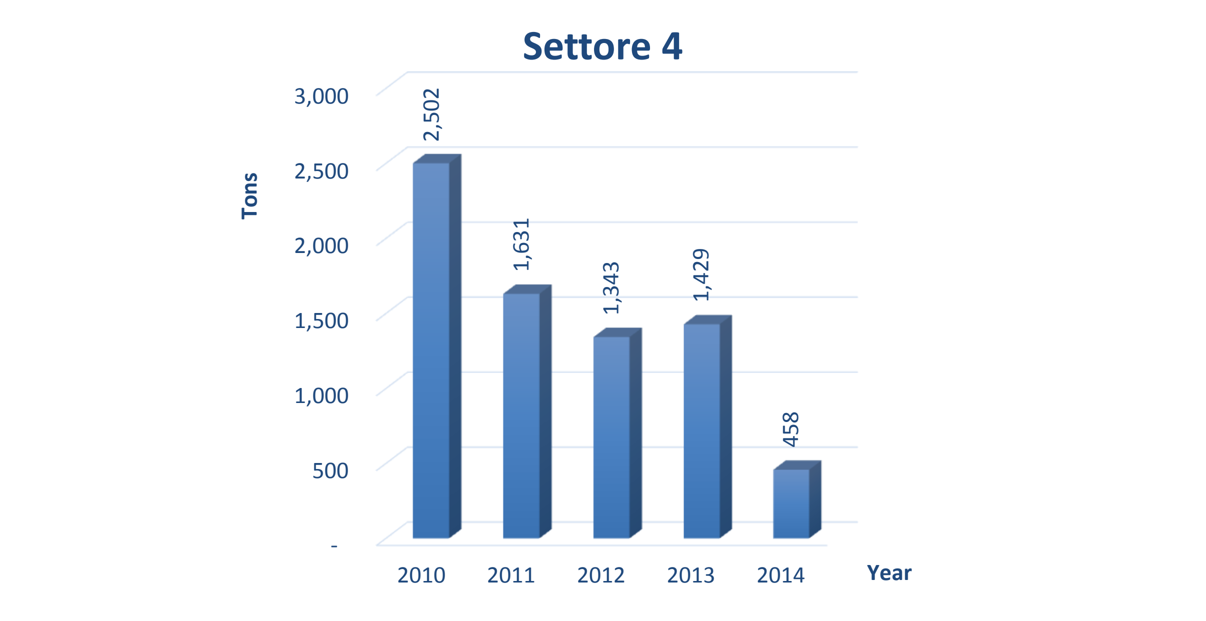

Figure 15: Road salt orders in the Autonomous Province of Trento during years 2010-2014 in the sector nr.4.

In the scope of this preliminary analysis, however, it has been decided to make reference to the estimated salt consumption data on the case study road, which is a subset of the entire road stretch covered by the involved team of road operators. This choice is related to the fact that a consistent comparison with the previous historical recordings is possible (Figure 16). In this case, the overall salt consumption estimation for year 2014 has been considered. The detailed data provided by the tracking system is going to be specifically discussed in the monitoring analysis covered by Action C1.

As far as the salt consumption related to the different project winters is concerned, during the **last two winter seasons** (the only covered by the project without CLEAN-ROADS system in place) have been **higher than 200 [q]**, in line with historical winter seasons with very intense and/or frequent snowfalls and/or cold temperatures (Figure 17 and Figure 18). **During the winter season 2013-2014**, differently from what one can expect in light of the exceptional winter conditions observed, **the estimated salt consumption on the case study road has been higher than in the previous winter season**, which has been colder and with frequent snow precipitations. The reason for that is to be associated to the **very uncertain meteorological conditions**, at the boundary between the decision to make a road treatment or not (e.g. rainy precipitation with temperatures just above 0°C).

Figure 16: Road salt consumption during years 2008 - 2014 in the case study road.

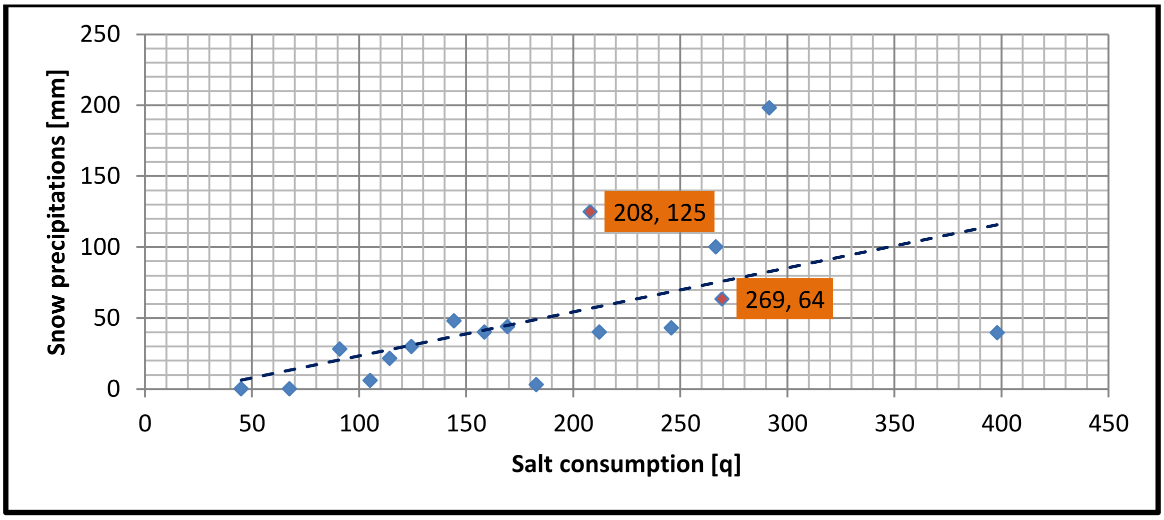

Figure 17: Historical estimated road salt consumption vs snow precipitations from winter season 1998/1999 in the case study road.

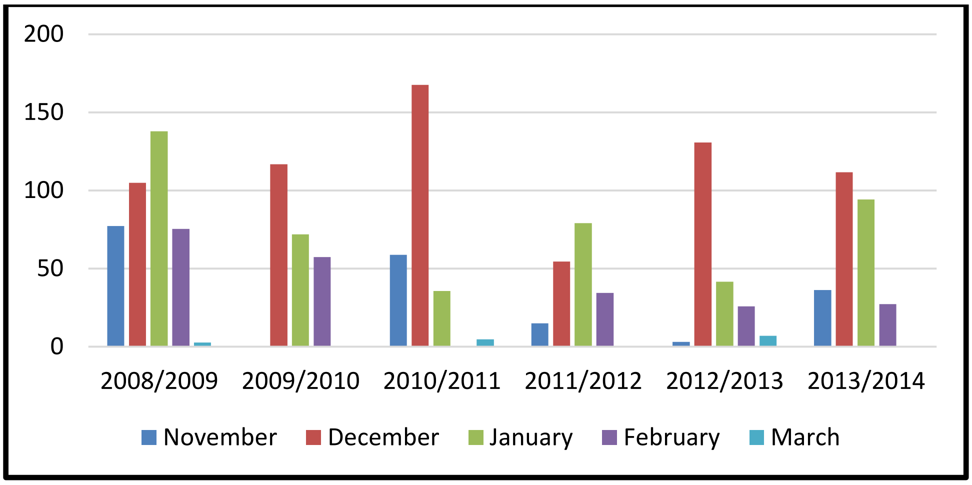

Figure 18: Estimated road salt consumption in the case study road during different winter seasons (period: 2008-2009 to 2013-2014).

4. Baseline assessment results

4.1. Confirmation of the exceptional winter season from a road weather point of view

As illustrated in the previous chapter, the exceptional winter season has determined the appearance of a very limited number of potentially icy road conditions, and therefore the need for a very reduced number of road treatments. The occurrence of snowfalls has been quite significant, but has however produced limited problems to the normal traffic circulation, since they have often alternated to unusual rainfall events which have provided a crucial contribution in the natural avoidance of snow adhesion phenomena on the roads.

These considerations are confirmed by the presentation of the road data gathered by the RWIS station installed in the test site of Cadino. Data have revealed that in only the 4.9% of the cases the road surface temperature has been below the theoretical boundary represented by water freezing point (0 [°C]), for an overall duration of about 177 hours (or 7.4 days) with respect the whole winter monitoring campaign (about 150 days). This population is even much lower if we consider a threshold value of -1 [°C]: in this case the number of events has been only the 0.1% of the whole cases (about 5.5 hours).

Road Surface Temperatures	Road Surface Conditions	Occurrence	Duration
Over 0 [°C]	Dry	57.6%	86.6 [days]
Below 0 [°C]	Dry	3.9%	5.9 [days]
Over 0 [°C]	Non-dry	3754%	56.3 [days]
Below 0 [°C]	Non-dry	1.0%	1.6 [days]

Table 2: Road surface temperatures and conditions occurrence during winter season 2013/2014.

What is completely missing is therefore the detailed knowledge (i.e. based on the data collected by the static RWIS stations) of how the test road will behave in correspondence of “harsh” winter conditions, with temperatures significantly lower than the threshold of 0 [°C]. The following scatterplots provide a comprehensive overview of the temperatures conditions measured in correspondence to different precipitation events (i.e. no precipitation, rain, snow).

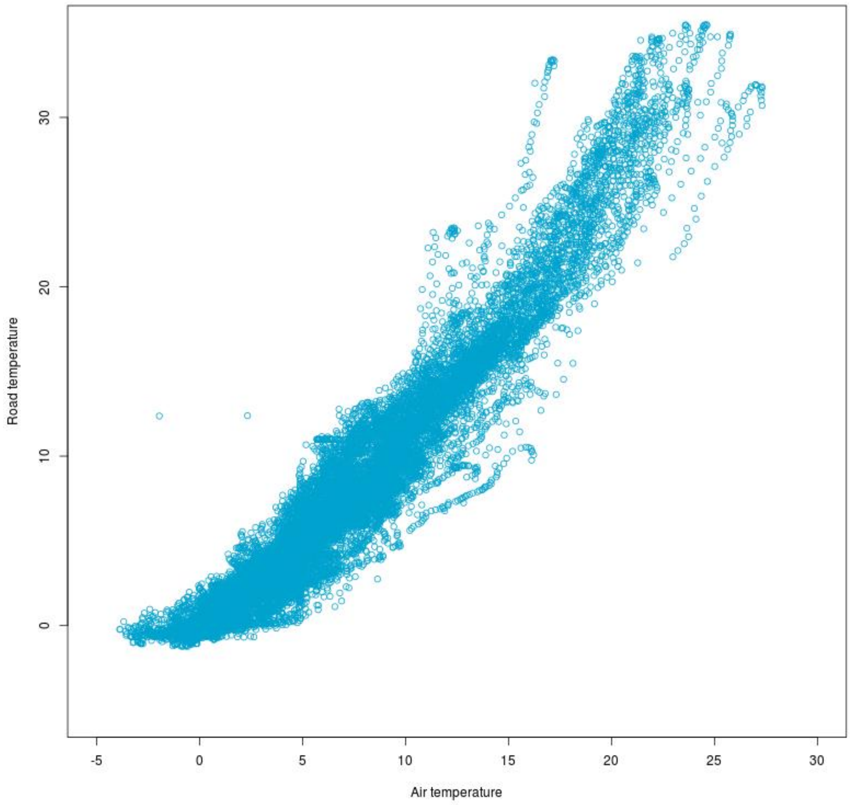

Figure 19: Road surface - and air temperatures dataset scatterplot in absence of precipitation.

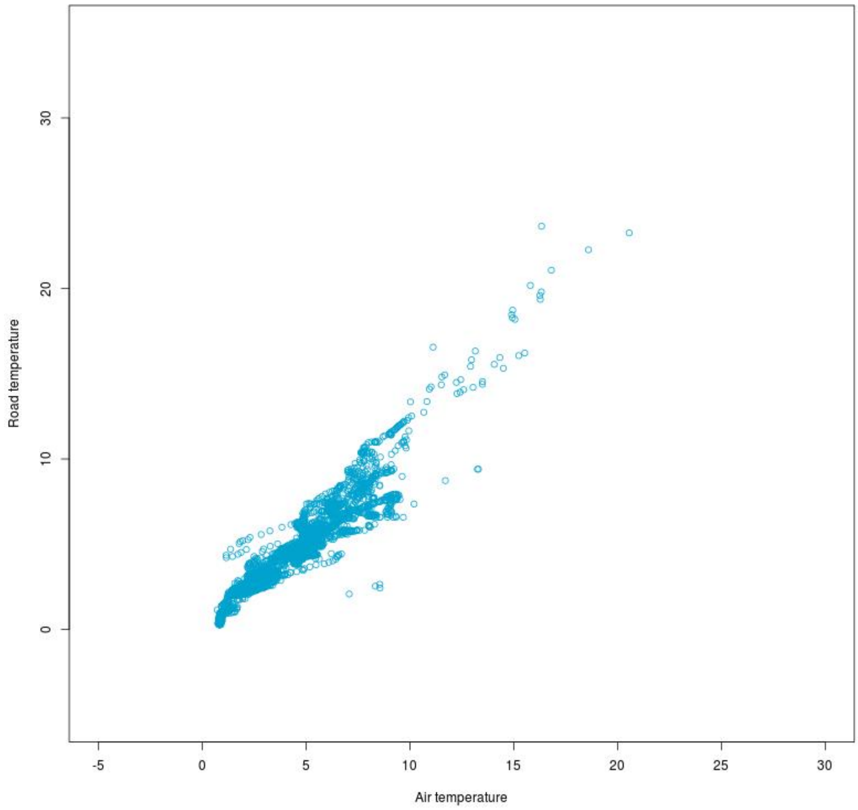

Figure 20: Road surface - and air temperatures dataset scatterplot in presence of rain.

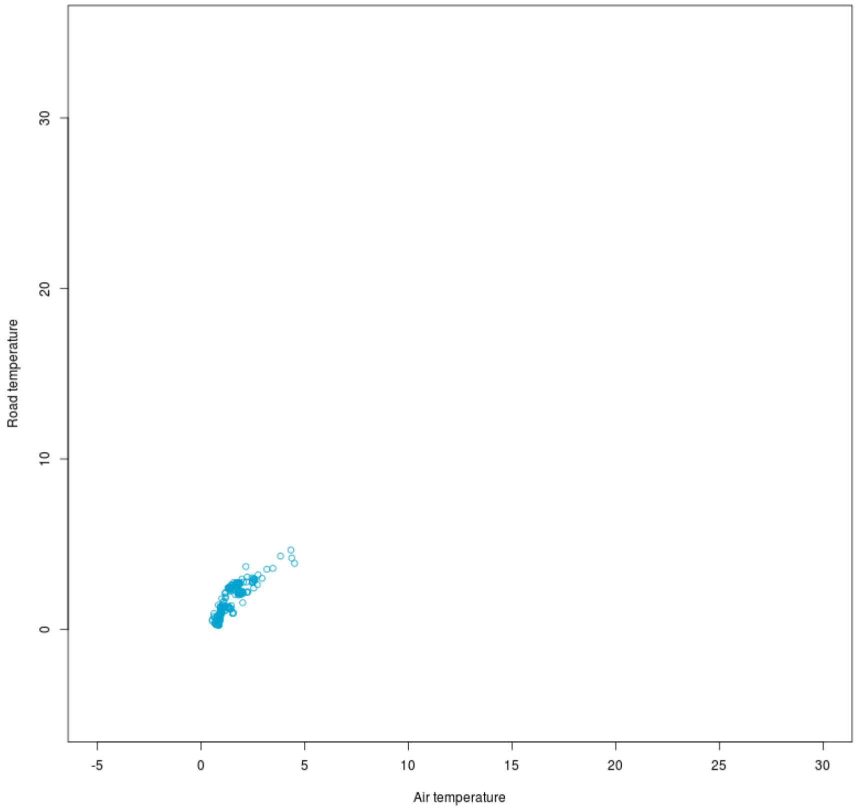

Figure 21: Road surface - and air temperatures dataset scatterplot in presence of snow.

4.2. Proposed model for the automatic estimation of the optimal road maintenance activities

As already highlighted in the previous chapter, he number of treatments has been significantly lower than the average ones, with an overall reduction equal to 72% if compared to the ones carried out in the previous winter season 2012/2013.

This reduction at a first glance seems however to be still too low with respect to what one could expect on top of the exceptional mild conditions observed during the winter season 2013/2014. In order to have a more detailed assessment of this statement, an optimization margin analysis has been carried out. This study represents the final activity associated to preliminary action A1. This analysis has tried to quantify the maximum optimization margin that it would be possible to achieve if one could be in the condition to know in advance without uncertainty the evolution of the road weather conditions. Future studies will be carried out within the project in order to quantify the optimization margin which it will be possible to achieve in practice through the advanced RWIS system which is proposed in CLEAN-ROADS[2]. The margin has been determined through a matching between the observed treatments and the treatments suggestions that have been defined on top of an automatic data evaluation tool, whose methodology is presented from a high-level perspective in Figure 22.

[2] In this case observed road weather data will be substituted with predicted one generated by proper forecasting engines.

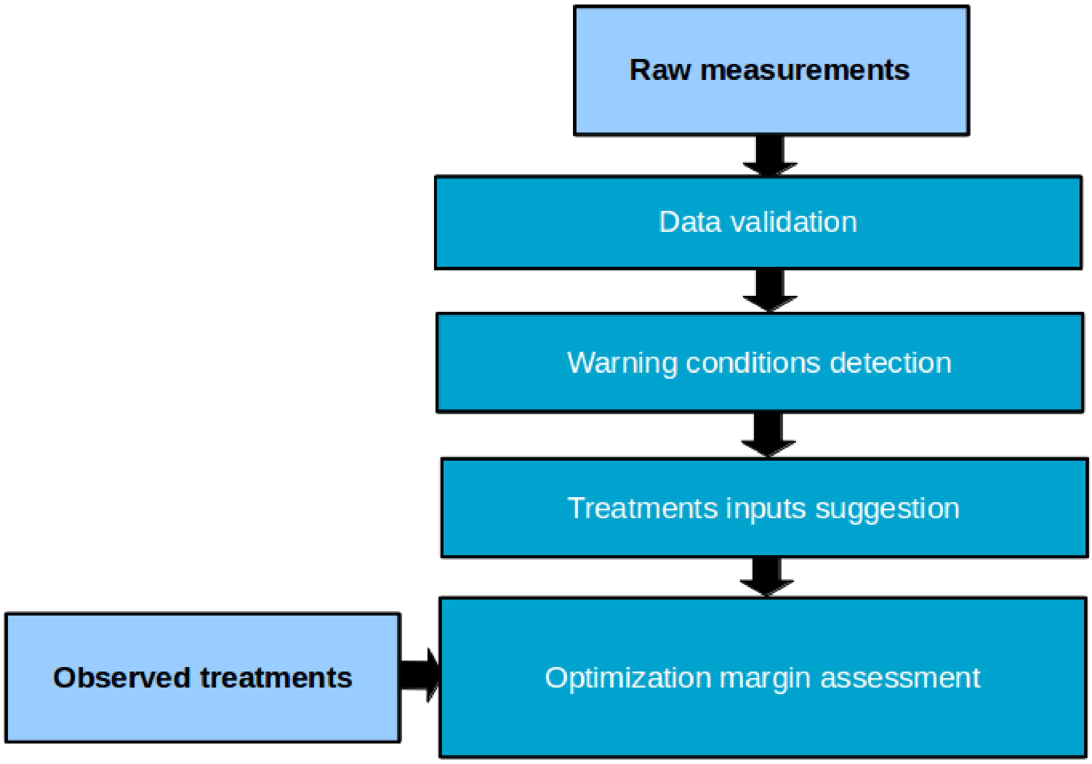

Figure 22: The methodology for the quantification of the optimization margin in the winter road treatments.

The set of data considered in this process of analysis, collected by the RWIS station in Cadino [4] - [5] is summarized in Table 3. Due to the availability of four different road surface temperature sensors, a selection of the most representative one was needed. As presented in detail in D.B1.1 [6], the differences in the measurements obtained are neligible, and can be ascribable to the limitation of the accuracy of the sensing technology.

Parameter	Code	Measurement Unit	Note
Air temperature	T_{air}	[°C]	
Relative Humidity	RH	[%]	
Dew Point	T_{dew}	[°C]	
Precipitation Type	PT	-	**Classification code**: • 0 … absence of precipitation • 1 … precipitation type: rain • 2 … precipitation type: snow • 3 … precipitation type: rain + snow
Precipitation Intensity	PI	-	**Classification code**: • 0 … absence of precipitation • 1 … precipitation intensity: light • 2 … precipitation intensity: medium • 3 … precipitation intensity: heavy
Road surface temperature	RST	[°C]	Based on the root mean square deviation (RMSE) criterium, sensor 4 has been chosen (Figure 23).
Road surface condition	RSC	-	**Classification code**: • 0 … not defined • 1 … road condition status: dry

	• 2 … road condition status: wet • 3 … road condition status: humid • 4 … road condition status: wet + salt

Table 3: Overview of the RWIS data considered in the optimization margin study.

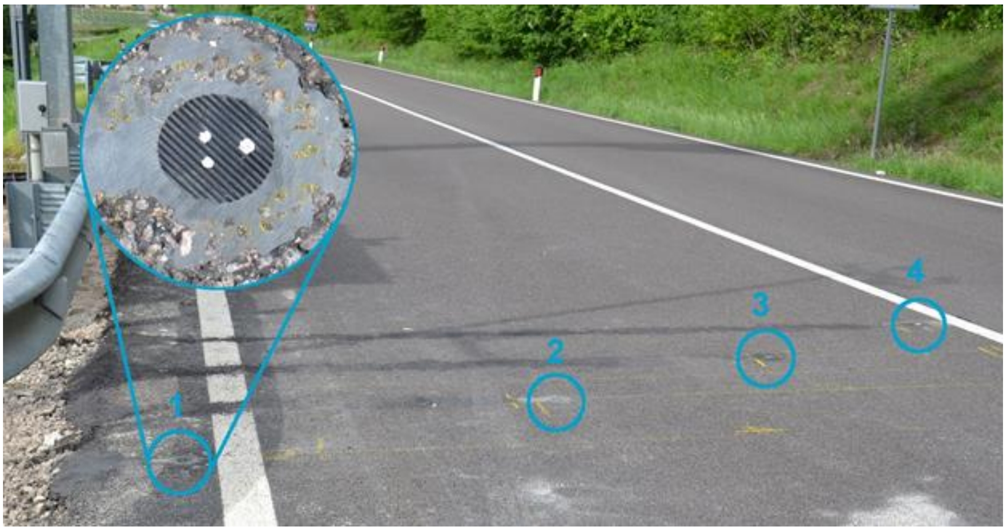

Figure 23: The road surface sensors of the static RWIS station in Cadino.

Ice formation process on the road can be directly linked to other meteorological parameters, which however are not considered in this analysis. In part, such information is already implicity included in other road weather data, and in part no measurements are available for measuring such parameters (Table 4).

Parameter	Impact	Reason for not taking into account
Wind speed	The absence of wind and clear sky are the perfect conditions for the accumulation of cold air in the lower atmospheric layers and the radiation cooling of the earth surface.	Risky situations caused by low wind are already visible by means of air and road temperature, as well as the dew point.
Global solar radiation	Solar radiation has obviously a direct impact on the daily increase of RST.	The availability of RST measurements makes global solar radiation data completely necessary for the needs of this analysis
Cloud cover	Cloud cover has a dominant role in the unexpected variations of RST.	The RWIS station does not have a sensor able to measure this parameter.

Table 4: Additional RWIS data not considered in the optimization margin study.

Data validation

The first step in the automatic evaluation of the RWIS dataset is to detect the presence of measurements outlayers. Two set of data validation controls are introduced: (i) **“correctness” controls**, which aim to check if the measured values are in line with the road weather conditions of the measurement site; and (ii) **consistency controls**, which aim to ensure the consistency between different raw measurements.

The set of automatic correctness controls is presented in detail in Table 5. Controls are applied to negative temperatures only, since the interest is focused on possible freezing events.

Parameter	Control	Correction
T_{air}	$T_{air} < -30$	Record set to Not Available (NA), not considered in the analysis
T_{dew}	$T_{dew} < -100$	
PT	Code different from admitted one	
PI		
RSC		
RST	$RST < -30$	

Table 5: Data validation process used in the optimization margin study.

As far as consistency controls are concerned, only one constraint has been introduced. The road is forced to be wet when a precipitation event is taking place, according to the following algorithm:

```
if(!is.na(datiStazioneFissa$precipitation_type[n])&&
       !is.na(datiStazioneFissa$road_condition[n])){

   if((datiStazioneFissa$precipitation_type[n]>0)&&
       (datiStazioneFissa$road_condition[n] == 1)){

        datiStazioneFissa$road_condition[n] <- 2

  }

}
```

Warning conditions detection

The second step in the automatic data elaboration is the association of a set of warnings to each single RWIS data record, sampled at a frequency of ten minutes. The set of warnings is briefly presented in Table 6. In case controls are not satisfied, warnings are not highlighted.

Warning type	Code	Reference controls
Snow accumulation warning	SW	$SW = "active" \leftrightarrow PT = 2 \; and \; RST < T_S'$
Ice warning	IW	$IW = "active" \leftrightarrow \{RST \leq T_{dew} < T_S''\}$ $or \; \{RSC > 1 \; amd \; RST \leq T_S'''\}$
Patrol trip warning	PTW	$PTW = "active" \leftrightarrow$ $\{RST \leq T_{dew} + \Delta \; and \; T_{dew} < T_S''\} \; or$ $\{RSC > 1 \; and \; RST \leq T_S^{iv}\}$

Table 6: Logic proposed for the automatic warning conditions evaluation.

The definition of the reference controls for the generation of the different warnings is linked to the following motivations:

- **snow accumulation warning**: this warning is not simply associated to a basic evaluation of it is snowing or not. RST is considered as well in order to understand if the snow which is falling is in the condition to accumulate on the road surface and form a thin layer of ice over it. It is important to underline that the precipitation intensity is not considered in this first detection phase, but will be actively considered in the following elaboration step;

- **ice warning**: this warning is associated to the possible formation of ice due to two completely different situations:
  - **risk of formation of hoar frost** on the road surface, a condition which might take place during clear and calm nights;
  - **risk of freezing of the water cover of the road surface**, a condition which might take place after a precipitation event followed by a sudden decrease in the temperature values;
- **patrol trip warning**: this warning is essentially identical to the ice warning, but constraints are less restrictive. In this way, it is possible to take in consideration possible uncertain situations and match them with the road operators' patrol trips.

The generation of warnings is therefore controlled by the value of four threshold parameters, as summarized in Table 7. By changing these threshold values it is possible to both evaluate the sensitity of the model and characterize the RWIS patterns as a function of the specific winter season.

Threshold	Reference warning	Associated control
T_S'	SW	Controls if snowfall can generate accumulation phenomena
T_S''	IW	Controls if hoarfrost formation can take place
T_S'''	IW	Controls if watercover can freeze
$T_S'^v$	PTW	Controls if conditions are approaching to a watercover freezing event (with constraint $T_S'^v > T_S'''$)
Δ	PTW	Controls if conditions are approaching to a watercover freezing event (with constraint $\Delta > 0\ [°C]$)

Table 7: Threshold parameters for the automatic warning conditions evaluation.

Treatment inputs suggestion

Treatments inputs suggestions are based on a posterior analysis of the number of occurrence of the warnings in the short-term period. Such occurencies are in a first step calculated for each data record of the available dataset. Based on these computations, it is possible to define if a certain treatment would have been needed in the following temporal window T based on the observed conditions (Figure 24). The set of treatment inputs is presented in Table 8.

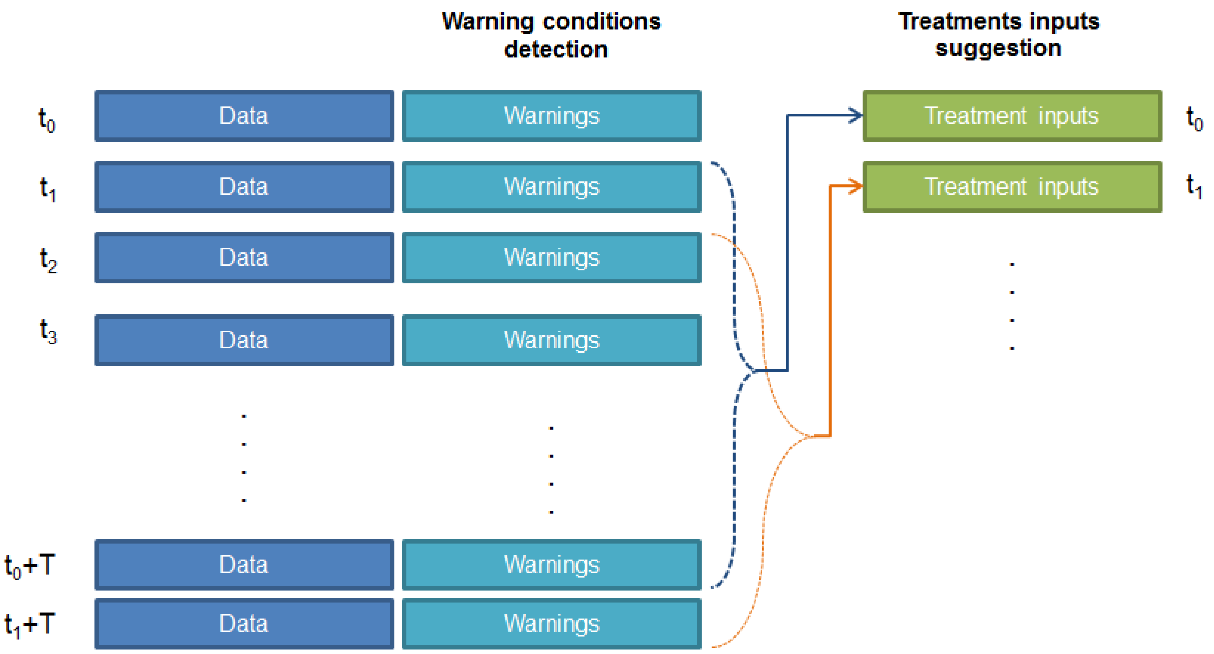

Figure 24: The approach used for the automatic determination of the treatments inputs.

Treatment input type	Reference controls
Anti-ice treatment	An anti-ice treatment input is associated to the data record measured at time t_0 if in the following temporal window of length $T = 12\ [hours]$at least 6 ice warnings are counted.
Patrol trip	A patrol trip input is associated to the data record measured at time t_0 if in the following temporal window of length $T = 12\ [hours]$at least 6 patrol trip warnings are counted.
Preventive snow treatment	A preventive snow treatment is associated to the data record measured at time t_0 if there is a correspondent snow accumulation warning active.
Snow removal operation	A snow removal operation is associated to the data record measured at time t_0 if a snow accumulation warning is active and at least one of these conditions is satisfied: • heavy precipitation conditions at the time t_0; • medium precipitation conditions at the time t_0 and snow accumulation warning detected at the time t_1; • light precipitation conditions at the time t_0 and snow accumulation warning at the times $t_1$and t_2.

Table 8: Logic proposed for the automatic determination of the treatments inputs.

The outputs of this processing elaboration are then downsampled so that a direct correspondence with the road operators' treatments is possible. In practice, road operators may regularly carry out a patrol trip or an anti-ice treatment in the early morning around 4:00 AM before the morning traffic peak or in the afternoon around 4:00 PM in order to maximize the road safety during the evening and at night. On the other side, preventive snow treatment and snow removal operations obviously do not have this fixed planning, and directly related to the arrival of a snowfall event. Based on these preconditions, only measured data (with associated warnings and treatments' inputs) recorded at 4:00 AM and 4:00 PM are considered, as well as all data records where a preventive snow treatment or a snow removal operation input has been highlighted.

4.3. Optimal versus real road operators activities

In order to estimate the optimal road operators activities on top of the proposed model, different runs were carried out by considering different threshold values. This analysis was performed with the purpose to evaluate the level of sensitivity of the model to the different parameters, and identifying the key threshold values to be considered for the final assessment of the results.

Preliminary tests demonstrated that the number of warnings considered for the suggestion of the treatment type has a minor impact on the obtained results. In fact, as one can expect, these parameters can have an important influence on the exact time of the suggested treatment, but are not decisive for suggesting if a treatment is necessary or not during a temporal window of 12 hours.

Dominant parameters are therefore the ones indicated in Table 7. Changing the threshold values of even just 1 [°C] can have a relevant impact on the number of identified warnings. In the following pages, the most reliable results obtained are reported.

Before entering into the details of the outputs of the proposed optimization margin assessment model, it is important to recall the number of real treatments carried out by road operators during the winter season 2012 – 2013. These numbers are summarized in Table 9. Snow removal operations were always carried out with two maintenance vehicles, except for the one carried out in February.

Treatment type	November	December	January	February	March	TOTAL
Patrol trip	2	11	3	2	0	18
Anti-ice treatment	0	5	10	6	0	21
Preventive snow treatment	0	1	2	0	0	3
Snow removal operation	0	0	6	1	0	7
TOTAL	2	17	21	9	0	49

Table 9: Observed treatments during winter season 2013/2014.

Table 10 present the estimated treatments obtained by considering the following thresholds, which are directly related to the theoretical freezing point of water. The choice of the value Δ is on the contrary related to the intrinsic accuracy in the calculation of the dew point temperature.

$$T_S' = T_S'' = T_S''' = T_S^{IV} = 0\ [°C]$$

$$\Delta = 2\ [°C]$$

Treatment type	November	December	January	February	March	TOTAL
Patrol trip	0	11	3	1	0	15

Anti-ice treatment	0	3	5	0	0	8
Preventive snow treatment	0	1	3	1	0	5
Snow removal operation	0	1	6	1	0	8
TOTAL						

Table 10: Estimated treatments during winter season 2013/2014 with threshold values set at 0 [°C] and ∆= 2 [°C].

The results of the comparison between estimated and observed treatments are expressed as a function of the following indicators. Numerical relationships are expressed in terms of the quantities reported in Table 11.

		Treatments observed	
		YES	**NO**
Treatments estimated	**YES**	a	b
	NO	c	d

		Treatments observed	
		YES	**NO**
Treatments estimated	**YES**	HR	FAR
	NO	MAR	CRR

Table 11: Reference confusion matrix for the assessment of the optimization margins.

- **false alarm ratio** (FAR), which expresses in percentage the number of times in which a treatment estimation is available, but a treatment is not observed. In this use case, this ratio represents an estimation of the **missed treatments**.

$$FAR = b/(a + b)$$

- **hit rate** (HR), which expresses in percentage the number of times in which a treatment is observed, and a treatment estimation is counted. In this use case, this ratio represents an estimation of the **correct treatments**.

$$HR = a/(a + c)$$

- **missed alarm ratio** (MAR), which expresses in percentage the number of times in which a treatment is observed, but no treatment estimation is counted. In this use case, this ratio represents an estimation of the **avoidable treatments**.

$$MAR = c/(a + c) = 1 - HR$$

- **correct rejection ratio** (CRR), which expresses in percentage the number of times in which no treatment is observed, and no treatment estimation is counted. In this use case, this ratio represents an estimation of the **correct no actions**.

$$MAR = d/(d+b)$$

			Treatments observed					
			YES					NO
			Patrol trip	Anti-ice	Prev.snow	S. Remov.	TOTAL	
Treatments estimated	YES	Patrol trip	5	3			8	7
		Anti-ice	3	1			4	4
		Prev.snow			2		2	3
		S. Remov.			1	7	8	
		TOTAL					**22**	**14**
	NO		10	17	0	0	**27**	**219**

Table 12: Confusion matrix with threshold values set at 0 [°C] and Δ= 2 [°C] (totals).

		Treatments observed	
		YES	NO
Treatments estimated	YES	HR = 44.9%	FAR = 38.8%
	NO	MAR = 55.1%	CRR = 94.4%

Table 13: Confusion matrix with threshold values set at 0 [°C] and Δ= 2 [°C] (percentages).

The matching between the model's outputs and the observed treatements is quite promising and highlights two different aspects:

- **about half of the observed treatments do not have a treatment estimation correspondence**, which confirms the presence of a not negligible margin in the avoidance of current treatment activities;
- **about 40% of the estimated treatments do not have an observed treatment estimation.** This is probably to be intended as an overestimation of the necessary treatments by the model, since it is unprobable that road operators currently miss a treatment action (an aspect which is confirmed by the absence of significant accident events associated to ice on the roads).

This latter consideration suggests that probably the choice of a threshold of 0 [°C] is too conservative. In practice, icy events on the road are more likely to occur at lower road surface temperatures. For these reasons, a reference threshold of -1 [°C] has been considered, namely:

$$T_S' = T_S'' = T_S''' = T_S'^{v} = -1\ [°C]$$

$$\Delta = 2\ [°C]$$

The obtained results are reported in the following tables.

			Treatments observed					
			YES					NO
			Patrol trip	Anti-ice	Prev.snow	S. Remov.	TOTAL	
Treatments estimated	YES	Patrol trip	4	2			6	7
		Anti-ice					0	
		Prev.snow			2		2	3
		S. Remov.			1	7	8	
		TOTAL					**16**	**10**
	NO		14	19	0	0	**33**	**223**

Table 14: Confusion matrix with threshold values set at -1 [°C] and ∆= 2 [°C] (totals).

		Treatments observed	
		YES	NO
Treatments estimated	YES	HR = 32.7%	FAR = 38.4%
	NO	MAR = 67.3%	CRR = 95.7%

Table 15: Confusion matrix with threshold values set at -1 [°C] and ∆= 2 [°C] (percentages).

The results are not very different from the previous ones, missed treatments have been decreased to 10 and the number of avoidable treatments further increased. What is more interesting to underline is the fact that at these conditions, no anti-ice treatment estimations have been counted. This is another confirmation of the exceptional winter conditions observed during the season 2014/2015. In order to further reduce the FAR contribution, an additional test has been performed by further decreasing threshold values to -2 [°C], i.e.:

$$T_S' = T_S'' = T_S''' = T_S^{iv} = -2\ [°C]$$

$$\Delta = 2\ [°C]$$

The obtained results are reported in the following tables.

			Treatments observed					
			YES					NO
			Patrol trip	Anti-ice	Prev.snow	S. Remov.	TOTAL	
Treatments estimated	YES	Patrol trip	3				3	2
		Anti-ice					0	
		Prev.snow			2		2	3
		S. Remov.			1	7	8	
		TOTAL					**13**	**5**
	NO		15	21	0	0	**36**	**228**

Table 16: Confusion matrix with threshold values set at -2 [°C] and ∆= 2 [°C] (totals).

		Treatments observed	
		YES	NO
Treatments estimated	YES	HR = 26.5%	FAR = 27.8%
	NO	MAR = 73.5%	CRR = 97.9%

Table 17: Confusion matrix with threshold values set at -2 [°C] and ∆= 2 [°C] (percentages).

The obtained results show interesting patterns. Patrol trips estimations are associated to observed patrol trips (except in two cases, which have however taken place always 12 hours after a patrol trip session in the morning). Preventive snow treatments and snow removal operations confirm the results previously obtained, and indicate, as expected, how the optimization in this kind of activity has to be seen more in the definition of the exact time of intervention more than in the possibility to avoid a maintenance session. The significant reduction of patrol trips suggest that maybe the constraint related to the control of patrol trips warnings is too strict. Therefore, a final simulation has been run with the following threshold values:

$$T_S' = T_S'' = T_S''' = -2\ [°C];\ T_S^{iv} = 0\ [°C]$$

$$\Delta = 2\ [°C]$$

The obtained results are reported in the following tables, and show a similar comprehensive picture as in the case of all threshold values set to -1 [°C].

			Treatments observed					
			YES					NO
			Patrol trip	Anti-ice	Prev.snow	S. Remov.	TOTAL	
Treatments estimated	YES	Patrol trip	6	1			7	6
		Anti-ice					0	
		Prev.snow			2		2	3
		S. Remov.			1	7	8	
		TOTAL					**17**	**9**
	NO		12	20	0	0	**32**	**224**

Table 18: Confusion matrix with threshold values set at -2 [°C] (with T_s^{iv} = 0 [°C]) and Δ= 2 [°C] (totals).

		Treatments observed	
		YES	NO
Treatments estimated	YES	HR = 34.6%	FAR = 34.6%
	NO	MAR = 65.3%	CRR = 96.1%

Table 19: Confusion matrix with threshold values set at -2 [°C] (with T_s^{iv} = 0 [°C]) and Δ= 2 [°C] (percentages).

Based on all these treatments' estimations, in which terms can be the overall maximum optimization margin be estimated? In order to provide a consolidated answer to this question, it is important to highlight the following considerations, which have become more and more clear during the detailed observation of the empirical decision-making process of road operators:

- **Information related to the "validity" of last treatment**. If the road has been already treated, and no precipitation phenomena have occurred since then, the level of risk is much lower, and lower threshold values should be considered for highlighting specific dangers. This can explain the residual components of false alarms (missed treatments).

- **Information related to the road surface conditions**. More detailed analysis of the beahviour of road surface conditions data have shown how in conditions of absence of precipitation and dry and “treated” road, patterns of non-dry roads have to be explained as an effect of road salt dilution.

These considerations suggest that it would be much more consistent to try to “merge” the results obtained through the different simulation, more than selecting just one of them. The idea is to consider the “right” threshold values depending on the estimated treatment status of the road. In other words, if the road can be classified as “treated”, the results of simulation with threshold values at -2 [°C] should be considered; whereas the road is in a more dangerous situation with no treatment, the most conservative case should be taken into account (0 [°C]).

Let’s try to formalize these concepts. First of all, the following definition is introduced:

The road is considered as “**treated**” if at least one the following conditions is satisfied: (i) the **previous state** of the road was “**treated**” and **no precipitation phenomena** have occurred in the last 12 hours; (ii) a **treatment has been carried out at the beginning of the current temporal window**, **without** any following **precipitation** phenomena.

Second, the following control logics are applied for post-processing the preliminary results:

Daily number of patrol trips. The estimation of patrol trips per day is limited to one.

Safety control: If the road is classified as “non treated”, an anti-ice treatment is finally suggested if one these conditions apply: (i) at least one “partial” anti-ice treatment is suggested through the simulations with threshold values set at -1 [°C] and -2 [°C]; (ii) at least two “partial” patrol trips are suggested through the simulations with threshold values set at 0 [°C], -1 [°C] and -2 [°C]; (iii) at least one “partial” patrol trips is suggested after a snowfall event through the simulations with threshold values set at 0 [°C], -1 [°C] and -2 [°C];

Memory control: If the road is classified as “treated”, the action suggested through the simulation with threshold values set at -2 [°C] is finally considered.

By applying these additional constraints, the following final results are obtained.

			Treatments observed					
			YES					NO
			Patrol trip	Anti-ice	Prev.snow	S. Remov.	TOTAL	
Treatments estimated	YES	Patrol trip	4				4	
		Anti-ice		4			4	
		Prev.snow			2		2	3
		S. Remov.			1	7	8	
		TOTAL					**18**	**3**
	NO		14	17	0	0	**31**	**230**

Table 20: Confusion matrix obtained through enhanced post-processing logics (totals).

		Treatments observed	
		YES	NO
Treatments estimated	YES	HR = 36.7%	FAR = 14.3%
	NO	MAR = 63.2%	CRR = 98.7%

Table 21: Confusion matrix obtained through enhanced post-processing logics (percentages).

The **final estimation** in terms of **maximum number of treatments that can be avoided**, if one could have at disposal in advance a perfect knowledge of the road conditions in the following 12 hours, is quantified for the winter season in the order of about **63%**. If one takes in consideration **patrol trips and anti-ice treatments only**, this optimization margin is even higher, and can be estimated in the order of **79%**: 31 of the 39 observed activities have been considered in fact as unnecessary..

4.4. Understanding road operators decision process workflow

In order to create the pre-conditions for improving the operative modalities with which road operators today decide and carry out winter treatments, it is at this point crucial to understand more deeply the reasons why road operators have decided to activate treatments during the last winter season. For this reason, road weather conditions detected in correspondence of each real treatment have been specifically taken in consideration.; the most significant patterns are described in the following pages.

Case 1: Possible conditions for frost formation

The first reported case is related to the days of December 10th – 15th 2013, already highlighted in Chapter 2 as the most likely days in which frost could have appeared on the case study road (Figure 13). This has been the first sequence of days and nights with stable meteorological conditions, absence of precipitation events, and night air and road temperatures just below 0 [°C].

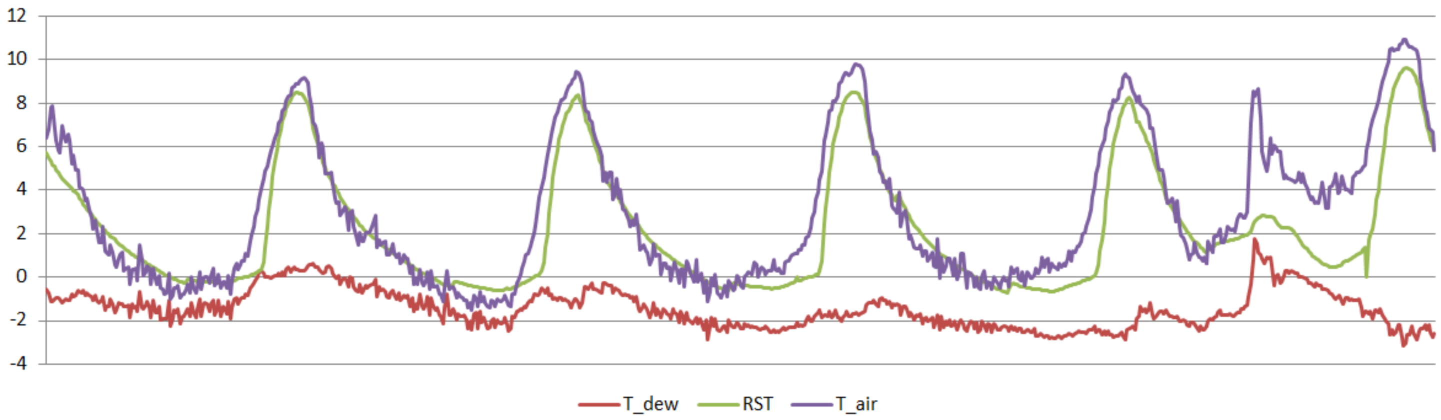

Figure 25: Case study 1 (December 10th – 15th 2013): possible conditions for frost formation.

In Figure 25 some of the measurements taken in the monitoring site of Cadino during these days are compared: dew point temperature (in red colour), road surface temperature (in green colour) and air temperature (in violet colour). The first reported night is the one between December 10th and 11th 2013. During these days, road operators have decided to carry out a patrol trip every morning, starting from December 12th. In this case, there has been a perfect correspondence with the recommended activity estimation, since the effective possibility of frost formation was not negligible. The level of attention of road operators has to be read not only in terms of the possible level of danger, but also in light of the fact that no treatment was previously carried out.

Case 2: Possible conditions for water cover freezing

The second reported case is related to the days of December 20th – 22nd 2013, the days immediately after the first snowfall event of the season, occurred on December 19th 2013.

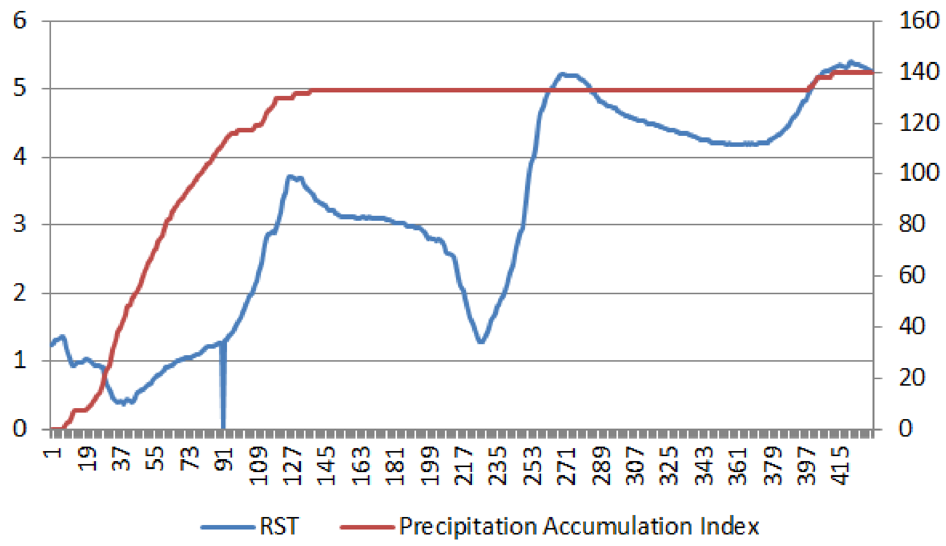

Figure 26: Case study 2 (December 20th – 22nd 2013): possible conditions for ice formation associated to the case of water cover freezing.

Figure 26 compares the road surface temperature (in blue colour) with the cumulated plot of precipitation intensity (precipitation accumulation index, in blue colour). The first reported night is the one between December 19th and 20th 2013. During these days, road operators have decided to treat the road twice: in the morning of December 20th and 21st 2013. The first event took place during a rainy precipitation event, but with temperatures with above 0 [°C]; the second one the day after, at conclusion of this precipitation event, probably due to the observation of a sharp decrease of temperatures which however remained above the threshold of 1 [°C]. This is a clear demonstration of the danger felt by road operators while icy conditions are approaching and the road is in a “non-treated” mode (in fact, the precipitation of the day before has probably had the effect to wash out the salt spread the day before).

Water cover freezing risk has been the most relevant danger of ice formation during the winter season under analysis. A similar case has been observed in a longer temporal window, namely from December 26th 2013 to January 6th 2014. The first reported night in Figure 27 is the one between December 26th and 27th 2013. During these days, road operators have carried out several activities: (i) an anti-ice treatment on December 27th morning; (ii) a patrol trip on December 28th morning; (iii) two consecutive anti-ice treatments between December 29th and 30th (one in the evening and one in the following morning); (iv) two patrol trips on December 31st and January 2nd; (v) again, two consecutive anti-ice treatments between January 2nd and 3rd (one in the evening and one in the following morning); (vi) two anti-ice treatments in the morning of January 5th and 6th. This pattern shows very well the situation in which the level of attention is higher in condition of "non-treated road", obtained after a precipitation event (e.g. the case of treatments of December 29th and 30th, associated to a constant decrease of temperatures), rather than in condition of "treated road", in which despite lower temperatures "only" a patrol trip is performed in order to check if residual salt is still present on the road.

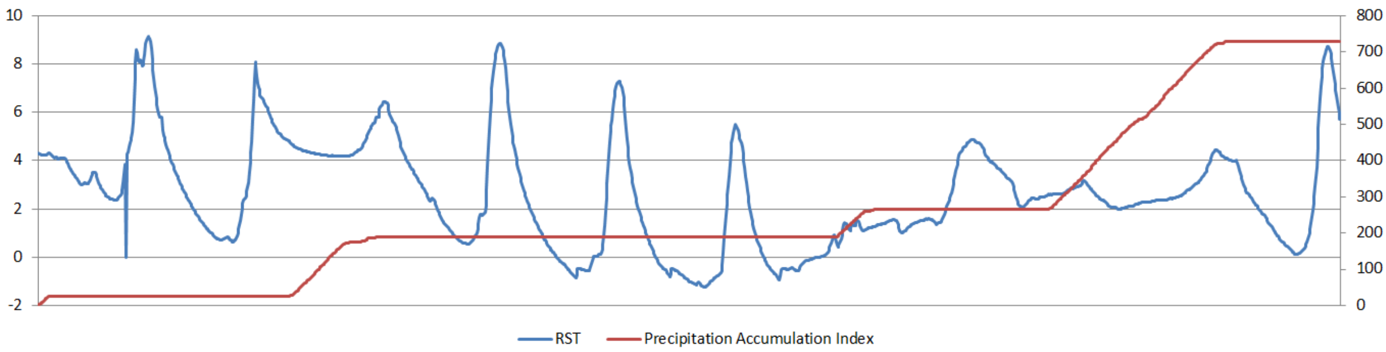

Figure 27: Case study 3 (December 26th 2013 – January 6th 2014): possible conditions for ice formation associated to the case of water cover freezing.

4.5. Final considerations and future assessment studies

The proposed model for the automatic estimation of the optimal road treatments based on a priori knowledge of the future conditions of the road is sufficiently generalized in order to be applied as is to the data sets that will be collected in the next winter season. The aspect which is more open for future improvement is related to the exact **estimation of residual salt** on the road, and its **effectiveness** in limiting the formation of ice on the roads **at certain harsh conditions** (at very low temperatures, which are quite unlikey for the case study road, one should consider the fact that traditional sodium chlorides completely useless).

A final assessment activity that could be carried out once the forecasting components of CLEAN-ROADS will be calibrated and validated is to check the **optimization margin** one could obtain in practice **through an advanced MDSS**. This could be carried out now quite simply, by considering the results of the proposed model with the forecasted data and not with the observed data. This will give a more reliable indication of the optimization margin that one could be in the condition to achieve if the CLEAN-ROADS system is used in practice in this particular scenario of application.

A final suggestion is to use the set of controls of this model in order to implement the **automatic chain for the real-time generation of alarms and warnings** to be delivered to the road operators. For such an application, controls and logics must be rewritten without considering what is going to happen in the next future, but just taking into account the historical RWIS station records.

5. Traffic analysis

In the first version of this deliverable it has been possible to empirically demonstrate how daily traffic patterns are significantly related not only to mobility demand, but also to meteorogical conditions. In reality, not all meteorological phenomena or events have demonstrated to have the same impact: for instance, travellers have shown to not take in particular consideration ice formation events, whereas they are much more influenced in their travel choices by precipitation conditions, and more specifically by snow. Meteorological bulletins have an important role in this travel decision work flow: travellers are strongly influenced by this information as well, and not only by real-time conditions. Traffic demand can be significantly reduced even if a snowfall is only predicted, but effectively not registered.

In deliverable D.C1.3 the results of similar analysis repeated for the test site of Cadino are mainly presented in [7]. Despite the first investigations have been carried out by correlating traffic data with weather data collected at a different (but nearby) monitoring site, these much more accurate analysis have been able to furthermore strengthen these initial results.Not only: thanks to reacher statistical correlation analysis, it has been possible to put the preconditions to compare seasonal traffic data despite the corresponding meteorological conditions in which they have occurred. In this way, it will be possibile to get a progressive overview of the variations of the traveling patterns and therefore have an estimation of the impact that the project is having on the local traveling audience.

In the scope of this deliverable, the focus is left on two detailed open aspects, namely:

- to which extend do **traffic flows and speeds change** in correspondence of different **precipitation events**, expressed in terms of intensity and type? And what is the **potential loss** in case dangerous road slipperiness conditions are present?

- to which extend do **traffic flows and speeds change at night**, in particular when the **road is wet** and possible ice hazards could occur?

Thanks to the capability of the monitoring station of Cadino to measure traffic conditions as well, it is possible to investigate in great detail and quantify such correlation patterns.

5.1. Traffic flows vs meteorological conditions assessment

In a first analysis, traffic records only have been considered. According to basic traffic flows fundamentals [8], two main variables have to be taken into account: the traffic flow q (typically expressed in [vehicles / hour]) and the traffic speed u (typically expressed in [kilometers / hour]). The third fundamental parameter is the traffic density speed k (typically expressed in [vehicles / km]), which is mathematically expressed in terms of the latter two variabiles. One of the most famous (and simplest) model is for example the Greenshield model, expressed as follows:

$$u = u(k) = u_f - \frac{u_f}{k_j} k$$

$$q = q(k) = u_f k - \frac{u_f}{k_j} k^2$$

$$q = q(u) = -\frac{k_j}{u_f} u^2 + k_j u$$

The relationship between flow and speed (or density) is modelled as a second order function, as plotted in Figure 28. The model is characterized by a certain number of degree of freedom, namely:

- k_j, which expresses the maximum density in correspondence of which a complete congestion of the road occurs (traffic flow and speed equal to zero), and typically indicated as “jam density”);
- u_f, which expresses the maximum speed one can experience in case of free flow conditions (density equal to zero), and typically indicated as “free-flow speed);
- q_m, which expresses somehow the optimal usage of the road (maximum flow at a certain “optimal” situation of number of vehicles u_m and density k_m). According to the Greenshield model, this optimal condition is obtained when $u_m = u_f/2$ and $k_m = k_j/2$.

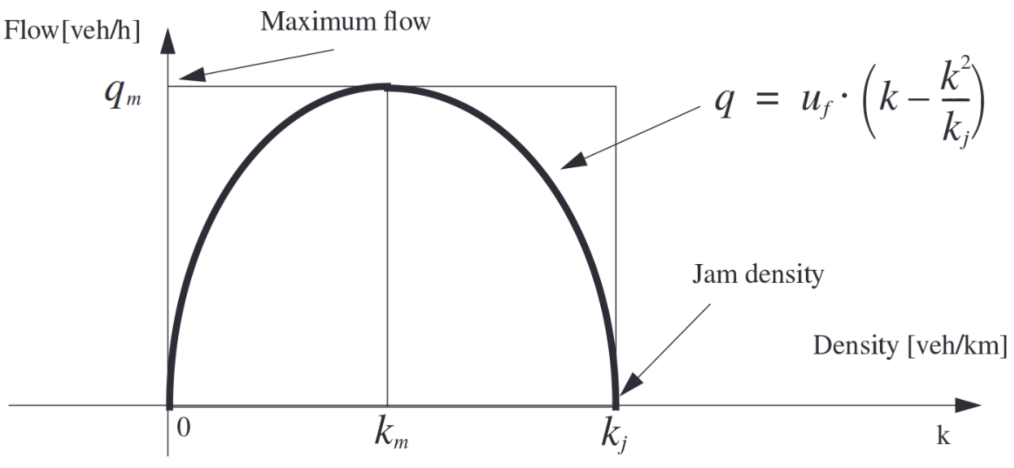

Figure 28: Theoretical relationship between traffic flow and speed according to the Greenshield model [9] .

Such theoretical behavior is possible to obtain thanks to the available collected data by plotting together the total number of vehicles counted in the time unit (in the case of study, equal to 15 [minutes]) and the average speeds. Considering together all records measured during the winter season 2013/2014 in both direction of travel, the result is the scatterplot presented in Figure 29. As one can immediately see, such a parabolic behavior can be immediately recognized. The optimal condition for the road under investigation seems to be located around the point $u_m \cong 80\ [km/h]$, $q_m \cong 130\ [vehicles/15\ min] = 520\ [vehicles/hour]$.

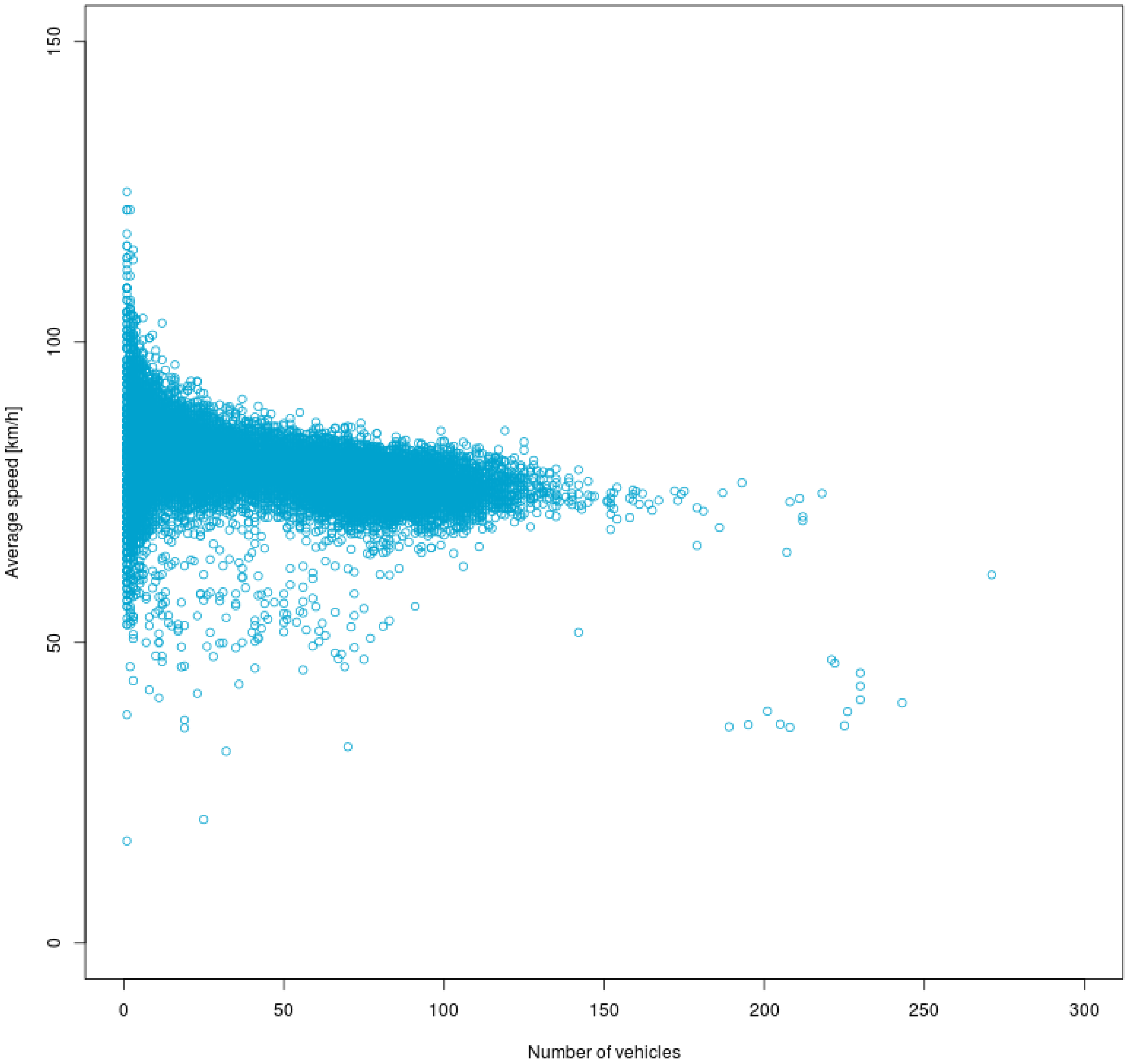

Figure 29: Scatterplot of measured fundamental traffic parameters during winter season 2013/2014.

What happens if particular road conditions occur? The answer to this question is summarized in Table 22, which presents some statistics of the traffic conditions in different situations: dry or wet road, snowfall on-going, and ice / patrol trip warning, as specified in the proposed model for the automatic estimation of the optimal road maintenance activities presented in Chapter 4 (reference threshold at 0 [°C]). According to the obtained statistics, the following considerations can be stated.

- **Dry road conditions**. This is the most likely case (about 61% of the total dataset). This is the nearest situation with respect to both the optimal case as well as the “jam density case”, as confirmed by the lowest values of gap and headway. In these conditions the impact of heavy vehicles is statistically the strongest one.

Road conditions	Nr. Intervals	Nr. Vehicles	Nr. Light Vehicles	Nr. Heavy Vehicles	Speed [km/h]	Gap [m]	Headway [m]
Dry road	12832	52	46	6	77.06	22.19	22.42
Wet road	6342	42	38	4	76.90	28.09	28.31
Ice warning	232	18	17	2	78.99	65.11	65.30
Patrol trip warning	1511	32	28	4	76.34	36.48	36.72
Snowfall on-going	165	34	29	5	60.45	32.66	33.13

Table 22: Traffic average conditions in correspondence of different road conditions.

- **Wet road conditions**. In the winter season under analysis, this has been the second case with the highest occurrence (about 30% of the total dataset). In these conditions, the level of congestion of the road is significantly lower, but the speed remains practically identical to the case of dry conditions. This probably means that the presence of wet road has the effect to reduce the typical traffic speed compared to the reference “dry” case.

- **Ice warning conditions**. In the winter season under analysis, this situation has been observed very few times (only the 1% of the total dataset). As later discussed, these records have been observed at night or in the first hours of the morning, where the road is almost entirely not congested. The possible presence of ice on the road does not seem to strongly influence the average speeds of vehicles.

- **Patrol trip warning conditions**. This condition has a stronger statistical representation (about the 7% of the total dataset). As one can expect, the obtained statistics are in the middle between the average situation obtained for wet road and ice warning conditions. What is probably the most interesting aspect to be underlined, is the slightly lower value of average speed.

- **Snowfall on-going conditions**. Despite the reduced number of observations (less than the 1%), these patterns are very interesting to understand how severe precipitation events can strongly influence the normal traffic circulation patterns. The average traffic congestion level demonstrates that snowfalls have occurred during periods of high and low traffic demand, as later confirmed. The decrease in average speeds is very relevant: about 20 [km/h] less than the other reference conditions.

In conclusion, the highest impacts on traffic conditions are typically observed in correspondence to snowfall events. Differently from what one can expect, the impact on traffic of potentially dangerous situations due to ice formation on the road (hoarfrost formation of water cover freezing) is less significant. This can explained as a function of the real perceived risk of danger on the road, which has demonstrated to be particularly low in the winter season of analysis.

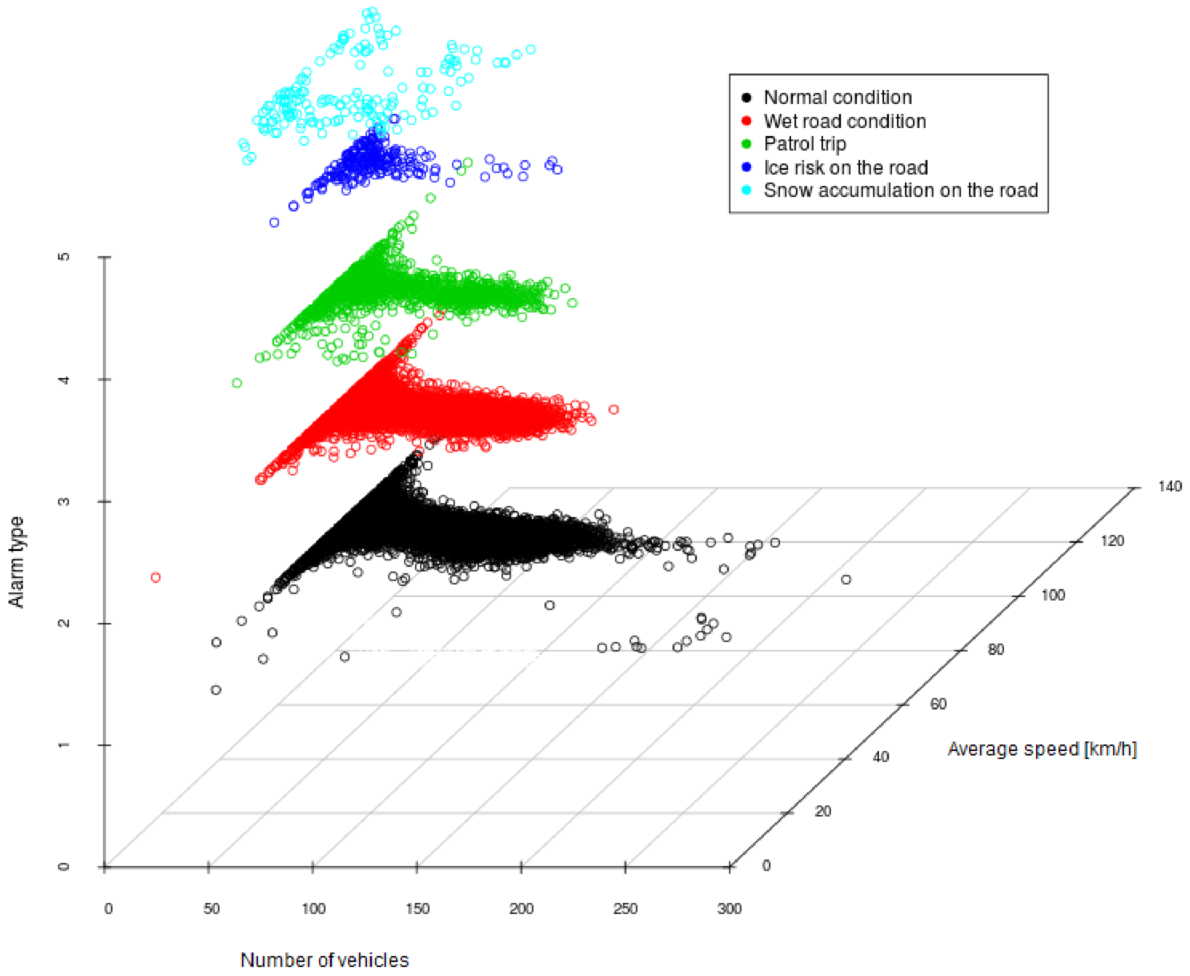

Figure 30: Scatterplot of measured fundamental traffic parameters in correspondence of different road conditions.

5.2. On the impact of traffic on RST at night

In order to better consolidate the results obtained through this first analysis, observed records have been classified in terms of records observed at night (between 10:00 PM and 6:00 AM) or during the day. This is important to distinguish between very different conditions of traffic demand, and to understand the related impact caused by particular road conditions events.

The total scatterplot of Figure 31 *Figure 30*presenting the observed patterns of number of vehicles and average speeds demonstrates the relevant difference between empirical values of maximum traffic flows q_m. At night, this value is about $q_m \cong 35\,[vehicles/15\,min] = 140\,[vehicles/hour]$, about 25% of the typical values observed during the day. On the other side, the dispersion of associated speeds is much more higher, both at high and low values. This is a very interesting result, which somehow does not confirm the preliminary considerations on the impact of potentially icy nights. In fact, this overall presentation of the traffic patterns demonstrates that speeds can range from very high values (even over the admitted speed value of 90 [km/h]) when the road is likely to be in the best conditions (i.e.

dry situation), to very low values when the road is likely to be in the "worst" conditions (i.e. ice / patrol trip / snow warnings).

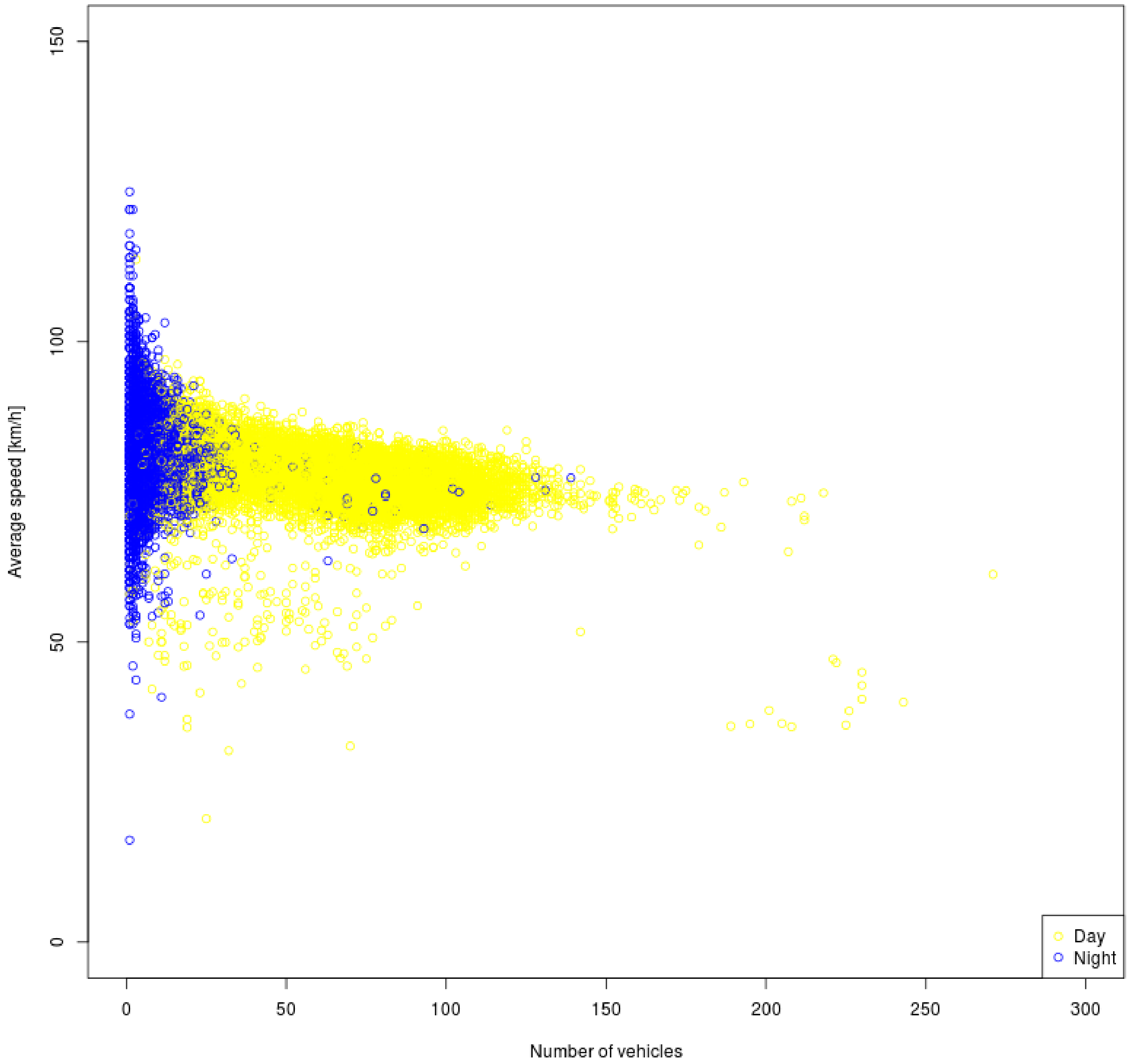

Figure 31: Scatterplot of measured fundamental traffic parameters during winter season 2013/2014: comparison between daily and nocturnal patterns.

The following scatterplots present the way observed patterns vary during the different road conditions. Following considerations can be stated.

- **Wet road conditions**. The presence of wet road conditions has only a very small effect on the dispersion of nocturnal traffic distribution. On the other side, during the day the value of observed maximum traffic flow is reduced to about $q_m \cong 115\ [vehicles/15\ min] = 460\ [vehicles/hour]$, about 20% less than the conditions of dry road.

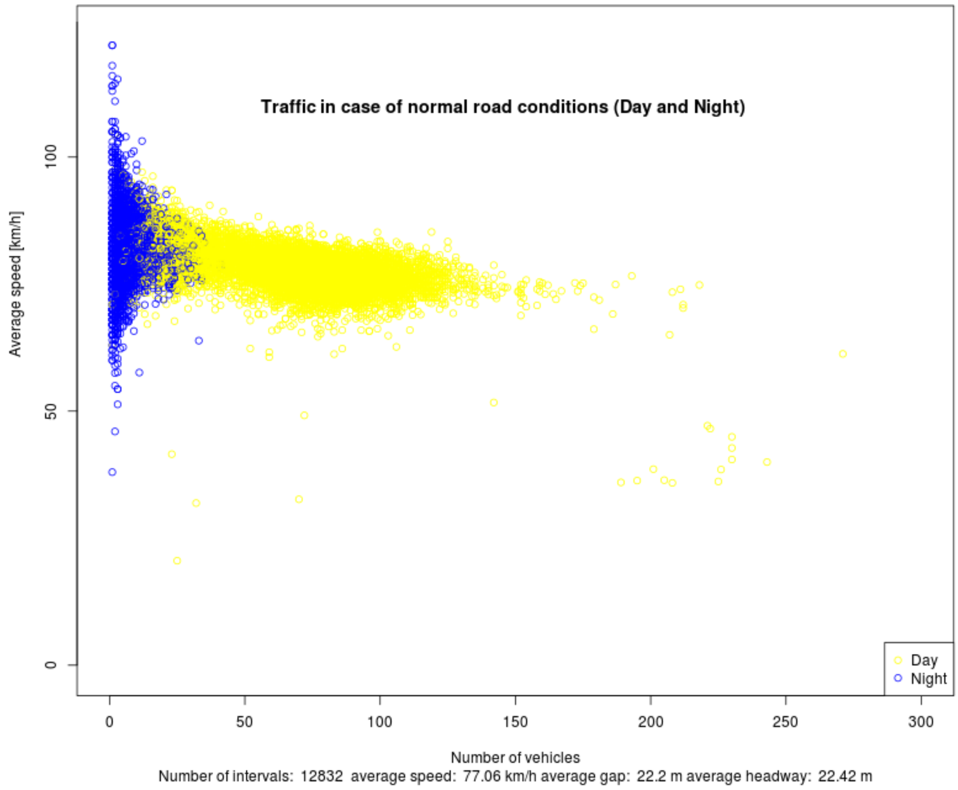

Figure 32: Scatterplot of measured fundamental traffic parameters in correspondence of dry road conditions with comparison between daily and nocturnal patterns.

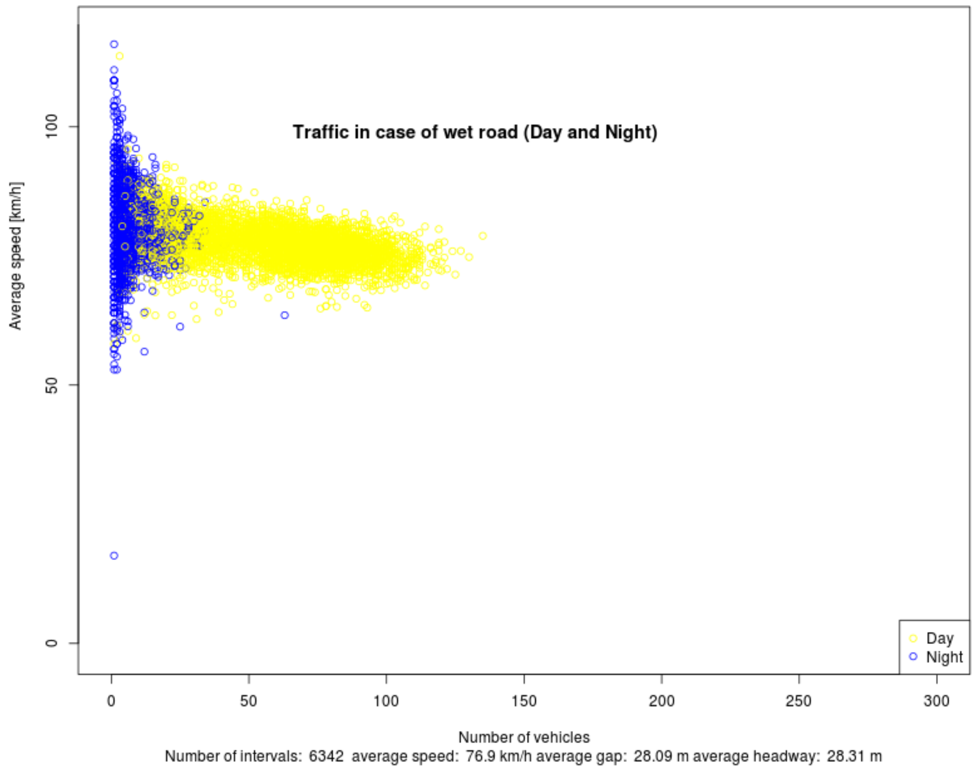

Figure 33: Scatterplot of measured fundamental traffic parameters in correspondence of wet road conditions with comparison between daily and nocturnal patterns.

- **Patrol trip / ice warning conditions**. In case of a patrol trip / ice formation warning, the dispersion of nocturnal traffic distribution is further decreased. The concentration of patterns with lower average speeds is significantly higher, but situations of vehicular transits at high speeds are still observed. The impact on daily patterns is very small, and comparable to the one observed for wet conditions.

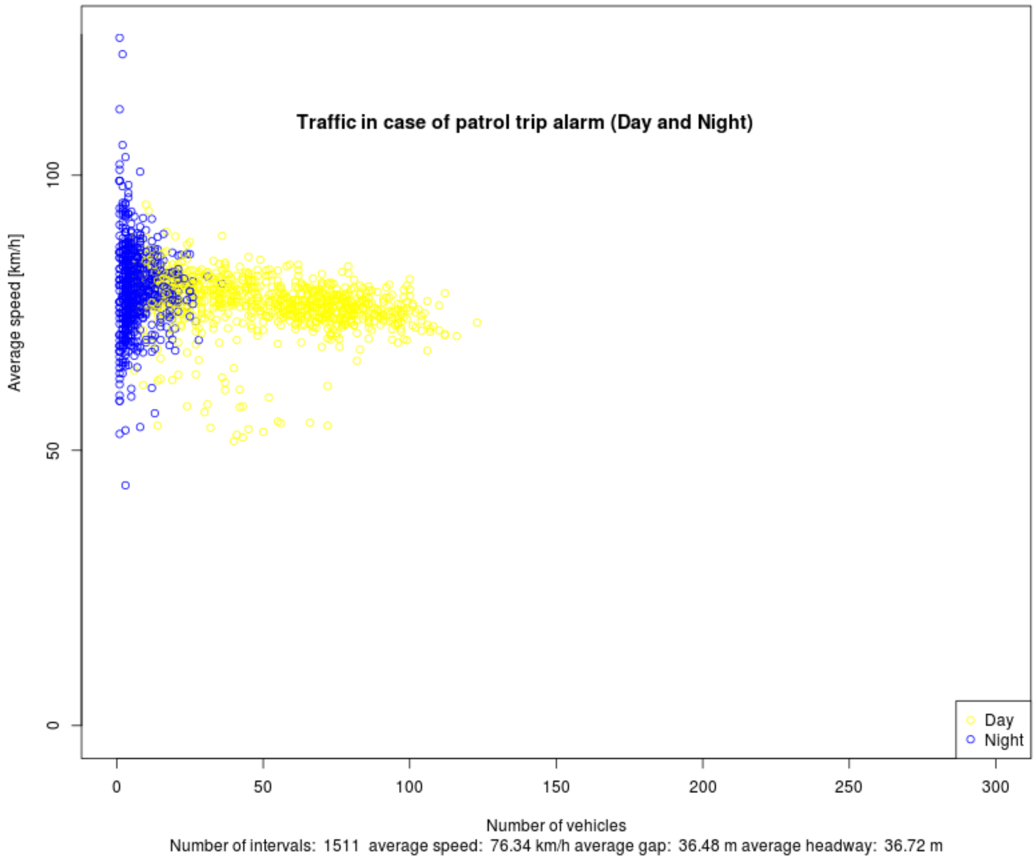

Figure 34: Scatterplot of measured fundamental traffic parameters in correspondence of patrol trips alarms with comparison between daily and nocturnal patterns.

- **Snow warning conditions**. These unfavorable conditions confirm to produce the highest impact on the normal traffic patterns, both at night and during the day. Observed patterns seem to naturally cluster together around different sub-classes, which are probably related to different snowy situations: higher speeds during conditions in which snow is not accumulating on the road, and much lower speeds (around 60 – 70 [km/h]), when such an accumulation phenomenon is taking place. The variation on daily patterns is much clearer than on nocturnal ones, both in terms of speeds as well as in terms of number of transit vehicles, as a demonstration that such precipitation events can also have a significant impact in terms of fluctuations of the mobility demand (i.e. travelers who decide to not to drive during snowfalls).

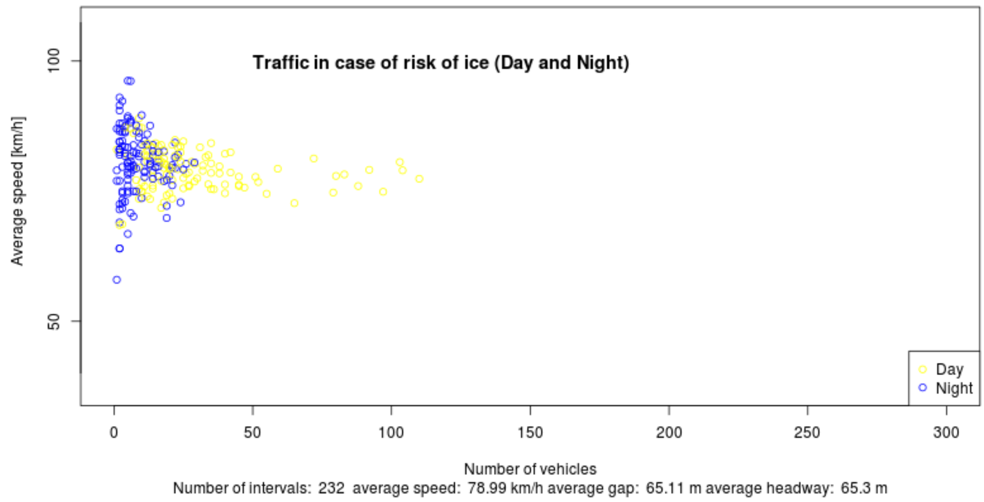

Figure 35: Scatterplot of measured fundamental traffic parameters in correspondence of alarms of icy conditions on the road with comparison between daily and nocturnal patterns.

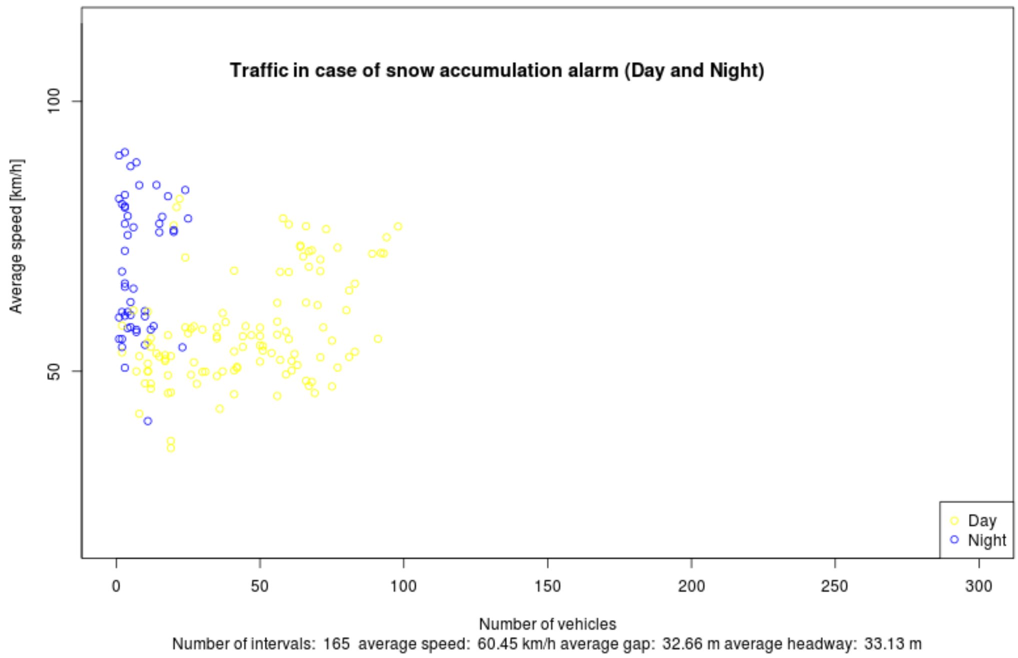

Figure 36: Scatterplot of measured fundamental traffic parameters in correspondence of alarms of snow accumulation on the road with comparison between daily and nocturnal patterns.

These considerations confirm the preliminary results of the previous paragraph, and more generally proof what was obtained during the preliminary studies carried out during winter season 2012/2013, which have evidenced a strict correlation between average daily traffic with current mobility demand and meteorological conditions. This relationship is particularly evident during snowfall events, while is much less emphasized in case of potential ice formation on the road: in this case, the perceived level of risk is much lower, comparable to what is observed when the road is simply wet. The implicite trust in road treatments activities could also play an important role in this behavior. Moreover, the very reduced number of accidents in winter demonstrate that the real level of danger in these conditions is rather low.

Conclusions

Meteorological analysis

Winter 2013-2014 was exceptional for the weather point of view. Temperatures well above average and frequent, abundant rainfalls made it one of the hottest and wettest winter seasons ever observed in the last century. These circumstances did not promote the formation of ice on the project test route. Data recorded from Cadino meteorological station indicate that ice formation occurred only five times in that location.

Salt consumption analysis

Despite the exceptional meteorological conditions, salt consumption estimated for the case study road has been higher than in winter season 2013/2014 than in 2012/2013, which has been colder and with less snow events. In both seasons the quantities of salt used have been more than 200 [q], about 140 [g] for each square meter of the case study road. As detailed in the baseline assessment results, this fact is to be associated to the **very uncertain meteorological conditions**, at the boundary between the decision to make a road treatment or not (e.g. rainy precipitation with temperatures just above 0°C).

Baseline assessment results

The **final estimation** in terms of **maximum number of treatments that can be avoided**, if one could have at disposal in advance a perfect knowledge of the road conditions in the following 12 hours, is quantified for the winter season in the order of about **63%**. If one takes in consideration **patrol trips and anti-ice treatments only**, this optimization margin is even higher, and can be estimated in the order of **79%**: 31 of the 39 observed activities have been considered in fact as unnecessary. These high percentages must be carefully read, according to the boundary conditions in which this analysis has been carried out. The first one is related to the exceptional winter season, with several situations of high uncertainity and complex operative management, further amplified by the absence of any support tools. Moreover, road operators could have been negatively influenced by the lower number of activities, if compared to what they are typically get used to: the absence of “harsh” winter conditions could have probably led to a further overestimation of the potential danger on the roads. Second, the analysis is related to a single evaluation site (Cadino), which is only in part representative of the whole road stretch that road operators have to manage. It is moreover important to underline that these estimates represent the upper boundary of the intrinsic improvement capabilities related to this challenge: a maintenance decision support system like the one introduced in CLEAN-ROADS, based on unperfect forecasts, will never be in the condition to fully exploit this unexpressed improvement potential.

Are this margins representative for a typical winter season in Trentino Alto Adige? Of course this analysis has given a very important indication of the existing optimization level that one could have in meteorological conditions that are more typical for the beginning or the end of the winter season. The results are indeed are much more in line with what was estimated during the season 2012/2013 in months like November or February and March. The conclusion is that probably a decision support system like CLEAN-ROADS could be of higher usefulness during boundary and uncertain conditions in which the gap between deciding to carry out a road treatment or not is very thin. In any case, there is the strong need to perform again similar optimization analysis in correspondence of harsher and more typical winter conditions, in order to get a more comprehensive, representative and consolidated overview of this optimization potential.

Traffic analysis

The studies covering the correlation between traffic patterns and road weather conditions have strengthen the results obtained during winter season 2012/2013. The level of usage of the case study road, according to the traffic fundamental variables density / flow / speed, is strongly related to the perceived current mobility demand and meteorological conditions. This dependancy has demonstrated to be particularly evident during important meteorological phenomena, i.e. snowfall events. On the other side, the perceived level of risk in case of potential ice formation on the road is much lower. This statement can be motivated on top of two considerations: (i) local travelers have a minor feeling that there is a danger on the road, simply because they are not informed of such a risk; and (ii) the real level of danger in these conditions is actually low, as demonstrated by the very reduced number of accidents in winter. Over sampled road treatments activities could also play an important role for further strengthening this second consideration.

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