NeTIRail

Needs Tailored Interoperable Railway Infrastructure

Deliverable D2.8

Tailoring lubrication to duty and climate: Safe, effective and eco-friendly avoidance of track wear and damage

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Executive Summary

The deliverable 2.8. is continuation report of the deliverable D2.7 “Lubrication Systems and Data Available, With Estimates of Costs and Benefits”. This report approaches the lubrication and the existing systems considering several aspects. The report prepared under NeTIRail-INFRA project for tailoring lubrication to duty and climate.

In Chapter 1 of this deliverable, the importance of the lubrication on track wear and damage is explained by examining the existing literature. During the literature research, addressing the previous deliverable, a brief analysis of lubrication systems is given. In the progress of the analysis, the working process of the lubrication systems and their pros and cons are evaluated. The summary of the analysis is presented in “Performance (Effectiveness) of the Existing Lubrication Systems” sub-chapter will be a basis for Chapter 3, namely “Selection of Lubrication Systems and Lubricants according to Climatic Conditions”. Besides, to understand what is bio-, eco- products /lubricants, related information about the environmental impacts of lubrication systems and environmentally acceptable lubricant labelling are explained briefly. The safety and health issues are important criteria for the maintenance personnel. Direct contact with the lubricant can cause the accidents, therefore, the following the environmental impacts, lubricants impacts on the safety and health are examined as well.

On the other hand, Chapter 2 was designed to focus on lubricant type and the behaviour. In the first stage, eco-friendly/biodegradable lubricants are defined, and their distinguishable characteristics are explained comparing to traditional lubricants. Depending on the lubricants types, their possible behaviours have been tried to be analysed according to basic parameters. In this stage, the effectiveness of the defined basic parameters on track wear and damage is detailed in the frame of the existing literature.

In Chapter 3, climatic conditions may have impacts on the lubrication systems are analysed in three perspectives: ambient temperature, heavy rainfall and snowing/icing. Köppen-Geiger climate classification is used to determine the suitable lubricant and lubrication system types. A selection methodology is developed in this chapter, not only restricted on Europe and Turkey. Additionally, several test and research results are used to support the developed methodology. The possible impacts of the climate and weather condition on the lubricant usage are described complying with the existing research performed in the World. All analysis results and review of the literature are arranged as an input where the selection of lubrication systems performed for the study lines in Slovenia, Romania and Turkey.

It is necessary to state that USFD, UIC, and SZ provided the necessary contributions and sent the related information and documentation which provided a base for this study. The submission date of the report was postponed by INTADER because of the internal procedures. We would like to thank our partners who provided their contribution to this deliverable and the experts who gave the necessary feedbacks to improve this deliverable content.

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Abbreviations and acronyms

Abbreviation / Acronym	Description
AAR	American Association Railroads
Banverket	The Swedish Rail Administration
BOD	Biochemical Oxygen Demand
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CoF	Coefficient of Friction
DOC	Dissolved Organic Carbon
DSB	Danske Statsbaner is the largest Danish train operating company,
Eurostar	Eurostar is a high-speed railway service connecting London with Amsterdam, Avignon, Brussels, Lille, Lyon, Marseille, Paris and Rotterdam.
FM	Friction Modifier
HKMTRC	The Mass Transit Railway is a major public transport network serving Hong Kong
ISO	International Organization for Standardization
LD	Lethal Dose
OECD	The Organisation for Economic Co-operation and Development
OSHA	Occupational Safety and Health Administration the USA
PAG	Polyalkylene Glycol
PAO	Polyalphaolefin
PG	Polyglycols
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RCF	Rolling Contact Fatigue
S&Cs	Switches and Crossings
SNCB	National Railway Company of Belgium
Spoornet	Transnet Freight Rail is a South African rail transport company, formerly known as Spoornet
ToR	Top of Rail
UIC	International Union of Railways
UN	United Nations

1 Importance of Lubrication on Decreasing Track Wear and Damage

The railway infrastructure managers have been paying very high costs for the maintenance of the track and its components. The amount generally covers at least 50,000 Euro/km/year [1], where this value can change according to line specification, traffic load, the types of the material used in the track, climatic conditions and also the usage behaviour [2]. To decrease the maintenance costs and human-based errors, recent researches have been focusing this complex system and have been trying to find solutions for reaching "effective, low power consuming, intelligent, reliable and safe" maintenance, in other words, predictive maintenance.

Considering this complex system and various operational procedures, the effective lubrication applications play a fundamental role to decrease the wear and damage on tracks where lubrication provides an adequate film thickness to decrease the friction between contact points and forms an invisible protection during the operational of the rolling stocks. By effective lubrication, the total cost of track maintenance can decrease dramatically and prolong the track life. For instance, according to American Association Railroads (AAR), American Railways spend more than USD 2 million each year to repairing or renewal for wheel/rail interface because of ineffective lubrication methods [3]. On the other hand, by using proper lubrication systems and lubricants, several countries have been able to reduce their maintenance costs dramatically. For instance, Canadian Pacific Rail announced the increment of rail life was estimated 110% by effective lubrication on their systems while HKMTRC saved £783,000 per year by using solid lubricant in wheel and rail maintenance [3]. To demonstrate in more detail, the costs of lubrication of some railway operators are given in Table 1. As seen in Table 1, the total cost of lubrication system can reach high numbers.

Table 1. Lubrication costs of some railway operators [3]

Railway	Quantity (tonnes/year)	Lubricator (£/year)	Lubricant (£/year)	Costs (£/year)
Spoornet	200	125,000	134,000	259,000
HKMTR	0.3	5,600	550	6,150
Eurostar	1.1	N/A*	N/A*	70,000
Banverket	20	N/A*	31,000 -62,000	N/A*
DSB	25	95,000	100,000	195,000
SNCB	40	1,000,000	479,000	1,479,000

*N/A represents "unknown values".

Therefore, to understand how correct application methods and selection of lubricant, considering climatic conditions and line densities can decrease track wear and damage, first of all, it is necessary to understand why track wear and damage occurs and which parameters affect the track.

It is known that the wheels of the rolling stock are sitting on the top of rail head and during the movement of the rolling stock, the contact forces between the rail and wheel are increasing. Although the total contact area is small, the amount of pressure on these contact points is excessive where the weight of the rolling stocks are transmitted to the track [4]. During the movement of the rolling stocks, specifically in switches and crossings (S&Cs), the pressure on the wheel/flange is shifting from one point to another for balancing the rolling stock. In the long time period, this creates an abrasion in the wheels and flange and also causes significant material loss of rail [2], as a result, the rail and wheels/flange start to wear out. The forces occurring in the movement of rolling stocks in the perspective of wheel and rail are demonstrated in Figure 1. As seen in Figure 1, the size of forces, lateral and vertical, affect the system changes with the movement of rolling stock. Lubrication acts as a preventive mechanism by helping to control coefficient of kinetic friction (CoF) and decreasing the impacts of the forces (especially lateral forces) that are a major cause for the derailments [4].

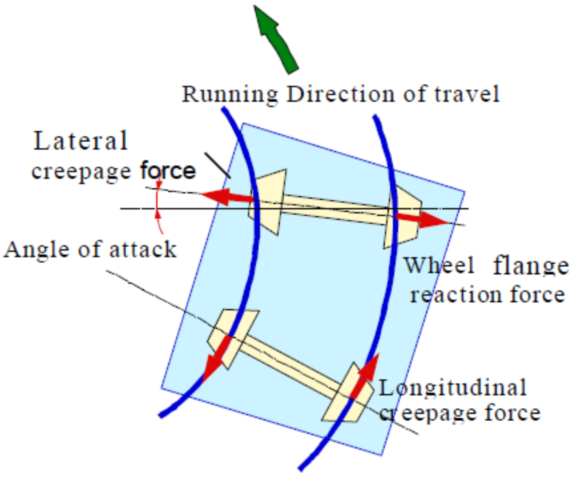

Figure 1 The forces interacting between the wheel and rail [4]

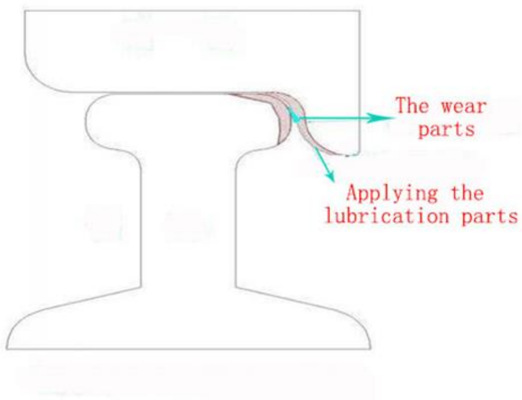

Figure 2 Application of the lubrication between wheel/flange and rail [5]

On the other hand, as shown in Figure 2, abrasion of the rail head is also an important factor for the derailment of rolling stocks and friction between wheel/flange and rail will over a long period of time, if the lubrication is not adequate and not properly selected according to the line and climate conditions. Mostly, this kind of wear is visible, however, the detection of wear and deterioration amount of the rail usually cannot be estimated during operation. Depending on this knowledge, it is necessary to emphasize that the appropriate lubrication amount and method can decrease the wear in track drastically. A study performed in 1984 where the lubrication system and lubricant components were not developed as much as today's one indicated that although the lubricant type is the same, just the amount of lubrication applied can dramatically change the track wear. The result of the study is given in Table 2.

Table 2 Rail wear rate for different lubrication levels [6]

Level of Lubrication	Wear Rate (in/mgt)	The factor of Improvement Over Dry Rail
Dry Rail	0.005-0.007	1 (Base)
Low	0.001	5
Medium	0.00029	17
High	0.000064	80

In conclusion, with appropriate lubrication methods and types, the maintenance cost can decrease tremendously as observed in directly in Canadian Pacific Rail example where efficient lubrication increased the life of high rail gauge face almost 80% by preventing rail grinding and 50 % with the usage top of rail friction modifiers [7]. After this point, the existing lubrication systems will be examined in a detail and their working mechanisms will be explained.

1.1 General Overview of the Existing Lubrication Systems

1.1.1 Wayside (On Track) Lubrication System

The wayside lubrication systems, as the name implies, are composed of various elements and integrated on the track as seen in Figure 3. The working methodology of the system is based on applying the lubricant with a wiper bar that arranged to lubricate the contact area of rail, flange or wheel. As shown in Figure 3, sensors located in the system detects and counts the axles of the rolling stocks and then sufficient amount of lubricant is applied by taking into account the location and track status that arranged by inside automatic system. The applied lubricant is carried by the wheel of rolling stocks to next locations such as upcoming curves or lines [8].

In this system, high pressure and low volume pumps are preferred because they enable the provision sufficient lubricants, in other words, to avoid the excessive usage. Therefore, this type of the wayside lubrication system also helps to prevent soil pollution/ contamination and environment damage. In addition , high pressure minimizes the clogging of the lube ports. Therefore, each lube port can receive the exact amount of grease/lubricant automatically where high-viscosity lubricant can be used in this systems [8].

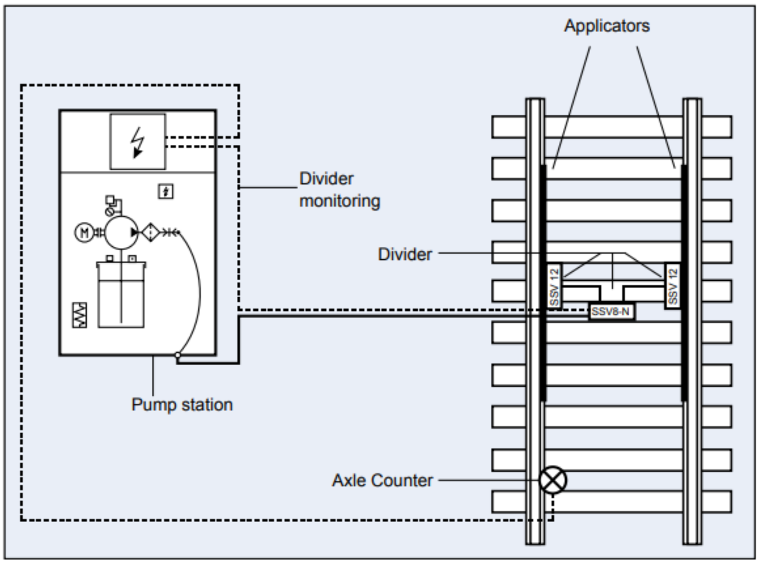

Figure 3. A typical wayside lubrication system for gauge face [9]

Lubrication of the rail and wheel-flange reduces the wear and noise raised from friction and by this way deterioration of the railway infrastructure system components will significantly decrease. Therefore, the wayside lubrication systems diversified through their service depending on their usage purposes. The main usage areas are lubrication of gauge face, top of rail (ToR) and restraining rail/check rail [8].

Lubrication of the gauge face is traditionally implemented in cases where several railway infrastructure managers have preferred because it reduces wheel-flange friction. An example of this lubrication system is given Figure 4. As seen from Figure 4, the system includes a large brush which is on the top of lube ports. When the lubricant comes out of the lube ports with high pressure, the brush helps to spread the lubricant through contact area and minimizes the migration of the lubricant to top of the rail. In addition, the large brush allows the holding of excess amounts in the system. By this way, the waste amount of lubricant can be decreased and as a result, contamination of the lubricant with soil can be significantly reduced [10]

On the other hand, the wayside systems for the top of rail protection is designed on the basis of reducing the slip-stick effect. In tight curves, the path of inner curve wheel is shorter, and the applied tension is increased then the frictional forces so that the inside wheel slips. The inside wheel shudders and the wear on the running surface of rail increases. Therefore, to prevent damage on the running surface and also impact on the wheel, a less amount of lubrication can be helpful to prolong the lifetime of rail and wheel. An example of the ToR wayside lubrication system is given in Figure 5 [10].

Figure 4. An example of the wayside lubrication systems for gauge face [10]

Figure 5. An example of the wayside lubrication system for Top-on Rail (ToR)[10]

Figure 6. An example of the wayside lubrication system for restraining rail[10]

ToR wayside lubrication systems are designed considering the Friction Modifier (FM) application without making any contact with rail and wheel. Friction Modifiers or FM are known as a water-based material including inorganic and polymeric (synthetic) materials. During the application of FM, the water part will evaporate, and finally, synthetic materials form a micro scale dry film on the top of the rail. This provides an intermediate coefficient of friction as a third body and creates an additional friction during the operation. The additional friction reduces the lateral forces and wears without compromising braking or traction [11]. Although the old version of ToR can be solely used for applying

FM and lubrication on the top of the the rail, the recent version of this systems can allow combining ToR lubrication application with gauge face lubrication.

Apart from these systems, the wayside lubrication systems can be designed for guardrails, mostly known as a restraining rail or check rail. The guard/restraining rails are used in transit systems especially in transition zones such as bridges, tunnels or viaduct etc [12] and switch and crossings. This type of rail enables the reduction of rail wear in sharp curves and increase the resistance flange climb derailment happening when vertical forces are reduced, and lateral forces are excessive that causes the flange to stop sliding along the gauge and then start to climb [13]. The wayside lubrication systems for guard/restraining rails are designed to reduce the noise pollution which occurs during contact with the flange and guard/restraining rail. Hence, by lubricating the contact area of the flange and guard/restraining rail can decrease the maintenance costs and also support the safety of the rolling stock from the derailment.

The three different wayside lubrication systems are introduced where several of them can be combined with each other depending on their design by the suppliers. It is essential to remember that these systems can work as a stand-alone, independently, so that in most cases, their maintenance and power supply have to be checked in regular periods. To secure the power supply, usually, the wayside lubrication systems are integrated with micro-scale solar panels and wind turbines or a hybrid combination of these. By this way, continuous power can provide the system during the nights as well. An example of the connection of micro-scale solar panels and wind turbines are given in Figure 7. At this point, it is essential to mention that although the wayside systems are supported by the micro-scale renewable system, they are exposed to the natural environment, in other words, weather conditions, wild animals, gnawing animals or natural disasters that increase the risk of interruption of the system other than an outage of the power.

Figure 7. An example of wayside lubrication system integrated with micro-scale solar panels and wind turbines [14]

1.1.2 On-Board Lubrication System

The on-board lubrication system is a system integrated with an attachment bracket to the bogie structure of the rolling stock. The system designed for wheel-flange lubrication and rail head conditioning. This lubrication generally provides a great advantage in terms of low installation and maintenance costs compared to the wayside lubrication systems. Because the system is integrated into the body of rolling stock, the efficiency of this system is estimated to be higher as well [8]. Like wayside lubrication system, on-board lubrication systems' pumping capacity or pressure can vary according to the type of rolling stock and the conditions on the site such as climatic conditions or deformation in the wheel/flange. As an additional advantage, maintenance of the on-board lubrication system is easier than wayside lubrication systems and because they are integrated on the part of the bogie, the damage risk is much lower than with wayside lubrication systems. Another perspective is that they can easily be installed without considering looking at the location parameters and can easily be monitored by using software applications. Therefore, in case of a malfunction, the elements of the system can be removed and/or changed within a short time which provides efficiency and great convenience for the remote area applications [15].

On-board lubrication systems are divided into the lubricant types: on-board spray or solid sticks. The on-board spray types are generally designed by taking into account low viscosity greases and biodegradable liquid lubricants. Because of their usage availability, depending on the liquid lubricant type, sometimes they can combine with Friction Modifiers (FM) or can dilute with additional additives such as kerosene [15].

Spray (grease) on-board lubrication systems are commonly used in Europe. The system includes a lubricant reservoir and depending on the design the system can be fine-tuned. The working mechanism of the system is similar to wayside lubrication system where lubrication reservoir pumps the lubricant to the spray nozzle with the help of the air and high pressure. The applied lubricant is transmitted to the wheel/flange area and then transferred to the gauge face of the rail [8].

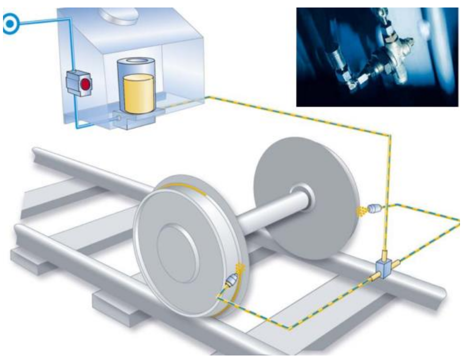

Figure 8. An example of on-board lubrication system with a spray application [15]

Another commonly known type is the solid stick application. The solid lube stick is dry lubricant and there are several types and designs based on its thickness and hardness. These systems provide a great advantage in terms of their application, maintenance and environment [8]. Because the solid stick is dry, the occurrence of the soil contamination/ pollution issue is close to zero which indirectly indicates that the maximum usage efficiency can be reached. Generally, solid sticks are composed of thermosetting resins which occur by using synthetic materials like vinyl ester, polyurethane, silicone and polyamide. Therefore, their degradation in the environment is slightly difficult because of complex structure compared to other lubrication types [16]. In Figure 9, an example of the usage of on-board lubrication type with the solid sticks is demonstrated for both metro systems and locomotive systems. As seen, the general logic of the system is similar to spray application, but for this case, the attachment bracket and applicator have to be designed considering the weight of the solid sticks. Usually, solid sticks can be used for at least one month and changed during the general inspection or maintenance activities [17].

Figure 9. An example of on-board lubrication system with a solid stick application[18]

1.1.3 High Rail Lubrication System

High Rail lubrication systems depend on vehicle-based lubrication systems as seen in Figure 10 where it is attached to end of the vehicle. This system is designed to apply spray lubricants to the track [8]. The system is not commonly used because of their inefficiencies and difficulties in their management. This system has several disadvantages comparing other lubrication systems mentioned before [19].

Figure 10. An example of hi-rail lubrication system[8]

1.2 Examination of the Existing Lubrication Systems

1.2.1 Performance (Effectiveness) of the Existing Lubrication Systems

Table 3. Comparison of existing lubrication systems

Lubrication System Type	Pros	Cons
Wayside Lubrication System	▪ The high contact area between rail and wheel/flange ▪ Easily to detect the trouble points in the track ▪ Combination of gauge face and ToR within one system ▪ No clog lubrication because of implementation of the high pressure ▪ Exact metering ▪ Able to work in island mode (off-grid) ▪ Integration with micro-scale renewable energy sources ▪ Availability of spare parts	▪ High maintenance and repair cost ▪ Exposed to the environment and extreme weather ▪ Difficulty in monitoring the system in remote areas ▪ Need to continuously replenishment due to weather conditions and track situation
On-board Lubrication System	▪ High implementation area between rail and wheel/flange ▪ No mechanical contact ▪ Applicable to both liquid and solid lubricants ▪ High reliability ▪ Exact metering ▪ Demand-driven activation (curve, time etc.) ▪ Easy to install and to perform the maintenance ▪ Low maintenance cost ▪ More protected from environmental damages compared to other lubrication systems ▪ High efficiency in extreme weather and harsh environmental conditions	▪ High installation cost ▪ Not having any mechanism to prevent contamination of soil for liquid lubricants ▪ Not having any mechanism to prevent the fall of solid sticks
High Rail Lubrication System	▪ Convenient to pump high viscosity lubricants ▪ Taking a long time to apply the lubricants ▪ Less protected from environmental damages ▪ Applicable in usually during periodic inspections ▪ Applicable for shorter and plain lines	▪ Restricted application area ▪ Usually applied manually ▪ High cost ▪ Low monitoring abilities ▪ Low efficiency for application of lubricants ▪ Difficult to find repair parts because of not commonly used in several countries

According to Table 3, as seen, the on-board lubrication systems are more advantageous than wayside lubrication and hi-rail lubrication systems. Hi-rail lubrication systems are generally used on in-service rolling stock such as metro trains etc. depending on its design, it is not usually preferred where the possession of track is required. It also decreases the track availability during high traffic conditions. On the other hand, wayside and on-board lubrication systems propose more efficiency during the lubrication. The research performed in Sweden about the effectiveness of lubrication systems considering the consumption of the lubricant showed that wayside lubrication systems consume nearly 20 ton where this amount can be lowered to 11 ton for on-board systems [20].

1.2.2 Environmental Perspective

The impacts of lubrication systems and lubricants are still discussed where the large amount of lubricants are consumed during the operations. For example, the total quantity of lubricants sold in Sweden in 2004 reached to 163 500 m^3 where this amount includes the recycled, disposed of lubricants and also total loss lubricants during the application. Hence, considering this large amount consumed, there is a high possibility to contaminate the soil and eventually groundwater while using a large number of lubricants where most of them include toxic materials although they are classified as biodegradable. Another example from Sweden shows that pollution from a wayside lubrication system on its the surroundings and applied area can reach to 50 -150 kg of lubricants annually for 10 consecutive years [20]. Hence, in this section, environmental impacts of lubrication systems and environmentally acceptable lubricant labelling are explained briefly. The biodegradability issue for the lubricants will be explained in the following Chapter “Lubrication Types and Behaviour” part.

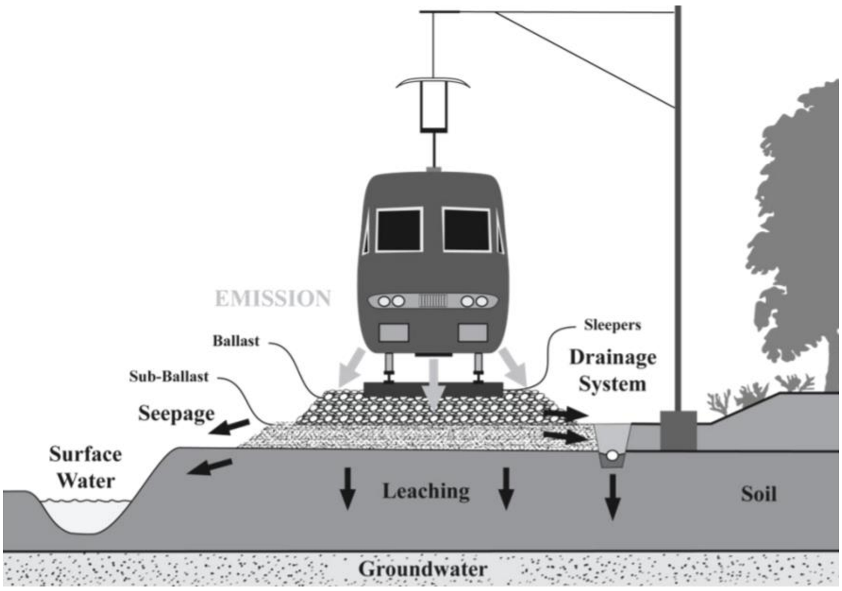

Figure 11. Contamination mechanism for the rail lubricants [21]

The possible environmental impacts of the lubrication system are related to their life cycle time and also the contamination of the soil or surface/ground water. For the lubrication systems defined in previous sections, in terms of their working mechanisms, contamination of soil and groundwater can be classified as a major environmental impact [21]. Especially for the lubrication systems with spray mechanisms (all type of the wayside lubrication systems and on-board spray lubrication system), the fine-tuning of the pumping mechanism must be necessary to avoid excessive usage of lubricants where this excessive amount does not stay on the wheel/flange or the rail top, but in progress of time, a recognizable amount transfer to soil or ballast section of the track depending on the track geometry, wear or cracks on the rail and also selected lubricant type [21]. It is necessary to emphasize that if the material loss in the track is high and also microscale cracks exists, excessive usage of lubricant can lead to increasing the wear and damage on the rail by filling the gaps in the rail surface and cracks and with extreme weather conditions and material reactions (chemical reactions like oxidizability). Therefore, during the selection of a lubrication system, their usage area (plain line, switches and crossings, line type, rolling stock types etc.), track condition, location and placement for wayside lubrication systems, the combination with several lubricant types, pumpability rate and preferred lubricant characteristic should be considered [22].

The track system and its components are in an intense interaction between each other, so it is impossible to eliminate all major factors during the selection of the lubricants and lubrication systems. Therefore, it can be suggested the railway operators use lubrication systems which have preventative mechanisms such as wiped bars or high capability for monitoring.

Although environmental concerns in lubrication systems basically lie on the lubrication system working condition parameters such as pumping, fine tuning of the small mechanisms, nozzle scale, the pressure amount etc., as predicted, the majority of the impacts are caused by lubricant type. However, these impacts cannot be categorized in detail without performing specific tests in several areas [23]. Before starting to explain the mentioned labelling programs, it is necessary to give a brief introduction about the primary criteria used for these specific tests.

Toxicity simply can be described as the quality and quantity of toxic materials which cause the major harm or irreversible damage to the receiving environment or on alive organisms. In terms of toxicity, as a parameter ***aquatic toxicity*** is preferred because living organisms in water have low resistance to toxicity and they are more sensitive even when their environment has a low quantity of toxic materials or under low exposure times. Because there is a high-risk of contamination with groundwater and surface water, aquatic toxicity is critical parameter during the evaluation phase of the lubricants. It also has to be used for lubricants because the majority of them generally include constituting substance such as thickening agent or additives. Besides, lubricants have to be evaluated according to OECD 201 and 202 to determine their acute and chronic toxicity levels. To measure their toxicity levels, Lethal Concentration, mostly known as ***Lethal Dose (LD)*** (defined as the critic amount of a toxic agent which is sufficient amount to kill half of the sample population of a specific test-organism in a certain time) is used as a major parameter. Therefore, several suppliers have to state the LD_{50} values of the lubricant in the technical sheets to state the harmful level of their products.

Biodegradability and bioaccumulation are different terms although they are used in the same way for several suppliers [24]. The majority of the suppliers prefers to take OECD 301 test to measure their lubricants biodegradability. The detailed explanation about biodegradability and the tests determining the biodegradability level of a product will be given in Chapter 2. ***Biodegradability*** is defined as the product can be broken down into simple components by microorganism/bacteria activities found in nature or dissolve naturally. The final elements of the product must be available in the form of carbon, hydrogen, oxygen, water or their simple derivatives that have weak bonds. On the other hand, bioaccumulation refers to the toxicity amount accumulating through the food chain [25]. OECD

107,117 and 123 tests determine the bioaccumulation potential for lubricants, most of the percentage of which is composed of organic compounds.

Hazard (Dangerous) materials: To classify as an environmentally acceptable, the lubricant should not contain the components listed in "R-phrases" (risk phrases) defined by European Union Dangerous Preparation Directive. The risk phrases mainly refer to explosiveness, flammability, carcinogenic potential, volatility, potential to cause birth defects etc. of the products [23].

Restricted substances: Halogenated organic compounds, nitrite compounds, metals or metallic compounds (exception of sodium-, potassium-, magnesium-, lithium-, aluminium-, and calcium based soaps used in several cases) should not be included as the lubricant components [23].

Renewable content: This term refers to the content of the lubricant which have potential to be recycled. In most cases, lubricants use vegetable oils or animal fats as a base oil or main components and can be classified as renewable although at least 45-50 % of them include greases or two-stroke oils[23].

A few international institutions in Europe classify the environmentally acceptable lubricants according to their possible impacts based on their components (mainly, defined criteria in above) and characteristic behaviour by defining labels similar to eco-labels [23]. The labels examined under this section are:

- *Blue Angel*
- *Swedish Standard*
- *Nordic Swan*
- *European Eco-Label*

Figure 12. Labels for environmentally accepted lubricants [26],[27],[28],[29]

Blue Angel: It is the first national scheme for lubricants developed by Germany in 1988. This labelling is used on several lubricant types including hydraulic fluids, oils and greases. To obtain this label, lubricants are classified according to their characteristics by taking into account biodegradability rate, toxicity level, bio-accumulation level, and hazard level. The labelled lubricant also needs to pass through OECD tests 301A-301F to measure ultimate biodegradability or CEC L-33-A-934 to measure primary biodegradability. On the other hand, Blue Angel does not have any conditions for renewability, in other words, petroleum derived lubricants can achieve the Blue Angel certification [23].

Swedish Standard: This standard generally used to classify hydraulic fluids (SS155434) and greases (SS 155470). This standard includes biodegradability and aquatic toxicity tests by taking into account the lubrication components and their formulation structure. Usually, the Swedish Standard prefers to use ISO 9439 test to evaluate the biodegradability and has unique evaluation parameters such as renewable resource content etc. Its uniqueness came from its developing stage where at the beginning, it is developed as a collaborative project between government and industry [23].

Nordic Swan: This labelling program was developed with the contribution of Norway, Sweden, Finland, Iceland and Denmark. In the beginning, the program was designed to introduce a labelling system for hydraulic oil, two-stroke oil, grease, and transmission and gear oil. Technical performance of lubricants, renewability, aquatic toxicity levels and biodegradability are the main evaluation parameters to obtain the Nordic Swan certificate. It also has a high renewability criterion (at least 50-65% renewable content) among the other labelling programme, thereof, only a few lubricants can fulfil the requirements' defined by Nordic Swan programme [23].

European Eco-Label: The European Union has developed Eco-label for the products which can be acceptable environmentally. It is the first major advancement to create a single international standard which can be applicable in several countries. The eco-label for lubricants was developed in 2005 that it covers several types of lubricants such as hydraulic fluids, greases, loss lubricant etc. The labelling as expected covers seven (7) main criteria: Biodegradability, aquatic toxicity, bioaccumulation and the presence of certain classes of toxic substances. This label aims to decrease the possible impacts of the lubricants on water and soil during their usage [23].

1.2.3 Safety and Health Perspective

During the past decade, the industrial sector has been trying to take serious precautions to prevent industrial accidents and to decrease especially hazard accidents. The lubricants, which are accepted as an industrial product even if defined as a biodegradable, have to be pass through specific safety standards to take the internationally approved certification. These standards established by the well-known institutions define the harmful levelness of the lubricants. The commonly known are ISO 45001: Occupational health and safety management systems – Requirements, ISO 9001: Quality Management, ISO 14001: Environmental Management, ISO 21469: Certification for Lubricants, ILO-OSH 2001: Guidelines on occupational safety and health management systems and OSHA Hazard Communication Standard. Apart from these international standards, domestic regulation enforced the suppliers to comply with the determined criteria. For instance, if the rail lubricant produced in the USA has a certificate to comply with OSHA, it also complies with domestic standards such as Clean Water

Act or United States Inventory. Another example is from European Union regulation Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). The most chemical producers, including lubricant manufacturers, must comply this regulation obligation. In this section brief information about the safety and health concerns about the lubrication systems and lubricants will be given.

Safety of the lubrication systems can be provided through mostly training of the maintenance personnel and also by developing a mechanism or structure that enables precautions and monitoring of the maintenance personnel. The reason is that although the lubrication systems mechanisms are either automatic or partially manual, human behaviour my lead to accidents such as during the maintenance wayside lubrication systems integrated with renewable energy sources, because of short circuit in its system, the maintenance personnel can expose to small electric shocks or although the on-board lubrication systems are called as the safest systems, there is high possibility of contact with the solid sticks during the changing procedure. For this reason, even though the lubrication systems are small and a simple part of the maintenance procedure, it is an open system which can result in usually minor accidents.

To develop protective measures, first of all it is necessary to know the possible negative impacts of lubricants and its systems on health. According to OSHA standard and ISO standard, the lubricants are evaluated for their impacts on health. For lubricants common damages to the human body are serious eye irritation, inhalation, skin contact and ingestion. For instance, direct contamination with liquid lubricants can result in skin and eye irritation because of the vaporization process and/or their adhesion capabilities. For instance, during the changing of the nozzles where the lubricant is pumped with high air pressure or force, the sprayed product can reach eyes that results in eye irritation and the worst is the partial loss of vision. For the solid lubricants, they do not cause the major accidents as much as liquid ones; however, during the changing of the solid stick, maintenance personnel should be careful.

In this chapter, safety and health issues are not covered in a detail because the liquid products have the similar negative impacts on the health. Therefore, the perspective is turned way to look at the protection of maintenance personnel.

Spilling and fire: During the storing the bulk fluids, it is impossible to eliminate the risk of some spills of contaminant. There are several methods which can be used such as special sponges, or solvent to remove or absorb the spill. However, in case of the spilling, the safety procedure must be to remove the lubricant material immediately. The reason is that most of the lubricants are flammable so any sparks coming from nearby would ignite the lubricant [30]. In case of the rail lubrication systems and lubricants, the procedure should be same for wayside lubrication systems as well as liquid lubricants.

Chemical exposure: Majority of the mineral-based fluids are mainly benign. However, they are not completely safe, in case of contact with the mineral based lubricant with a bare hand will lead to skin irritation. The lubricants can be potentially hazardous. Considering their hazard level, the necessary precautions such as wearing industrial gloves and eye and face protection should be taken [30]. For the lubrication systems, it is necessary to wear the obligatory protective equipment: hand protection, eye and face protection, and protective footwear.

Machinery interaction: The physical act of interaction will happen during re-greasing a bearing, visually inspecting a machine, taking an oil sample, or repairing equipment due to a lubrication-related failure. There is always a potential for injury from falling. Therefore, before working with lubricants, their content and impacts have to be known to protect the maintenance /inspection personnel. This background can be prepared by giving essential training to personnel and certificate them according to the international standards [30].

Apart from these, lubricant systems can have safety issues such as clogging of the nozzles or electrial short circuit etc. Therefore, during the inspection, refilling procedure as well as the maintaining, the obligatory protective equipment/clothes must be wear.

Other standards related to lubrication system and reference methods/standards are defined in below as stated in D2.7. “Lubrication Systems and Data Available, With Estimates of Costs and Benefits”.

- *EN 15427 Railway applications – Wheel/Rail Friction Management - Flange Lubrication;*
- *EN 16028 Railway Application – Wheel/Rail Friction Management - Lubricants For trainborne And Trackside Applications;*
- *EN 13674-1 Railway Applications - Track - Rail - Part 1 Vignole Railway Rails 46 Kg/M and Above;*
- *UIC 510-2 Trailing Stock: Wheels And Wheelsets. Conditions Concerning The Use Of Wheels Of Various Diameters;*
- *EN 13715 Railway Applications - Wheelsets And Bogies - Wheels - Wheels Tread?; ISO 9001 Quality Management Systems.*

2 Lubrication Types and Their Behaviour

2.1 Lubrication Types: Eco-friendly / Biodegradable Lubricants and Their Distinguishable Characteristics

After Rio +20 Conference and Paris Agreement in 2015, the industry has continued its way to pass through low-carbon development especially in the transportation sector. The global trends, in 2014, "Low Carbon Rail Transport Challenge Action Plan" was published United Nations (UN) with the support of UIC. According to the Action Plan, 50% reduction in specific average CO_2 emissions for train operations are stated and the actions are gathered around energy efficiency and management, decarbonization of electricity supply, improving load factors, procurement of more efficient rolling stocks and efficient driving [31]. Therefore, operation and maintenance of railway systems have gained more importance than before where they have a direct impact on the factors stated in the Action Plan. Under this scope lubrication of rail and wheel/flange have significant importance to decrease track wear and damage which provides a high advantage during management of the operation and decreasing the maintenance cost of the railway systems.

A lubrication formula can include many additives and agents addressed to application areas and performance issues. Additives can be used depending on oxidative aging, corrosion, high pressure and low and high temperature [23]. In railways systems, traditional methods of lubrication are based on using oil-based derived products (mainly grease) with additives such as kerosene. For instance, the grease used in wheel/flange usually contains base oil, 10% of thickening agent and various additives. Therefore, chemical compositions of traditional lubricants are highly complex so that majority of them are indigestible in the environment. Considering the application amounts and periods used in the systems and having uncertainties in traditional lubricants effectiveness on the railway systems, one of the factors disregarded for a very long time has surfaced lately, which is "residence time" both in the system and on its surroundings.

The large portion of lubricants lost in the environment also cause several health problems, mostly known are cancer and asthma (respiratory tract diseases), and irreparable damage on the environment such as soil contamination, pollution of surface waters and underground waters/aquifers etc [32]. As a consequence, with the movement to greener growth in the railway sector, a question directed to suppliers and authorization/operation bodies is: "Could the traditional lubricants easily breakdown or tolerated by nature? Or are there any substitute which have lower impacts on human health and the environment?" Hence, the new concepts raised as a consequence of these questions which are called "eco-friendly", "environment friendly" or "biodegradable" lubricants.

The lubricants referred as eco- or bio- usually include mineral oil, synthetic, vegetable oil as a base. Sometimes, petroleum derived oils, where their formulas can be easily broken down by the microorganisms/bacteria in the environment, are used with the various type of additives which can be classified as biodegradable lubricants [33]. These types of lubricants are developed considering three basic parameters: biodegradability, toxicity and bioaccumulation potentials [23]. It cannot be said that eco-friendly or biodegradable lubricants have a zero impact on the environment but can be said that they are less harmful than traditional lubricants.

To estimate the biodegradability of a product, various tests must be applied according to OECD 301C or CEC-L-33-A-93 test (Biodegradation Test Procedure) and other tests detailed explained in Table 4. The fixed tests are defined as toxicity studies with daphnia magna fish and element analysis for oxygen, carbon, hydrogen, nitrogen and sulphur [34],[35]. It is important to note that passing these tests just represent the product content/context are under the acceptable limits. Additionally, some parameters such as "aquatic toxicity" are provided by the manufacturer of the product [36]. Hence, during the selection of the lubricant, the technical data sheet provided by the manufacturers should be carefully examined before purchasing procedure.

Table 4. Internationally Standardized Test Methods for Measuring Biodegradability [23]

Test Type	Test Name	Measured Parameter	Pass Level	Method
Ready Biodegradability (If a substance has a lower than %20 biodegradability, it is classified as inherently biodegradable)	DDAT	DOC	≥70	OECD 301A
	Strum test	CO_2	≥60	OECD 301B
	MITI test	DOC	≥70	OECD 301C
	Closed Bottle test	BOD/COD	≥60	OECD 301D
	MOST	DOC	≥70	OECD 301E
	Sapromat	BOD/COD	≥60	OECD 301F
	Strum test	CO_2	≥60	ASTM D-5864
	Shake flask test	CO_2	≥60	EPA 560/6 -82 -003
	BODIS test	BOD/COD	≥60	ISO 10708
Hydrocarbon degradability	CEC test	Infrared Spectrum	≥80	CEC L-33-A-934
Screening tests (semi-official)	CO_2 headspace test	CO_2	≥60	ISO 14593

DOC: Dissolved organic carbon; BOD: Biochemical oxygen demand; COD: Chemical oxygen demand

Despite their interrogable nature, OECD divided biodegradable lubricants in two ways: ***"inherently biodegradable"*** and ***"readily biodegradable".*** Inherently biodegradable means the lubricant will turn into its natural state when it exposed to sunlight, water and microbial activities. The biodegradable percentage is changing from 20% to 60 % in 28 days. On the other hand, readily biodegradable means that the product has a natural ability to be degraded or dissolve in nature while it is exposed to sunlight, water and microbial activities. The biodegradable percentage for readily biodegradable products generally range from 60 % to 100 % in 28 days [37].

As stated previously, eco- or bio- lubricants have various bases but the majority of them use mineral oil, synthetic, vegetable oil as a base. The amount of the base is generally higher than thickening agent and various additives amounts. As seen from Table 5, when the base components of the lubricant are turning to complex structures or more synthetic combinations, the biodegradability rate also decreases.

On the other hand, solid lubricants are mainly composed of polymer components or synthetic esters and the majority of them cannot pass the biodegradability test because of their stiffness and hardness to which it is needed to use several additives such as "lithium".

Table 5. Typical test results for lubricants[36]

Lubricant Type	Primary Biodegraded Quantity
Vegetable Oils	70-100 %
Polyols and Diesters	55-100 %
White Oils	25-45 %
Mineral	15-35 %
Polyalkylene Glycol (PAG)	15-20 %
Polyalphaolefin (PAO)	5-30 %
Polyether	0-25 %

2.2 Lubricants Behaviour

2.2.1 Basic Parameters Determining the Behaviour of the Lubricants

To clearly understand the behaviour of the lubricants and also to select the correct/appropriate lubricants for the lubrication system, it is essential to know the basic parameters which describe and specific the lubricants characteristics'. The basic parameters are viscosity, viscosity index, flash point, pour point, autoignition point and base oil.

Viscosity described as resistance to flow of a liquid. The higher lubricant's viscosity means that the thicker it is and the more energy required to move an object through the oil. [38]

Viscosity Index (VI) is the index describes the reaction of the viscosity with change in temperature. When the temperature increases the viscosity parameter is decreased. Higher viscosity indexes mean more stable oil viscosity and less change in viscosity in case of temperature changes [38].

Pour point is the lowest temperature that the lubricant will flow. In other words, it is the minimum temperature that lubricant will be able to operate [39].

Flash Point and Autoignition Point are important concepts since the lubrication sometimes can burn through wheel/flange-rail movements. Flash point is defined as a temperature when the lubricant can vaporize or can be ignited by an external intervention. Autoignition point is described as a temperature where external intervention is not needed to ignite the lubricant. In other words, if a lubricant can reach the autoignition temperature it can burn itself without any external igniter [40].

Base Oil refers to lubrication grade oils that are derived from petroleum, in other words, it is an oil that is obtained through the physical and chemical process of the petroleum. The base oil can be obtained refining of crude oil, called as mineral based oil, and also through a chemical process, such as a synthetic base oil. In addition vegetable oil, synthetic ester, PAG can be defined as a base oil as well [41].

Apart from these basic parameters belonging to lubricant characteristics, lubricity, retentivity (residence time) and pumpability are also important characteristics because of their impacts on the operational process of the lubrication systems.

Lubricity addresses the lubricant capacity to reduce the friction so that reduce the track wear and damage. Majority of the lubricants can provide less than 0.25 friction value. The lubricity is a rare factor used during selection the lubricants [42].

Retentivity or Residence time is the time the lubricant is able to retain on the applied surface. There is an indirect relationship between the residence time and the load. If the load in the applied surface is increasing, the residence time is decreasing. The same relationship occurs between the residence time and creepage as well where the retentivity decreases, the creepage increases [42].

Pumpability is an important parameter for demonstrating that the lubricant is delivered continuously. This significant parameter becomes crucial in the extreme weather conditions where the temperature change gap is rather high[42].

2.2.2 The effectiveness of Defined Basic Parameters on Track Wear and Damage

Considering the extensive experiments and tests performed on lubrications, the specific research on lubrication used in track components are restricted. The manufacturers/suppliers offer a large range of lubricants and lubrication systems. These companies specify their lubricant properties usually based on usage area and the results gathered through several tests, but only a few of them propose appropriate lubrication systems and lubricant considering the customer needs. A small questionnaire (verbally and written), given in Annex I, was performed during the preparation of D2.8 and demonstrated that the majority of suppliers do not inform their customers about the detailed characteristics/behaviour of lubricants. It is confirmed that they have categorized their products according to their usage areas such as switches and crossings, plain line, motor bearing, door mechanisms and pantograph line etc. During the communication stage, it is also observed that several suppliers do not provide detailed technical sheets to their customers and give the defined basic parameters. The current situation is supported by a research performed in 2006. According to this research, the suppliers' specify their products based on their properties, mainly specific soap type, solid lubricants and suitability for grease applicators [43].

The soap type is preferred because of two main reasons. One of them is that it enables the temperature to stabilize so that pumping of lubricant (usual grease) becomes easy and spilling risk can be avoided. Another reason is water resistance, in adverse weather conditions, the residence time of lubricant between wheel/flange-rail increases. On the other hand, the solid lubricants have recently started to be used where it provides great convenience for installation and maintenance. However, its effectiveness is still in question [43]. As a consequence, it is difficult to say which lubricants or lubrication systems are the best without analysing the current condition of track and maintenance procedure.

This section is based on reviewing all the basic parameters described in the previous section. Therefore, during the examination track conditions, maintenance procedures and also usage area characteristics such as track condition, curves, switches and crossings are neglected. On the other hand, basic parameters of lubricants, lubricants and their integrated system provide track wear protection and noise prevention on the rail head are examined.

In terms of the basic parameters, base oil, viscosity, viscosity index, water resistance and flash point are the main parameters during the selection procedure. An area of the research performed during

NETIRAIL project and published 2017 demonstrated that two parameters come the fore during the selection of the lubricants for the switches and crossings. The research emphasized that the viscosity must provide sufficient thickness to form a film and reduce the track wear in S&Cs and also the viscosity must be thinner where it should not prevent the flow rate to spread onto the contact area. In addition to this, the research performed during this project stated that the high viscosity index means low change in viscosity during the temperature variations. However, it is important to remember that lubricants used in railway sector includes several additives and also thickening agents with high chance to change the base lubricant behaviour under certain conditions such as temperature increase [44]. In consequence, the selection of the lubrication cannot be made just by looking at the basic characteristics of the lubricants and its usage area, on the contrary, specific parameters and conditions likewise track condition, track geometry, applied area weather conditions, used additives and thickening agents must be considered.

After this point, to pass through the low carbon growth in the railway sector, biodegradable lubricants and their basic characteristics are defined. The reason to focus on the biodegradable products is that firstly, UIC, the partner of this project, and UN have serious targets defined in the “Low Carbon Rail Transport Challenge Action Plan” which aims to decrease the CO_2 equivalent releases in railway sector while improving railway sector in perspective of health, safety, environment, energy and also railway management. To reach the mentioned targets, biodegradable products have an effect to decrease track wear and damage while damaging nature less than the traditional products. Hence, INTADER prefers to focus the selection of the best fitted biodegradable lubricants for the study lines.

The summarized table, Table 6, is prepared to provide a clear image about the biodegradable lubricant base oils characteristics and their nature. As seen in Table 5, the lubricant base oil has more advantage than synthetic and vegetable oil where most of the basic parameters enable it to work under different conditions. However, for vegetable base oils, because their nature is sensitive to change in the temperature, usually, they are harmonized with the additivities. On the other hand, as given in Table 7, synthetic and polyglycol (PG) oils are costlier than vegetable oils. For polyglycol (PG) oils, although they are commonly composed of petroleum and synthesized hydrocarbon, their biodegradability level is comparable to other base oils because their biodegradability percentage is above to 20% which is in the range of readily biodegradable oils. However, the for derivatives such as polyalphaolefin (PAO) and polyether as stated in Table 5, their biodegradability range is lower than 20% so that majority of them classified as in inherently biodegradable.

Some of the solid lubricants are able to operate under an ambient temperature that means they have high viscosity index. The formation of the solid lubricants usually depends on the derivatives of the polymers, graphite and also synthetic oils, therefore, they usually supported by the thickening agents or additives including toxic metal types. Hence, the majority of them cannot be classified as biodegradable. On the other hand, they usually provide resistance to corrosion. Unfortunately, they are not efficiently operable under harsh weather conditions where their maintenance is also a problem because sometimes the solid sticks can be completely consumed during the movement of the rolling stocks [45].

Although different types of researches are going to understand the rail lubricant behaviour and their effectiveness due to weather conditions, track conditions and specific usage areas like S&Cs, in this research, the authors decided to take into account the simplest selection parameters to determine lubrication types for the study lines for partner countries. After this point selection of lubrication systems and lubricants to climatic conditions will be detailed.

Table 6. Pros and cons of biodegradable lubricant base oils

Lubricant Base Oil	Pros	Cons
Vegetable Oil	▪ High viscosity index ▪ Good lubricity ▪ Low volatility ▪ Fully biodegradable ▪ Having low ecotoxicity ▪ High flash point ▪ Additive response and mineral compatibility ▪ Wear protection	▪ Vulnerable to oxidation ▪ Limited capacity in lubricants of higher performance levels ▪ Poor performance at low and high temperature without using a thickening agent
Synthetic Oil	▪ Appropriate usage of all operating conditions ▪ Low temperature ▪ Low volatility ▪ Low toxicity ▪ Superior viscosity index ▪ High oxidation stability ▪ Increasing wear protection	▪ High cost ▪ Low biodegradability
Polyglycols (PG) Oil	▪ Good lubricant performance ▪ Low pour point ▪ High viscosity index ▪ Good lubricity ▪ High temperature adaptation ▪ High biodegradable	▪ Easily mixed with the water ▪ High mobility in the soil ▪ High cost

Table 7. Cost ratio of biodegradable lubricant base oils [23]

Lubricant Base Oil	Ratio of EAL cost to Conventional Mineral Oil Lubricant Cost 1
Mineral Oil	1
Vegetable Oil	1.2
Synthetic Oil	2 to 3
Polyglycols (PG) Oil	2 to 3

3 Selection of Lubrication Systems and Lubricants according to Climatic Conditions

3.1 How the Climatic Conditions Impact the Lubrication Systems

3.1.1 Ambient Temperature

Extreme temperature is one of the major driving forces to increase track wear and damage. The seasonal affect may accelerate track degradation. One of researches performed on Russian Northern Railway System demonstrated that extreme temperature change such as from +20°C in the summer season or -20°C in the winter season is a major impact on the track degradation as well as the lubrication system. According to the test result, in the summer season, the 70% of derailments which happened on the test line were triggered by high temperature increase and this percentage reached to 80% in dry weather conditions. The observed area of the derailment is due wheel climb over the rail head type. After collecting data from the test site, a simulation made by the researchers that indicated that coefficient of friction (CoF) is unexpectedly high between wheel/flange and rail head where the lubrication was not performed, i.e. under dry conditions. On the other hand, the lubrication performed in gauge face reduced to derailment risk and is now widely preferred in Russia [46].

The same study emphasized that low temperature has a negative effect on rail performance and driving. The safety issues raised during rail brakes and for this case, safety comes to the fore more than track degradation and increment in the wear. In the research, it is stated that rail brakes in the winter period are 1.6-1.8 much more likely than warmer seasons. In addition, the increment of the rolling contact fatigue (RCF) was observed during winter-spring time rather than summer time. Seasonal changes and large gaps in temperature values are directly correlated with spreading of the lubricant and entrapping the cracks occurring in the track [46].

Figure 13. An example to track degradation in extreme cold weather in Russia

In most cases, the temperature is examined only by taking into account the changes in the location weather. However, there are a few studies which imply that focusing on the rail temperature also has significant effect where this temperature rises to high values during braking periods due to releasing of energy. One of the research projects performed in Richards Bay Coal Export Line in South Africa shows that there is a good correlation between lateral forces and temperature increase of the rail. During the passing of a two hundred truck coals train which is heavily loaded with the speed of 50 to 55 km/h, the increment of the rail temperature rose to 8°C to 10 °C within a short-term time. To foresee the rail temperature change and lubrication interaction, the second test was executed in the same area, but in this case temperature change on the rail was tested under dry, un-lubricated and lubricated conditions. The test site was arranged according to these criteria where the track was not lubricated with a distance of 60 km before reaching the evaluation site. In the first and second tests, the same site was used with 604 m radius curve at 59/9 km between Vryheid and Ulundi on the coal export line.

As a result of the performed tests, it was observed that the low leg rail surface temperature is increased, roughly 80 % reached unexpectedly high values. The factors which caused this overheat on the wheels and interaction with the rail surface are the increment of the friction during the braking which lead to change the energy form to heat and the bearing on which the axle runs, malfunctions and overheats.

The temperature distribution shown in Figure 14 is related to 1500 spots of rain passed the brake temperature sensor situated at Intshamanzi near Vryheid from February 2008 to May 2008. The statistics demonstrated that more than 64 % of the wheels were run at temperatures from 130°C to 190°C while exposed to varied ambient temperature. As seen from Figure 14, wheel and rail temperature can raise to unexpected numbers to 200°C where it can surpass the maximum limit of the lubricant maximum temperature as a result of this, the lubricant is burned without showing its effect. Hence, the rail surface /wheel temperature is important as much as ambient temperature during the selection of the lubricant type [47].

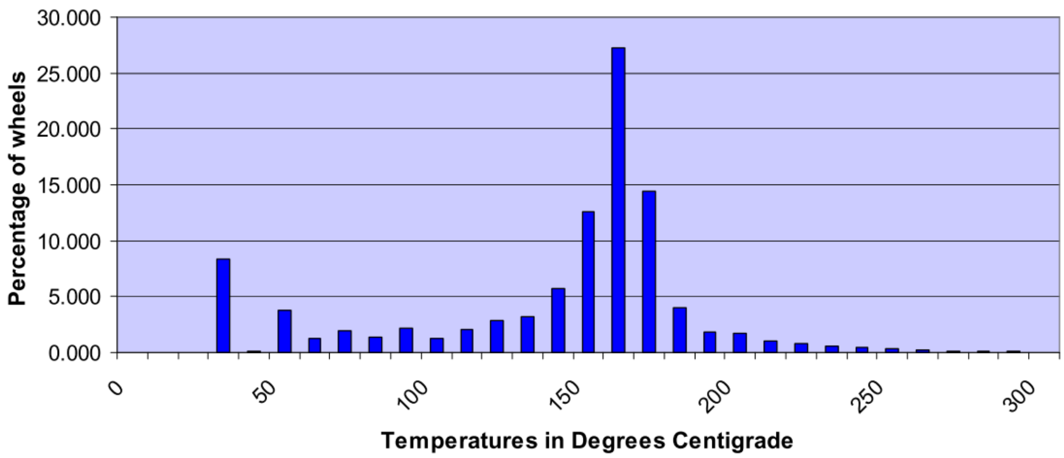

Figure 14. Temperature distribution on 1.2 million wheels on the Richardsbay Coal Line [47]

Apart from that, in view of the operation of the system, the nozzles of the lubrication system can be clogged in the summer time because of not using frequently [48]. In addition to this, creepage can become a serious problem during the summer time and vaporization rate of the lubricant can go up and conclude as excessive consumption.

3.1.2 Heavy Rainfall

During the 1970s, heavy rainfall effects on the railway operations were researched by a British rail researcher. The research indicated that the water can act as a lubricant and have a high impact on the friction in the wheel/rain interface. On the other hand, moisture in small quantities causes very low friction. The water mixed with lubricant can create slurry viscous and decrease the coefficient friction to 0.015 [49].

As mentioned, the water can act as a lubricant under stable conditions, however, it also can damage the rails by entrapping the cracks in the rail. With the pressure or by the exposing the colder temperature, it can freeze or form a solid force to enlarge the existing crack. As a consequence, the rail crack can be observed if a large amount of the water or in the form of snow entrapped between rail cracks. One of the important factor to occur is, the rail head cannot dry up easily and is always exposure to the temperature changes and extreme weather conditions.[48]

Research based on friction modifier effectiveness for heavy haul operating conditions also examined the precipitation impacts on the wear damage of the track. The test was conducted under three different rain conditions: light rain, rain and heavy rain. To ensure validity when carrying out the test, the rail surfaces were exposed to steady precipitation and only rain and heavy rain periods are chosen for the evaluation. The analysis was implemented during May-August 2008, 2009 and 2010 where the rainfall is excessive. In addition, analysis of the dry baseline conditions were executed during September-October 2008 without friction modifier. During the dry conditions where FM was not applied, the third body layers were defined as constituent composed from wheel/rail wear such as iron oxide wear particles, semi random foreign components likewise sand, dirt and chemical reactions due the pressure and heat at the interface. On the other hand, under rain and heavy rain conditions, the third body layers were flushed and replenish with the water and iron oxide by precipitation and wheel/rail interaction. In the case of the drying of the rain and decrease in the precipitation, the conditions on the surface of the rail turned out to replicate the dry condition case [50]. Hence, in this case, the washout parameter of the lubricant becomes important when the rain is excessive. It is an important parameter because almost 30-40 % of Europe is exposed to heavy rain during the autumn season with high wind speed.

There is also a high possibility to face floods and thunderstorm during the wet seasons. Under the wet season, the possible barriers are overwhelming the drainage system that slows down the rail movement, destabilization of the track and washout of the ballast, runoff water between tracks and short circuits or cutting of the power for the small electrified equipment. In the perspective of the lubrication systems, these barriers may cause serious problems such as short circuits for electrified equipment such as pumps, nozzles etc. Runoff water may lead to deprecation of the cable and the integrated partial equipment on the track and the nozzles can clog with the runoff water or drainage water can have a high possibility of consisting of sand, mud, external components etc. [50] The effectiveness of the system is decreased because there will be forces applied by the heavy rainfall and runoff water depending on its debris. Hence, the maintenance of the lubrication system must be performed in periodic ways and to protect from the excessive rain damage, the system has to be able to monitor and preventive measures should be taken such as constituting barrier like sponge to absorb the rain and also if it is applicable on-board system can prefer to avoid the possibility failure of wayside lubrication systems.

Figure 15. An example from England how the excessive rainfall damages on track and its surroundings [51]

3.1.3 Snowing / Icing

Figure 16. An example from the UK railway operations under the snow/icing weather conditions [52]

Winter is a natural phenomenon that can lead to interruptions in the operations of rolling stocks and maintenance activities as well as increase track degradation. Its impacts are not only restricted to damage on the track and malfunctions of the related parts of the rolling stock but are also valid for reliability, robustness, resilience, and performance of systems and services, as well [53].

Therefore, considering the impacts of the snowing/icing on the lubrication systems; most European countries have preferred to disable the wayside lubrication systems during the winter because the excessive snow fall that can result with severe icing issues. Also the snow is able to act as the flange lubricant. There are two reasons behind this. The first one is lubricant applicators cannot function efficiently in the cold where sometimes clogging occurs while lubricant cannot even reach to the nozzle head and also for the wayside lubrication systems, the partial equipment and components of the lubrication system buried under the snow and directly exposed to cold temperature and icing issues. The second is the snow itself which provides adequate lubrication as proven in a Sweden case that shows from wear measurements that snow can be classified as effective lubricant [43]. In addition the build-up of the snow can prevent lubrication migration which can be evaluated as a positive effect [54].

To see the effects of the lubricants under snow, water and dry conditions, research was conducted in 2001. During the research grease consisting of varied mixed components, mainly rapeseed oil, mineral oil and graphite, were applied to curves which have a different radius and super the elevation. A partial result of these tests indicates that during winter conditions, the wear on track is slightly higher than water lubricated conditions, in contrast under dry conditions, the wear becomes larger than the winter (snow) case [49].

If the railway operator still wanted to use the lubrication system, it has to be rearranged according to the snowing conditions where the snow is able to reach the nozzle head. One of the corporations provided a guideline for trackside lubrication, i.e., wayside lubrication, to change the plunger location to be 1.2 mm higher in winter season where the lubricant becomes more viscous than summer-time. Addition to change of the plunger location, it is important to check the whether the applied lubricant migrates from the surface of oil or not, in case of migration, plunger height should be arranged considering snow height on that location [55].

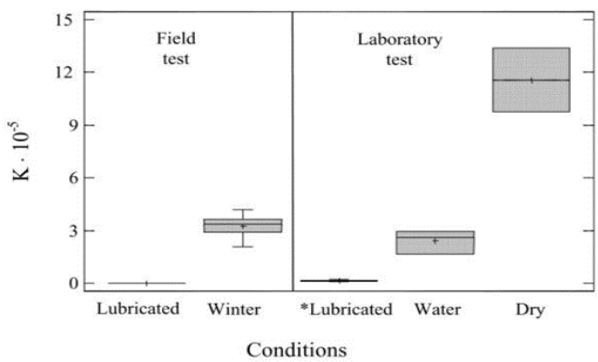

Figure 17. Comparison of the dimensionless wear coefficient (K) of field test and laboratory test[49]

3.2 Climate Classification of Europe and Turkey

3.2.1 Brief Information about Köppen- Geiger Climate Classification

The climatic condition has significant impacts on the lubricants' behaviour and lubrication systems. During the selection phase, although the study lines climatic conditions are examined, the selection methodology can be extended through the climate classification of Europe and Turkey. To determine lubrication types according to climate zones, the Köppen-Geiger climate classification map is chosen as a baseline. This map was presented by the German scientist Wladimir Köppen in 1990 and was updated by Rudolf Geiger in 1954 and 1961. The latest update was performed in 2006 [56].

The logic of distinguishing the climatic zones of this map was established on five vegetation groups determined by the French botanist De Candolle. Köppen – Geiger classification is explained in Figure 18. As seen in Figure 18, the climate classification firstly divided into five basic types: **(A)** Equatorial zone, **(B)** Arid zone, **(C)** Temperate zone, **(D)** Snow zone and **(E)** Polar zone. The second letter indicated after the classification type demonstrates the precipitation (such as Dw for snow and dry winter) and the third letter shows the air temperature (such as Dfc for snow, fully humid with cool summer [56].

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18\ °C$
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
Am	Equatorial monsoon	$P_{ann} \geq 25(100-P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climates**	$P_{ann} < 10\,P_{th}$
BS	Steppe climate	$P_{ann} > 5\,P_{th}$
BW	Desert climate	$P_{ann} \leq 5\,P_{th}$
C	**Warm temperate climates**	$-3\ °C < T_{min} < +18\ °C$
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\,P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\,P_{wmin}$
Cf	Warm temperate climate, fully humid	neither Cs nor Cw
D	**Snow climates**	$T_{min} \leq -3\ °C$
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\,P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\,P_{wmin}$
Df	Snow climate, fully humid	neither Ds nor Dw
E	**Polar climates**	$T_{max} < +10\ °C$
ET	Tundra climate	$0\ °C \leq T_{max} < +10\ °C$
EF	Frost climate	$T_{max} < 0\ °C$

Figure 18. Köppen- Geiger climate classification threshold values [56]

Type	Description	Criterion
h	Hot steppe / desert	$T_{ann} \geq +18\ °C$
k	Cold steppe /desert	$T_{ann} < +18\ °C$
a	Hot summer	$T_{max} \geq +22\ °C$
b	Warm summer	not (a) and at least 4 $T_{mon} \geq +10\ °C$
c	Cool summer and cold winter	not (b) and $T_{min} > -38\ °C$
d	extremely continental	like (c) but $T_{min} \leq -38\ °C$

Figure 19. Köppen- Geiger climate classification criteria for the third letter [56]

For the third letter of the classification, the criteria are defined as stated in Figure 19. The parameters are stated in Figure 18 and Figure 19 are described in below. During the classification, all temperatures are stated in Celsius degrees and the monthly precipitations are shown as millimetre (mm)/month where P_{ann} is in mm/year.

- T_{ann}: The annual mean near-surface (2m) temperature;
- T_{max}: The monthly mean temperature of the warmest month
- T_{min}: The monthly mean temperature of the coldest month
- P_{ann}: The accumulated annual precipitation
- P_{min}: The precipitation of the driest month
- P_{smin}: The lowest monthly precipitation values for the summer
- P_{smax}: The highest monthly precipitation values for the summer
- P_{wmin}: The lowest monthly precipitation values for the winter
- P_{wmax}: The highest monthly precipitation values for the winter
- P_{th}: if at least 2/3 of the annual precipitation occurs in winter, calculated as 2*(T_{ann}); if at least 2/3 of the annual precipitation occurs in summer, calculated as 2*(T_{ann})+ 28; for the other conditions, calculated as 2*(T_{ann})+14 [56].

Figure 20. Köppen-Geiger climate classification [57]

Table 8. Climate types and their specifications [58]

Type	Specific Climate Type	Köppen-Geiger Classification	Specifications
A	*Wet Equatorial Climate*	Af	▪ Temperature of coolest month 18 °C or higher ▪ Precipitation in driest month **at least 60 mm**
	Tropical monsoon and trade-wind littoral climate	Am	▪ Temperature of coolest month 18 °C or higher ▪ Precipitation in driest month less than 60 mm but equal to or greater than 100 – (r/25)
	Tropical wet-dry climate	As, Aw	▪ Temperature of coolest month 18 °C or higher ▪ precipitation in driest month less than 60 mm and less than 100 – (r/25)
B	*Tropical and subtropical desert climate*	Bwh, Bwk	▪ **for B:** 70% or more of annual precipitation falls in the summer half of the year and r less than 20t + 280, or 70% or more of annual precipitation falls in the winter half of the year and r less than 20t, or neither half of the year has 70% or more of annual precipitation and r less than 20t + 140 ▪ **for Bwh :** r is less than one-half of the upper limit for classification as a B type; *t* equal to or greater than 18 °C ▪ **for Bwk:** r is less than one-half of the upper limit for classification as a B type; t less than 18 °C
	Mid-latitude steppe and desert climate	Bsh	▪ **for B:** 70% or more of annual precipitation falls in the summer half of the year and r less than 20t + 280, or 70% or more of annual precipitation falls in the winter half of the year and r less than 20t, or neither half of the year has 70% or more of annual precipitation and r less than 20t + 140 ▪ **for Bsh:** r is less than the upper limit for classification as a B type but is more than one-half of that amount; t equal to or greater than 18 °C
	Tropical and subtropical steppe climate	Bsk Bwk	▪ **for B:** 70% or more of annual precipitation falls in the summer half of the year and r less than 20t + 280, or 70% or more of annual precipitation falls in the winter half of the year and r less than 20t, or neither half of the year has 70% or more of annual precipitation and r less than 20t + 140 ▪ **for Bsk :** r is less than the upper limit for classification as a B type but is more than one-half of that amount ; *t less than 18 °C* ▪ **for Bwk:** r is less than one-half of the upper limit for classification as a B type; t less than 18 °C

Table 9. Climate types and their specifications (Cont'd) [58]

Type	Specific Climate Type	Köppen-Geiger Classification	Specifications
	Humid subtropical climate	Cfa, Cwa	▪ **For Cfa:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month less than 18 °C but greater than –3 °C; precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied; temperature of warmest month 22 °C or above ▪ **For Cwa:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month less than 18 °C but greater than –3 °C; precipitation in driest month of the winter half of the year less than one-tenth of the amount in the wettest month of the summer half; temperature of warmest month 22 °C or above
C	*Mediterranean climate*	Csa,Csb	▪ **For Csa:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month less than 18 °C but greater than –3 °C; precipitation in driest month of summer half of the year is less than 30 mm and less than one-third of the wettest month of the winter half; temperature of warmest month 22 °C or above ▪ **For Csb:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month less than 18 °C but greater than –3 °C; precipitation in driest month of summer half of the year is less than 30 mm and less than one-third of the wettest month of the winter half; temperature of each of four warmest months 10 °C or above but warmest month less than 22 °C
	Marine west coast climate	Cfb, Cfc	▪ **For Cfb:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month less than 18 °C but greater than –3 °C; precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied; temperature of each of four warmest months 10 °C or above but warmest month less than 22 °C ▪ **For Cfc:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month less than 18 °C but greater than –3 °C; precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied; temperature of one to three months 10 °C or above but warmest month less than 22 °C

Table 10. Climate types and their specifications (Cont'd) [58]

Type	Specific Climate Type	Köppen-Geiger Classification	Specifications
D	*Humid continental climate*	Dfa, Dfb, Dwa, Dwb	▪ **For Dfa:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month –3 °C or lower; precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied; temperature of warmest month 22 °C or above ▪ **For Dfb:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month –3 °C or lower; precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied; temperature of each of four warmest months 10 °C or above but warmest month less than 22 °C ▪ **For Dwa:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month –3 °C or lower; precipitation in driest month of the winter half of the year less than one-tenth of the amount in the wettest month of the summer half; temperature of warmest month 22 °C or above ▪ **For Dwb:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month –3 °C or lower; precipitation in driest month of the winter half of the year less than one-tenth of the amount in the wettest month of the summer half; temperature of each of four warmest months 10 °C or above but warmest month less than 22 °C
	Continental subarctic climate	Dfc, Dfd, Dwc, Dwd	▪ **For Dfc:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month –3 °C or lower; precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied; temperature of one to three months 10 °C or above but warmest month less than 22 °C ▪ **For Dfd:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month –3 °C or lower; precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied; temperature of coldest month less than –38 °C ▪ **For Dwc:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month –3 °C or lower; precipitation in driest month of the winter half of the year less than one-tenth of the amount in the wettest month of the summer half; temperature of one to three months 10 °C or above but warmest month less than 22 °C ▪ **For Dwd:** temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month –3 °C or lower; precipitation in driest month of the winter half of the year less than one-tenth of the amount in the wettest month of the summer half; temperature of coldest month less than –38 °C

Table 11. Climate types and their specifications (Cont'd) [58]

Type	Specific Climate Type	Köppen-Geiger Classification	Specifications
E	*Tundra climate*	ET	▪ Temperature of warmest month less than 10 °C; temperature of warmest month greater than 0 °C but less than 10 °C
	Snow and ice climate	EF	▪ Temperature of warmest month less than 10 °C; temperature of warmest month 0 °C or below
	Highland climate	H	▪ Temperature and precipitation characteristics highly dependent on traits of adjacent zones and overall elevation—highland climates may occur at any latitude

**In the formulas above, r is average annual precipitation total (mm), and t is average annual temperature (°C).*
***The summer half of the year is defined as the months April–September for the Northern Hemisphere and October–March for the Southern Hemisphere.*
****Most modern climate schemes consider the role of altitude.*

Type A

Wet equatorial climate: The regions are classified as high temperatures (*around 30°C*) with plentiful precipitation (*15,000-100,000 mm*), heavy cloud cover and high humidity. The temperature variation is little. The climate is shown by the abbreviation of "Af" according to Köppen-Geiger classification where it generally addresses the regions lie within about 12° latitude of the Equator.

Tropical monsoon and trade-wind littoral climate: Small annual temperature ranges and high temperatures, plentiful precipitation (more than wet equatorial climate) are the main features of this climate type. Although most of the features resemble to wet equatorial climate, it has a short dry season and low-sun season. The typical examples for this climate type are southern and south-eastern Asia regions.

Tropical wet-dry climate: Wet and dry seasons can be observed where most of the precipitation occurring in the high-sun ("summer") season. The dry season is longer comparing two other Type A climate types. The temperature is high through the year; however, the temperature variation is larger than wet equatorial climate and tropical monsoon and trade-wind littoral climate. The range of the temperature may change between 19°C to 27°C depending on the season [58].

Type B

Tropical and subtropical desert climate: The climate is dominated in all months by the subtropical and anticyclone and having a clear sky. Depending on the location, sometimes precipitation can be observed. Most of Earth's tropical, true desert (Bw) climates occur between 15° and 30° latitude. The climate is divided tropical desert (Bwh) and subtropical desert (Bwk).

Mid-latitude steppe and desert climate: The climate has extreme variable temperature conditions and has little precipitation. This type of climate can be observed in North and South America and Central Asia. The climate is observed internal sides of the countries. The mid-latitude steppe (Bsk) subtype is slightly wetter than the mid-latitude desert (part of Bwk) subtype. Because of the extreme temperature gaps, the climate brings harsh weather conditions, in the higher latitudes, winters are severely cold and brings snow. In the summer, the precipitation is more convective and evaporation rate is high.

Tropical and subtropical steppe climate: The climate is observed in true deserts in low-latitude semiarid steppe regions. The Bsh classification shows the similar features of this climate type. It is transitional to the tropical wet-dry climate on the equatorward side and to the Mediterranean climate on its poleward margin. The annual precipitation is greater than other two B climate types (3800mm-6300 mm) [58].

<u>Type C</u>

Humid subtropical climate: The climate shows relatively high temperatures and distributed precipitation throughout the year. This climate type is found on the eastern sides of the continents between 20° and 35° N and S latitude. The climate is divided as Cfa and Cwa where Cfa subtype is usually dominating. These regions are influences of moist. Temperatures are high and the warmest months generally average about 27 °C, with mean daily maximum from 30 °C to 38 °C and warm. The summers are wetter than winters. The coldest month is usually in 5–12 °C range, although frosts are not uncommon. For Cwa, it generally is shown in the monsoon influence results in a modified humid subtropical climate where dry winter is overwhelming and have larger annual temperature range comparing to Cfa types. Winters are sunny and rather cool. Annual precipitation totals average about 10,000 mm but vary from 7,500 to 20,000 mm.

Mediterranean climate: It is the major climate type of Köppen classification have hot, dry summers and cool and wet winters. This type of climate usually can be seen in 30° and 45° latitude north and south of the Equator and on the western sides of the continents. It has two main subtypes Csa and Csb. Annual temperature ranges are smaller comparing to marine west coast climates. This type of climate tends to be drier than humid subtropical ones where the precipitation totals ranging from 3,500 to 9,000 mm. Some regions like California demonstrates cool summer conditions where fogs are common. Only in Europe, where the latitude for this climate type fortuitously corresponds to an ocean basin (that of the Mediterranean Sea, from which this climate derives its name), does this climate type extend eastward away from the coast for any significant distance.

Marine west coast climate: It has few extremes of temperatures and ample precipitation in all months. It is located poleward of the Mediterranean climate region on the western sides of the continents, between 35° and 60° N and S latitude. This climate type has two subtypes Cfb and Cfc. The precipitation total varies depending on the location and elevation, however, the annual accumulations range from 5,000 mm to 25000 mm. The precipitation is plentiful and also reliable and frequent. Fog is common in autumn and winter, but thunderstorms are infrequent. The range of annual temperature is rather small (between 10-15°C). In Europe, the major mountain chains (the Alps and Pyrenees) run east–west, permitting Cfb and Cfc climates to extend inland some 2,000 km (about 1,250 miles) into eastern Germany and Poland [58].

Type D

Humid continental climate: It demonstrates large seasonal temperature contrasts with hot summers and cold winters. It is found between 30° and 60° N in central and eastern North America and Asia in the major zone of conflict between polar and tropical air masses. This climate divided into Dfa, Dfb, Dwa and Dwb subtypes. For Df section, precipitation is ample through the year. Winter precipitation often occurs in the form of snow where the retention time of snow is changing from one to four months depending on the region. Mean temperatures are below freezing in several months and the frost-free season varies from fewer than 150 to 200 days per year. Total annual precipitation ranges from 5,000 mm to 12,500 mm. A monsoonal variant of the humid continental climate (Dwa, Dwb) is seen in eastern Asia. This climate type has a pronounced summer precipitation maximum and a cold and dry winter.

Continental subarctic climate: The climate is dominated by the winter season, long and cold period where it has little precipitation, short cleat days. The number of snowy days rather high and humidity is low. It is located north of the humid continental climate, from about 50° to 70° N, in a broad swath extending from Alaska to Newfoundland in North America and from northern Scandinavia to Siberia in Eurasia. The climate divided into Dfc, Dfd, Dwc, and Dwd subtypes. The source of continental polar air dominates the interior of Asia and the mean temperatures 40–50 °C below freezing are not unusual. Frost-free period is estimated 50-90 days per year and snow remains on the ground several months. Comparing to that summers are short and mild. Mean temperatures in summer are rarely excess 16 °C. Thereof, extreme temperatures and variation in annual temperature are usual. Annual precipitation totals are mostly less than 5,000 mm. For Dwc and Dwd subtypes occur in eastern Siberia [58].

Type E

Tundra climate: It has sub-freezing mean annual temperatures, in other words, large annual temperatures ranges. The precipitation is quite low. The tundra climate region occurs between 60° and 75° of latitude. The winters are long and cold (below 0^{o}C) and the dry snow observed in winter. The rainfalls are less than 3500 mm but can range from 2500 to 10000 mm. In contrast, the summers are mild and daily maximum temperature can vary from 15 ^{o}C to 18^{o}C.

Snow and ice climate: The climate has cold temperatures and scant precipitation. It occurs poleward of 65° N and S latitude over the ice caps of Greenland and Antarctica and over the permanently frozen portion of the Arctic Ocean. Temperatures are mostly below freezing throughout the year and annual temperature variation is large. Winters are frigid and mean monthly temperatures from -20 °C to −65°C. The precipitation is low and stable (500 mm to 5000 mm).

Highland climate: It contains all highland areas not easily categorized by other climate types. In this type of climate, the general features are diversified depending on the location, therefore, mostly highland regions such as the Plateau of Tibet of Asia is covered under this climate type. With increasing height, temperature, pressure, atmospheric humidity, and dust content decrease. Altitude also tends to increase precipitation, at least for the first 4,000 metres [58].

Table 12. A few examples according the climate classification of Köppen- Geiger [59]

Classification	Köppen-Geiger	Examples
Warm humid continental climate	Dfb	Moscow, Saint Petersburg, Berlin, Kyiv, Minsk
Oceanic climate	Cfb	London, Paris, Birmingham, Cologne, Amsterdam
Hot-summer Mediterranean climate	Csa	Istanbul, Madrid, Izmir, Bursa, Rome
Humid subtropical climate	Cfa	Belgrade, Milan, Tbilisi, Turin, Skopje
Warm-summer Mediterranean climate	Csb	Valladolid, Vigo, A Coruña, Porto, Braga
Hot humid continental climate	Dfa	Bucharest, Almaty, Rostov-on-Don, Volgograd, Dnipropetrovsk
Warm humid continental climate	Dsb	Hasanoğlan, Aleksandrovsk-Sakhalinskiy, Lerik, Hacıbektaş, Milia
Subarctic climate	Dfc	Krasnoyarsk, Irkutsk, Ulan-Ude, Arkhangelsk, Chita
Cold semi-arid climates	BSk	Baku, Yerevan, Valencia, Thessaloniki, Zaragoza
Hot humid continental climate	Dsa	Ankara, Shymkent, Taldykorgan, Сайрам, Арысь
Subarctic climate	Dwc	N/A
Hot semi-arid climates	BSh	Murcia, Alacant/Alicante, Nicosia, Santa Cruz de Tenerife, Cartagena
Tropical rainforest climate	Af	Les Abymes, Saint-Laurent-du-Maroni, Matoury, Petit-Bourg, Sainte-Rose
Subpolar oceanic climate	Cfc	Reykjanesbær, Tórshavn, Klaksvík, Grindavík, Hoyvík
Tropical savanna climate	Aw	Saint-Denis, Nouméa, Saint-Pierre, Mamoudzou, Saint-Louis
Tundra climate	ET	Bilibino, Гыда, Эгвекинот, Депутатский, Сёяха
Subarctic climate	Dfd	Yakutsk, Aykhal, Udachny, Чурапча, Zhatay
Cold desert climates	BWk	Aktau, Kyzylorda, Atyrau, Zhanaozen, Baikonur
Tropical monsoon climate	Am	Fort-de-France, Cayenne, Baie-Mahault, Le Gosier, Papeete
Warm humid continental climate	Dwb	Cukanovo, Kamyshovoe, Shahterskoe
Hot desert climates	BWh	Las Palmas de Gran Canaria, Arrecife, Puerto del Rosario, Agüimes, Telde
Subarctic climate	Dsc	Anadyr, Susuman, Yagodnoye, Омсукчан, Угольные Копи

3.2.2 Selection of Lubrication Systems according to Climate Zones

In previous sections, a brief introduction to the working of Köppen-Geiger climate classification and examples for the defined climate types are given. As stated before the Köppen-Geiger classification based on two critical parameters: temperature and precipitation. Depending on temperature range and the total amount of annual or mean precipitation, as seen in Figure 3, it is difficult to perform a detailed analysis of the selection of the lubrication and the convenient lubrication system. Therefore, in this analysis, we also take into account humidity, precipitation, icing, snowing and freezing issues as a part of analysis depending on defined climate types and their characteristics'.

In Table 13, the explanation for the selection of the lubricant and lubrication systems are given by checking each specific climate type and their characteristics'. As seen Table 13, the climate types are divided into five main categories where the sub-climate types are detailed under each main type. In a detailed perspective, it is necessary to indicate that the sub-climate types under each main type have a very slight difference, i.e., they are showing the similar characteristics. For instance, for humid subtropical climate and mediterranean climate, although the temperature variation is small, and the precipitation is evenly distributed according to Köppen-Geiger climate classification, the divergence can be seen at humidity level, precipitation amount in summer and winter seasons. The variations and specific graphs of each type of sub-climate types are given in Annex II.

Even though the selection of the lubricant types and lubrication systems performed according to climatic types where the identification address to extended areas like in Cfa and Cfb case, we recommend the infrastructure managers to choose the lubricant types firstly depending on Köppen-Geiger climate classification, and then to perform a specific analysis according to chart given in Figure 21. The specific details related to selection method is given in Table 13, and detailed chart is also presented in Annex III.

Additionally, traffic density of the lines has a crucial to determine the usage amount of the lubricants where the pumpability and applied amount (thickness) of the lubricant are the main criteria. In this stage, without knowing the line characteristics, it will be difficult to identify the lubricant types and lubricant systems. The traffic density classification is performed considering *UIC 714 – Classification of lines for the purpose of track maintenance*. According to UIC thresholds, the high and light density of traffics are describes as in below. Tf described as theoretical traffic load.

<u>High traffic density</u>

- Group 1: 130 000 t/j < Tf
- Group 2: 80 000 t/j < Tf ≤ 130 000 t/j
- Group 3: 40 000 t/j < Tf ≤ 80 000 t/j
- Group 4: 20 000 t/j < Tf ≤ 40 000 t/j

<u>Low traffic density</u>

- Group 5: 5 000 t/j < Tf ≤ 20 000 t/j
- Group 6: Tf ≤ 5 000 t/j

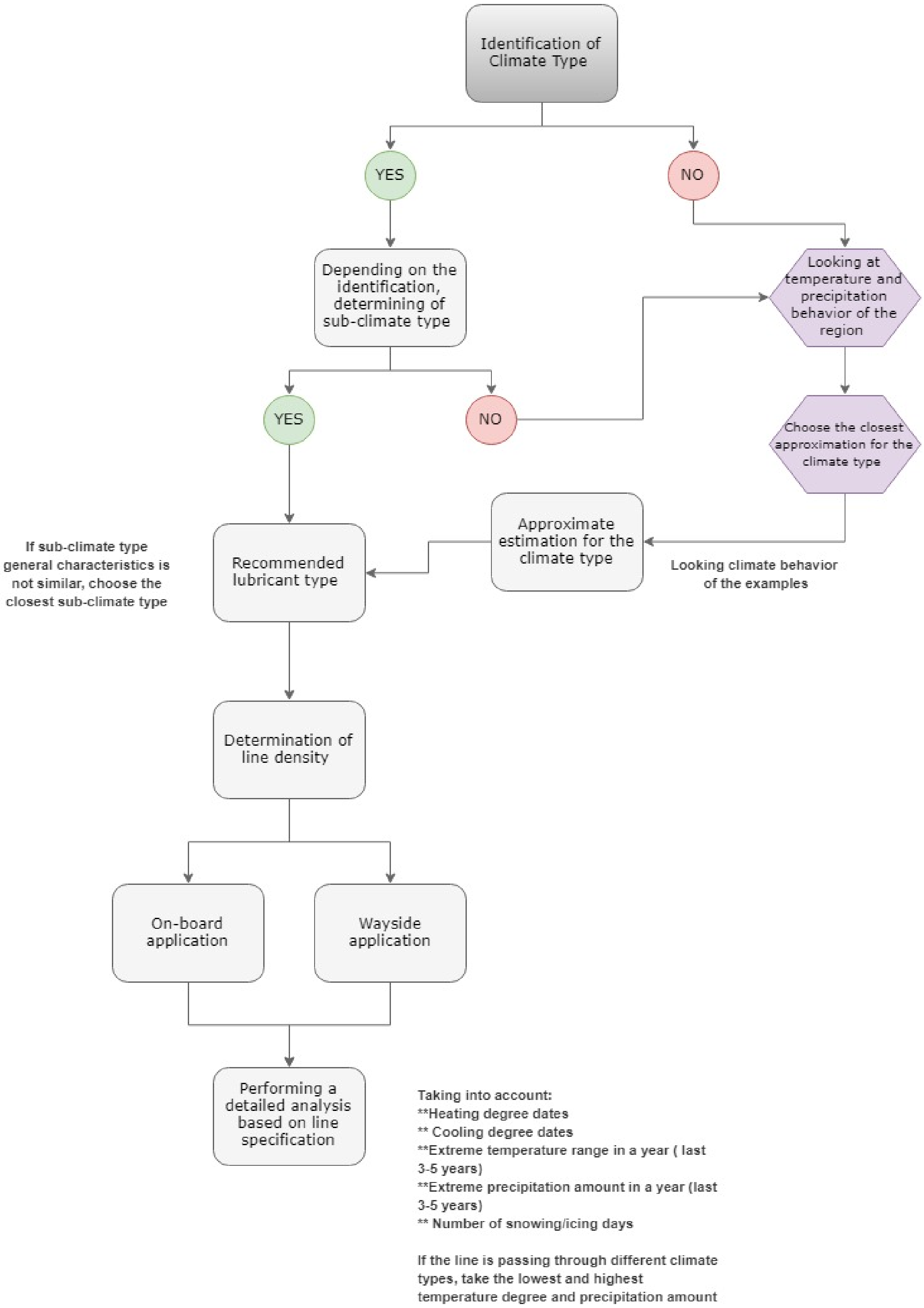

Figure 21. Basic flowchart for the selection method

Table 13. Identification of lubricant type and lubrication system based on Köppen Geiger Climate Classification

Type	Specific Climate Type	Köppen-Geiger Classification	Critical Parameters	Risks for Lubrication System	Recommended Lubrication Type	Recommended Lubrication System
A	*Wet Equatorial Climate*	Af	▪ High temperatures ▪ High temperature variation ▪ Plentiful precipitation ▪ High humidity	▪ High temperature ▪ Flood risk ▪ Exposure to hot-wet climate ▪ High depreciation rate of the partial equipment ▪ Difficulty in maintenance for long distance areas ▪ Clogging of the nozzles because of sand, dirt available in the environment	▪ High temperature durability ▪ Non-water-based lubricants ▪ For high speed lines, flash and autoignition points ▪ High water resistance ▪ Not preferred to use FM	▪ **Low density lines** *On-board applications* --Not efficient for liquid lubricants --Recommended to use solid sticks *Wayside applications* -- More convenient for application in the closest region -- High efficiency for lubricants have high viscosity -- Combining power supply with micro scale applications -- Ability to combine with FM efficiently ▪ **High density lines** *On-board applications* -- Not efficient for liquid lubricants --Recommended to use solid sticks --Usually not convenient for extreme high temp. *Wayside applications* --More convenient for application in the closest region --High efficiency for lubricants have high viscosity -- Combining power supply with micro scale applications --Ability to combine with FM efficiently
	Tropical monsoon and trade-wind littoral climate	Am	▪ High temperatures ▪ Small temperature variation ▪ Excessive precipitation ▪ High humidity	▪ High temperature ▪ Flood risk ▪ Exposure to hot-wet climate ▪ High depreciation rate of the partial equipment ▪ Difficulty in maintenance for long distance areas	▪ High-low temperature durability ▪ Non-water-based lubricants ▪ High water resistance ▪ Not preferred to use FM	
	Tropical wet-dry climate	As, Aw	▪ Larger annual temperature variation ▪ High and low temperatures ▪ Sudden excessive precipitation in a short time	▪ Temperature variation ▪ Flood risk ▪ High depreciation rate of the partial equipment ▪ Difficulty in maintenance for long distance areas	▪ High-low temperature durability ▪ High water resistance ▪ FM can be used in summer season	

Type	Specific Climate Type	Köppen-Geiger Classification	Critical Parameters	Risks for Lubrication System	Recommended Lubrication Type	Recommended Lubrication System
B	*Tropical and subtropical desert climate*	Bwh, Bwk	▪ Extreme temperature variation between day and night temperatures ▪ High temperature ▪ High vaporization rate ▪ Dry seasons, too low precipitation	▪ Clogging of the nozzles because of sand, dirt available in the environment ▪ High temperature ▪ Difficulty in maintenance for long distance areas ▪ Usage of excessive lubricant (if liquid) ▪ Exposure to hot-dry climate ▪ Clogging of the nozzles because of sand, dirt available in the environment	▪ High temperature durability ▪ For liquid lubricants, high flash and autoignition points ▪ Convenient for solid lubricants ▪ Implementing FM and TOR	▪ **Low density lines** *On-board applications* -- Applicable for liquid lubricants (efficient) --Operable at high, low and compact pressure *Wayside applications* -- More convenient for application in the closest region -- High clogging risk -- Combining power supply with micro scale applications --Ability to combine with FM & TOR efficiently ▪ **High density lines** *On-board applications* --Low efficiency for liquid lubricants have high viscosity -- Convenient for solid sticks *Wayside applications* -- More convenient for application in the closest region -- High clogging risk --Able to work efficient with high viscosity lubricants -- Combining power supply with micro scale applications --Ability to combine with FM & TOR efficiently
	Tropical and subtropical steppe climate	Bsh	▪ Small temperature variation ▪ High vaporization rate ▪ Rain shadows	▪ Temperature variation ▪ High depreciation rate of the partial equipment ▪ Difficulty in maintenance for long distance areas ▪ Exposure to sudden and excessive precipitation ▪ Clogging of the nozzles because of sand, dirt available in the environment	▪ High-low temperature durability ▪ High flash point and autoignition point ▪ FM can be used in summer season	
	Mid-latitude steppe and desert climate	Bsk Bwk	▪ Large temperature variation ▪ Meagre precipitation (as snow) ▪ Cold and dry winter ▪ Warmer summers	▪ Difficulty in maintenance for long distance areas ▪ Exposure to temperature shocks ▪ Clogging of the nozzles because of sand, dirt available in the environment	▪ Not using lubricants in icing/snowy days ▪ If needed, high tolerance to low and high temperatures ▪ FM can be used in summer season	

Type	Specific Climate Type	Köppen-Geiger Classification	Critical Parameters	Risks for Lubrication System	Recommended Lubrication Type	Recommended Lubrication System
C	*Humid subtropical climate*	Cfa, Cwa	▪ Small temperature variation ▪ Evenly distributed precipitation ▪ High humidity ▪ Sometimes dry winter	▪ Difficulty in maintenance for long distance areas ▪ Exposure to excessive humidity	▪ Low temperature tolerance ▪ High water resistance	▪ **Low density lines** *On-board applications* -- Applicable for liquid lubricants (efficient) -- Convenient for solid sticks in high speed lines --Restricted combination with FM *Wayside applications* -- More convenient for application in the closest region -- Medium clogging risk -- Combining power supply with micro scale applications --Ability to combine with FM & TOR efficiently ▪ **High density lines** *On-board applications* -- Applicable for liquid lubricants (efficient) -- Convenient for solid sticks in high speed lines and for long track distance --Restricted combination with FM --More efficient for the braking *Wayside applications* -- More convenient for application in the closest region -- Medium clogging risk --Risk for icing issue -- Combining power supply with micro scale applications --Ability to combine with FM & TOR efficiently -- Low ability working in winter--Ability to combine with FM & TOR efficiently
	Mediterranean climate	Csa, Csb	▪ Small temperature variation ▪ Evenly distributed precipitation ▪ Normal humidity ▪ Fog issue ▪ Hot, dry summer and cool, wet winter ▪ Mild climate	▪ Difficulty in maintenance for long distance areas ▪ Clogging of the nozzles because of sand, dirt available in the environment ▪ Flood risk ▪ High depreciation rate of the partial equipment	▪ High temperature durability ▪ Non-water-based lubricants ▪ For high speed lines, flash and autoignition points ▪ High water resistance ▪ FM can be used depending on the season	
	Marine west coast climate	Cfb, Cfc	▪ Extreme temperature ▪ Small temperature variations ▪ Ample precipitation, frequently ▪ Fog issue ▪ High humidity ▪ Warm, humid summers, cold and snowy winters	▪ Difficulty in maintenance for long distance areas ▪ Clogging of the nozzles because of sand, dirt available in the environment ▪ Flood risk/ Freezing risk ▪ High depreciation rate of the partial equipment ▪ Ice/Snow issues	▪ High-low temperature durability ▪ For liquid lubricants, high flash and autoignition points ▪ Convenient for solid lubricants ▪ Implementing FM and TOR ▪ Water resistance ▪ Icing agents can be used depending on weather	

Type	Specific Climate Type	Köppen-Geiger Classification	Critical Parameters	Risks for Lubrication System	Recommended Lubrication Type	Recommended Lubrication System
D	*Humid continental climate*	Dfa, Dfb, Dwa, Dwb	▪ Large seasonal temperature variation ▪ Ample precipitation, frequently ▪ Warm, hot summers and cold, humid winters ▪ Sometimes frigid winters ▪ Icing/snowing issue	▪ Difficulty in maintenance for long distance areas ▪ Clogging of the nozzles because of sand, dirt available in the environment ▪ High depreciation rate of the partial equipment ▪ Exposure to excessive humidity ▪ Ice/Snow issues	▪ High-low (extreme) temperature durability ▪ Convenient for solid lubricants ▪ Non-water-based lubricants ▪ Water resistance ▪ Icing agents is needed.	▪ **Low density lines** *On-board applications* -- Convenient for solid sticks and for long track distance --Restricted combination with FM --More efficient for the braking *Wayside applications* -- More convenient for application in the closest region -- High clogging risk -- High risk for icing/freezing issue -- Low ability to produce energy from micro scale app. -- Low ability working in winter ▪ **High density lines** *On-board applications* -- Convenient for solid sticks and for long track distance --More efficient for the braking *Wayside applications* -- More convenient for application in the closest region -- High clogging risk -- High risk for icing/freezing issue -- Low ability to produce energy and Low ability working in winter --Implementation with icing agent ***Recommendation: not using lubricant for this climate type***
	Transition between Humid continental climate and Continental subarctic climate	Dsa, Dsb, Dsc	▪ Large seasonal temperature ▪ Little precipitation ▪ Snowing issue ▪ Normal humidity ▪ High elevation	▪ Difficulty in maintenance for long distance areas ▪ High depreciation rate of the partial equipment ▪ Exposure to humidity	▪ High-low (extreme) temperature durability ▪ Non-water-based lubricants ▪ High water resistance ▪ Icing agents is needed ▪ FM and TOR can be used depending on elevation and temperature variation	
	Continental subarctic climate	Dfc, Dfd, Dwc, Dwd	▪ Low humidity ▪ Little precipitation ▪ Cold and strong winters ▪ Freezing issue ▪ Extreme temperature variation ▪ Snowing/ice issue	▪ Difficulty in maintenance for long distance areas ▪ Freezing risk ▪ High depreciation rate of the partial equipment ▪ Ice/Snow issues ▪ Extreme temperature variation	▪ Low temperature durability ▪ High water resistance ▪ Icing agents is needed. ▪ Non-water-based lubricants ▪ Additional thickening agent is needed.	

Type	Specific Climate Type	Köppen-Geiger Classification	Critical Parameters	Risks for Lubrication System	Recommended Lubrication Type	Recommended Lubrication System
E	*Tundra climate*	ET	▪ Large annual temperature variation ▪ Dry snow, cold winters ▪ Scant precipitation ▪ Low temperature	▪ Difficulty in maintenance for long distance areas ▪ High depreciation rate of the partial equipment ▪ Ice/Snow issues ▪ Extreme temperature variation	▪ Recommend to not use lubricants. ▪ Extremely high and low temperature durability ▪ Icing agent is strongly needed.	▪ **Low and high-density lines** *On-board applications* --Convenient for solid sticks and for long track distance --Can provide excessive force for breaking -- High risk of freezing -- Recommend not use *Wayside applications* -- Not Applicable ***Recommendation: not using lubricant for this climate type***
	Snow and ice climate	EF	▪ Extremely cold ▪ Extreme low temperature ▪ Extreme snow and ice issues ▪ Scant precipitation ▪ Freezing is usual	▪ Difficulty in maintenance for long distance areas ▪ Freezing risk ▪ High depreciation rate of the partial equipment ▪ Ice/Snow issues ▪ Extreme temperature variation ▪ Non-operable conditions	▪ Not applicable because this climate type can be seen in polar regions of the World	
	Highland climate	H	▪ Extreme temperature variation due to elevation ▪ Snow/icing issues in high elevations	▪ Difficulty in maintenance for long distance areas ▪ High depreciation rate of the partial equipment ▪ Ice/Snow issues ▪ Extreme temperature variation	▪ Recommendation cannot made because the climate type can unexpectedely change depending on elevation	

The Köppen-Geiger climate classification is also available as GIS data which allows it to be imported and analysed in GIS software and the can be imported into the web based GIS tool developed within WP6 of NeTIRail-INFRA, and relate to geographical location to recommended lubrication methods.

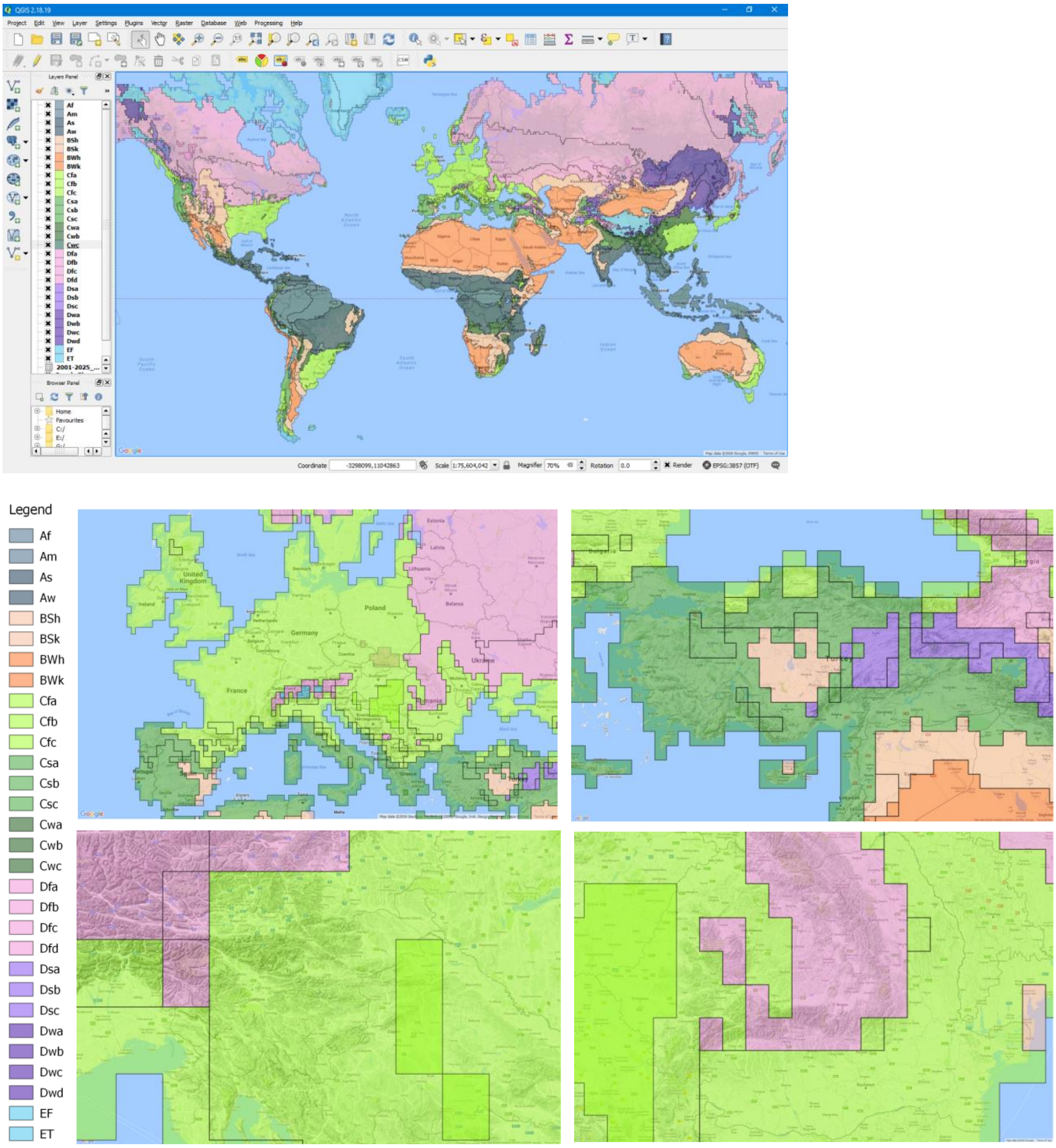

Figure 22. Examples of the Köppen-Geiger regions represented in the qGIS software, including maps for West Europe, Turkey, Slovenia and Romania

3.3 Selection of Lubrication Systems for Slovenia, Romania and Turkey

The selection criteria of the lubrication systems for study lines are based on considering the lubricants behaviour under certain climatic conditions. To understand the climatic conditions, the climate map and weather conditions of the regions of the study lines are examined carefully. During this stage, factors considered include precipitation changes, the maximum and minimum temperature during a year by taking into account seasonal impacts, temperature differences, extreme high and low temperature conditions, snowy/icing days, humidity which form the basis of the selection procedure. The selection procedure is carried out according to Annex III.

As mentioned in the previous sections, the lubricants and the system types have to be selected according to line specification and track situation where small changes in the system can increase or decrease track wear and damage. For instance, using water-based lubricants in a region can be a solution for the lines in mild climates where the vaporization is not an issue and excessive precipitation is rare. However, if the track has microscale cracks and also have a significant material loss, unexpected rail breakages can occur especially for the welded rails. Therefore, it is impossible to say without knowing the track situation and line specification which lubricant or the system will be the best one. The literature and results of several tests in laboratories can only show the experiences gained through the small-scale implementations. Of course, in a real application, the usage areas like in S&Cs and curve sections, the lubrication implementation should be performed with respect to line conditions and track situation.

This research is limited to the selection of the lubricants and lubrication systems according to climatic conditions. The line characteristics are restricted to high and low traffic densities and rolling stock type. The lubrication dosage and specific applications are disregarded since the most suppliers' lubricants types can be usable in both plain lines, curve sections, S&Cs. The only difference is the lubricant dosage which is arranged considering the track situation and load weight of the rolling stock. Therefore, the lubricants and lubrication systems are not classified as a specific usage area. The reason is that the obtained data from suppliers are limited and also the current situation of the track for selected study lines are unknown. To make a detailed study, some tests should be performed on the sites which require high budget and long-time period.

3.3.1 Slovenia

3.3.1.1 Pivka-Ilirska Bistrica-d.m.

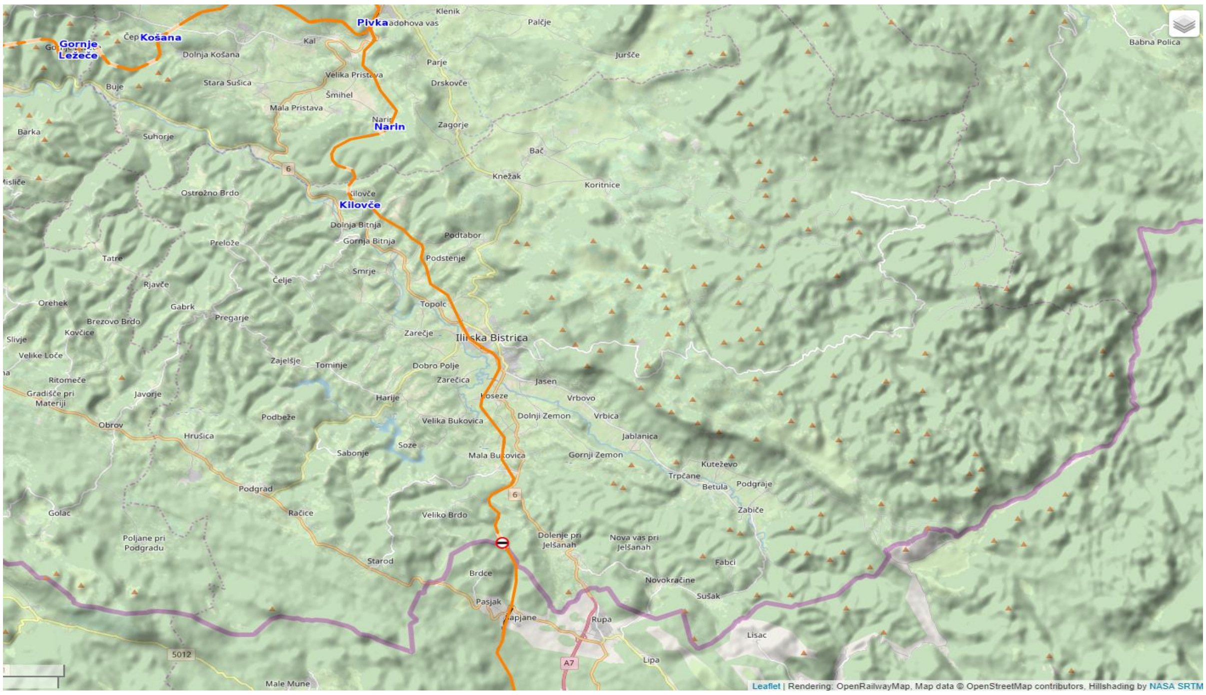

Figure 23. Demonstration of the main line of Pivka-Ilirska Bistrica-d.m [60]

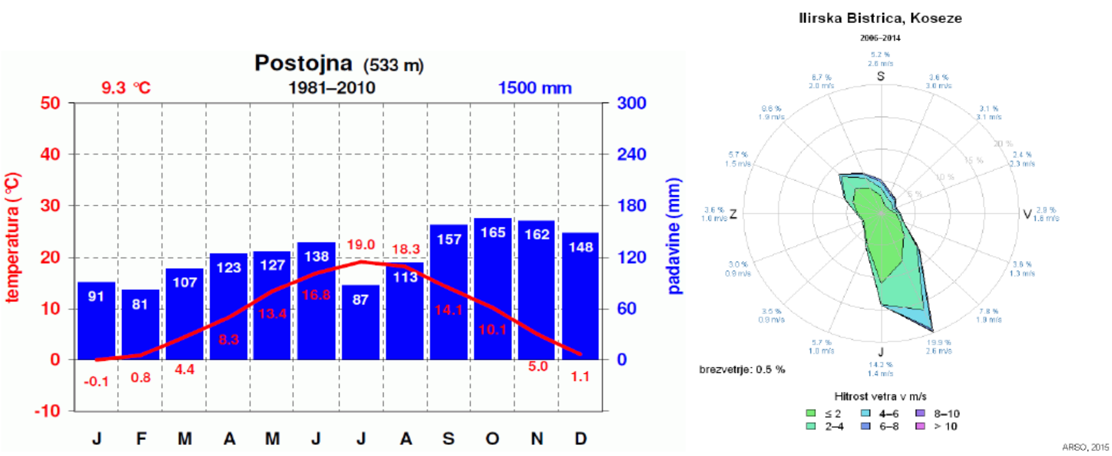

Figure 24. The climatic condition of Postojna [61]

Extreme values of measured yearly, monthly and daily values of chosen meteorological parameters in 1950–2014

	maximum	year / date	minimum	year / date
mean annual air temperature (°C)	11.1	2014	7.2	1956
absolute extreme air temperature (°C)	36.4	Aug. 4 2013	−30.5	Feb. 16 1956
annual number of days with min. temperature ≤−10 °C	32	1963	2	1975, 1977, 1988, 2002, 2011, 2014
annual number of days with max. temperature ≤ 0 °C	51	1963	1	1951, 1974
annual number of days with min. temperature ≤ 0 °C	137	1952	44	2014
annual number of days with max. temperature ≥ 25 °C	94	2003	8	1960
annual number of days with max. temperature ≥ 30 °C	35	2003	0	15 years out of 65
annual number of days with min. temperature ≥ 20 °C	1	1994, 2011	0	61 years out of 65
annual bright sunshine duration (hours) (from 1954)	2360	2011	1616	1972
annual precipitation (mm)	2073	1979	1019	1957
monthly precipitation (mm)	513	Oct. 1992	0	Jan. 1989
daily precipitation (mm)	137	Oct. 9 1980	/	/
annual number of days without precipitation	246	1983	115	1960
annual number of days with precipitation (at least 1 mm)	154	1960	79	2011
annual number of days with snow cover	98	1952	2	1989
maximum snow cover depth (cm)	94	Feb. 17 1952	2	Mar. 18 1975, Mar. 1 1989
fresh snow depth (cm)	61	Mar. 4 1970	/	/

Figure 25. Extreme weather values measured yearly for Postojna [62]

As seen from the Figure 24 and 25, spring and autumn seasons of the Postojna are under heavy rainfall considering the amount and the period. The mean annual air temperature is maximum 11°C and minimum 7.2°C which is low compared to other Mediterranean regions. While the temperature has been significantly increasing between 1991 and 2011, the total precipitation for a year has been decreased from approximately 1700 mm in 2011 to 1000 mm in 2012 depending on the season [63]. In addition to this, humidity has been increased. As seen from Figure 25, the maximum snow cover depth has not been as high as 61cm since 1970. Hence, it can be said that the maximum temperature cannot reach the high values but depending on the weather and seasonal changes, the temperature can drop below 0°C [62].

Postojna climate is defined as Cfb where average annual temperature and precipitation are measured as 9.8°C and 1326 mm respectively in long-time period [64]. Depending on the detailed chart developed for this research (Annex III), both wayside and on-board lubricant systems are efficient where medium viscosity lubricants should be preferred. Medium and low pressure are suggested to use depending on lubrication system type. Additionally, the temperature range of the lubricant must be in acceptable range where we suggest to infrastructure managers to take into account not average temperature range, but also number of heating and cooling degree days and the extreme low and high temperature values. Depending on season and low temperature values in winter, icing agents, FM and TOR can be combined with application of lubrication depending on preference again. For further details, please examine the detailed chart given in Annex III.

In a detail analysis, by examining last 3 years weather behaviour, for this case study it is best to use a lubricant having low solubility (i.e. high-water resistance) and also resistance to temperature changes and temperature shocks. For wheel/flange lubricants, a lubricant mixed with vegetable oil or synthetic and lithium or calcium sodium/sulfonate soap can be efficient where generally operating temperature range can be -30°C to 85°C and have high drop point. The general water resistance of this type of lubricants can differ between 85% to 98 % depending on the product type and base oil amount. On the other hand, solid lubricants can be used as well, however, as said there is no indication or supportive research that they are biodegradable inherently or directly. Because the majority of them includes polymer type components mixed with metal additivities or thickening agents, they may be more harmful. Considering their amount and usage type, it can be advantage use them in wheel/flange with on-board lubrication systems. In addition, solid lubricants have low operating temperature ranges. The solid lubrication type for this line can be composed of lithium and polymer components where the operating temperature range should between -12°C to 32°C. It is important to remind that for Postojna; the lowest temperature might be below -15°C [63] where this type of lubricant can be useless during the winter season. It can be suggested that the solid lubricant should not be used in winter seasons. The rail flange lubrications are not suitable to work on under low temperature conditions. If they wanted to be used, they should include some additivities or thickening agents to lower the operating temperatures.

3.3.1.2 Divača -Koper

Figure 26. Demonstration of the main line of Divača -Koper [60]

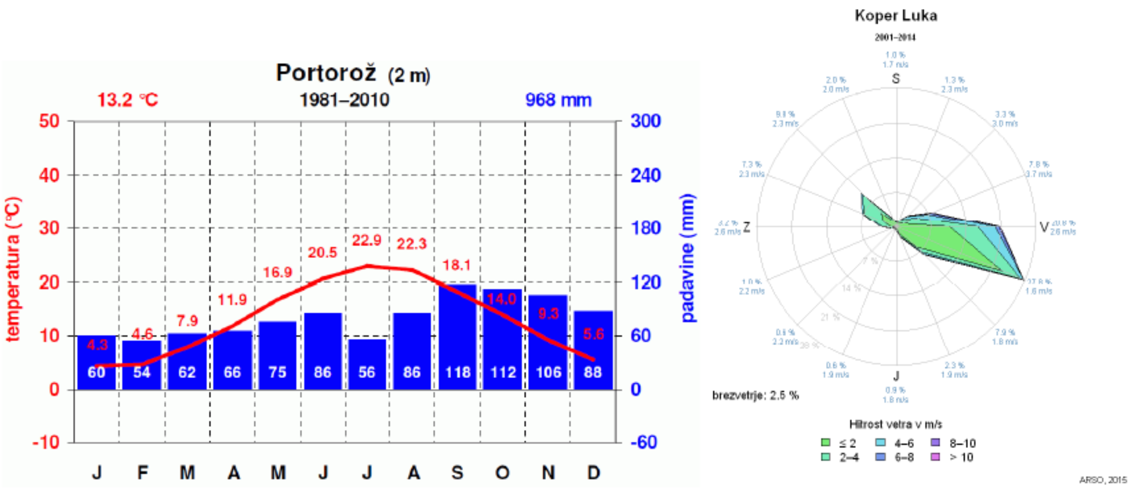

Figure 27. The climatic condition of Portorož [61]

Extreme values of measured yearly, monthly and daily values of chosen meteorological parameters in 1987–2014

	maximum	year / date	minimum	year / date
mean annual air temperature (°C)	15.4	1988	10.2	1991
absolute extreme air temperature (°C)	37.7	Aug. 8 2013	–10.5	Mar. 2 2005
annual number of days with min. temperature ≤–10 °C	3	1991	0	26 years out of 28
annual number of days with max. temperature ≤ 0 °C	6	2012	0	21 years out of 28
annual number of days with min. temperature ≤ 0 °C	67	2005	24	2007
annual number of days with max. temperature ≥ 25 °C	131	2011	67	1987
annual number of days with max. temperature ≥ 30 °C	70	2003	8	1996
annual number of days with min. temperature ≥ 20 °C	26	2003	2	1989, 2014
annual bright sunshine duration (hours) (from 1993)	2730	2011	2128	2014
annual precipitation (mm)	1462	2014	614	2011
monthly precipitation (mm)	325	Aug. 2006	0	Jan. 1989, Mar. 2012
daily precipitation (mm)	136	Sept. 22 1996	/	/
annual number of days without precipitation	258	2011	176	2014
annual number of days with precipitation (at least 1 mm)	118	2014	54	2011
annual number of days with snow cover	6	2003	0	20 years out of 28
maximum snow cover depth (cm)	11	Dec. 8 2012	0	16 years out of 28
fresh snow depth (cm)	11	Dec. 8 2012	/	/

Figure 28. Extreme weather values measured yearly for Portoroż [65]

Portorož climate is defined as Cfa where average annual temperature and precipitation are measured as 14.1°C and 1055 mm respectively in long-time period [64]. Depending on the detailed chart developed for this research (Annex III), the suggested lubricant type and lubrication systems are the same for the Postojna case because Cfa and Cfb belongs to same climate type, Type C. For further details, please examine the detailed chart given in Annex III.

In a detail examination, as observed from the Figure 27 and 28, Portorož has a mild climate where its temperature changes are not sudden or the gaps between seasonal temperature are lesser. The snowing or icing does not present an issue here because the record of the maximum snow cover depth is rare [65]. Because of the line is close to the sea, the effecting parameter can be humidity and excessive precipitation. Total precipitation value has reached to 1400 mm during 2011 [66]. Therefore, the lubricant must be water resistance and also can have an impact during excessive humidity. There is no need for extending operating temperature. In here, the lubricant base oil should be synthetic for liquid types or polymer derived for solid types. For liquid types, the thickening agent can be calcium soap based and operating temperature range can be from -15°C to 100°C to guarantee to prevent lubricant burning. Because the average temperature range is not low, the rail surface temperature and wheel temperature can be raised unexpectedly depending on track condition. The lubricant has high water resistance will be good choice to prevent rail cracks during the operation as well. The rail flange lubricant can be more convenient than wheel/flange lubricant. If the wheel/flange lubricant usage is necessary, then on-board systems solid type of lubricant can be chosen which can have polymer mixed with various types of metals. The lower operating temperature of solid lubricants for these climate conditions is -12°C where the maximum temperature value can be 32°C. Of course, it is important to be reminded that with curve sections solid lubricants may not be suitable.

3.3.1.3 Ljubljana Šiška-Kamnik Graben

Figure 29. Demonstration of the sub-line of Ljubljana Šiška-Kamnik Graben [60]

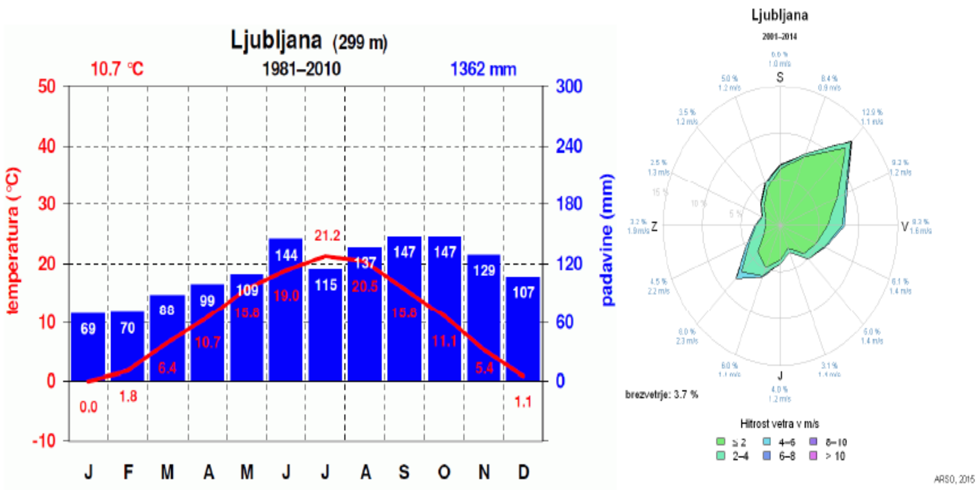

Figure 30. The climatic condition of Ljubljana [61]

Extreme values of measured yearly, monthly and daily values of chosen meteorological parameters in 1948–2014

	maximum	year / date	minimum	year / date
mean annual air temperature (°C)	12.6	2014	8.6	1956
absolute extreme air temperature (°C)	40.2	Aug.. 8 2013	–23.3	Feb. 16 1956
annual number of days with min. temperature ≤–10 °C	34	1963	0	10 years out of 67
annual number of days with max. temperature ≤ 0 °C	49	1963	1	1974
annual number of days with min. temperature ≤ 0 °C	123	1952	27	2014
annual number of days with max. temperature ≥ 25 °C	109	2003	38	1984
annual number of days with max. temperature ≥ 30 °C	54	2003	0	1978
annual number of days with min. temperature ≥ 20 °C	8	2003	0	45 years out of 67
annual bright sunshine duration (hours) (from 1949)	2260	2012	1377	1954
annual precipitation (mm)	1848	1965	954	1949
monthly precipitation (mm)	505	Oct. 1992	0	Jan. 1964
daily precipitation (mm)	140	Sept. 18 2010	/	/
annual number of days without precipitation	209	1983, 2011	130	1960
annual number of days with precipitation (at least 1 mm)	149	1960	79	2011
annual number of days with snow cover	110	1996	2	1989
maximum snow cover depth (cm)	146	Feb. 15 1952	1	Nov. 26 1989
fresh snow depth (cm)	57	Feb. 15 1952	/	/

Figure 31. Extreme weather values measured yearly for Ljubljana[67]

The Ljubljana has more extreme conditions than Postojna. Its climate is defined as Cfb, same with Postojna, where average annual temperature and precipitation are measured as 10.4°C and 1290 mm respectively in long-time period [64]. Thereof, the suggested lubricant type and lubrication systems are the same for the Postojna. For further details, please examine the detailed chart given in Annex III.

For a detail examination, as seen from Figure 30, the precipitation rate is close to Postojna's [67]. The total precipitation value for a year can reach to 2000 mm and the temperature can decrease to -20^{o}C in January, and where the average temperature was approximately 11.5°C in 2011 [68]. It means that harsh weather conditions are overwhelming where the temperature is lower, as expected outside of the city and also snow/icing issues become a problem during the winter. In this case, it is more logical to suggest a lubricant which can even work under -30^{o}C. These type of lubricants uses synthetic or ester base oils with a thickening agent usually silicate. This combination makes the lubricant more resistive to sudden temperature changes. The lubricants can be used for both rail flange and wheel flange purposes. According to the research made in lubricant suppliers, there could not be found that no solid lubricant offered for the snowing/icing cases. In terms of biodegradability, the liquid lubricants having vegetable oils as a base oil and strong additives are able to work till -35^{o}C conditions. However, in this case, the maximum lower temperature is so close to -25^{o}C, therefore, during the sudden drop of the temperature in high elevations can cause several problems. In addition, many European countries, during the winter season, the railway operator choose to not use lubricants after considering its disadvantages.

For Slovenia study line, we suggest the infrastructure manager to choose the lubricants for Type C case according to Annex III. However, although general specs of the lubricant and lubrication types are defined separately for high and low densities, it is crucial to examine heating and cooling degree days and lowest and highest values in season based. Additionally, precipitation amounts of Cfa and Cfb are close to each other, thereof, humidity comes a crucial parameter which may impact the efficiency of the lubricant types as well as can change the pumpability rate.

3.3.2 Romania

3.3.2.1 Faurei Testing Ring

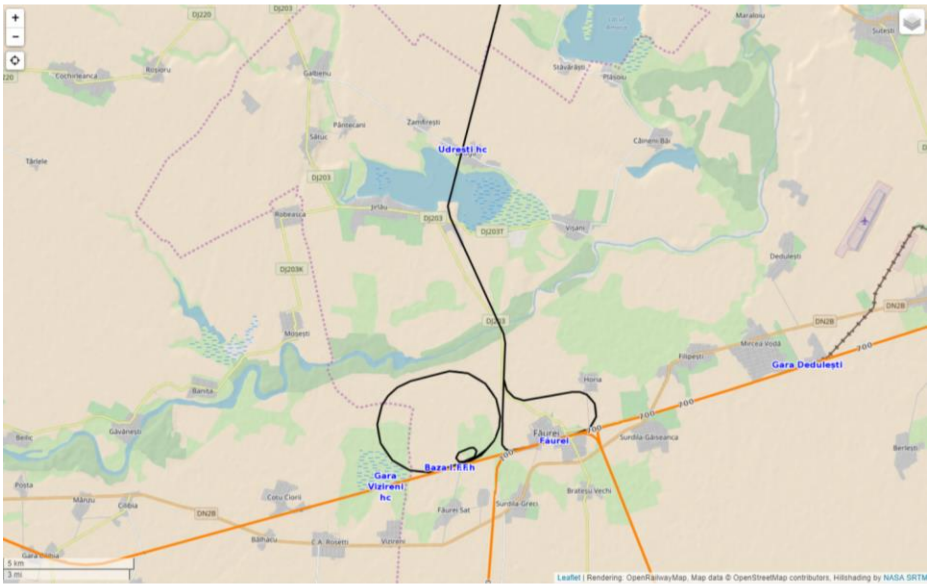

Figure 32. Demonstration of the Faurei Testing Ring near to Bužau

Bužau climate is defined as Cfb where average annual temperature and precipitation are measured as 10.5°C and 533 mm respectively in long-time period [69]. According to detailed chart given Annex III, both wayside and on-board lubricant systems are efficient where medium viscosity lubricants should be preferred. Medium and low pressure are suggested to use depending on lubrication system type. Additionally, the temperature range of the lubricant must be in acceptable range where we suggest to infrastructure managers to take into account not average temperature range, but also number of heating and cooling degree days and the extreme low and high temperature values. Depending on season and low temperature values in winter, icing agents, FM and TOR can be combined with application of lubrication depending on preference again. For further details, please examine the detailed chart given in Annex III.

Depending on this and statement given in D2.7, there is big temperatural change between the summer and winter time whereas the summer season is mostly cold and dry, and the winter season is very cold, windy and snowy. The data collected from Romanian National Meteorological Office website demonstrated that the average temperature in summer rises to at maximum 26°C and for the winter time, it decreased to -1.9°C for 2015 [61]. On the other hand, in generally, the variation in temparatues can be estimated as 23.9°C where the gap is significantly high. The indications about the weather refer that the prepicipation gap between the driest and wettest seasons can reach to 46 mm [69].

Buzău Monthly temperatures 2015 - 2018

	January	February	March	April	May	June	July	August	September	October	November	December
Daytime Temperature	2°C	8°C	12°C	19°C	21°C	27°C	31°C	33°C	27°C	17°C	13°C	8°C
Night-time Temperature	-10°C	-3°C	0°C	6°C	11°C	16°C	17°C	17°C	13°C	5°C	1°C	-5°C
Rainy days	1	4	5	5	11	9	4	3	4	5	7	2
Snow days	4	3	3	0	0	0	0	0	0	0	0	0

Figure 33. The climatic condition of Bužau [70]

Therefore, it is important to choose the lubricant type and system which are able to work under harsh weather conditions. In this case, solid lubricants will be out of our examination scale and we solely focusing on using lubricants have large temperature range and also have high water resistance. The lubricants composed of synthetic oils mixing with lithium-calcium soap or silicate can adaptable to the defined harsh conditions. The usual temperature range of this type of lubricants is between -50°C to 120°C. They are at least 90% resistance to the water. The lubrication systems should be prefered to on-board lubrication systems where wayside lubrication systems have the possibility to fail because of the heavy snow amount and duration. However, if the railway operators have the capability to rearrange their maintenance such as changing nozzle head due to the clogging risk or changing nozzle position etc., the wayside lubrication systems can be convenient. It is important to emphasize in here that as mentioned before the railway operator can choose not to apply the lubrication in winter season like Sweden, Norway, Finland etc.

3.3.3 Turkey

3.3.3.1 Sincan- Kayaş

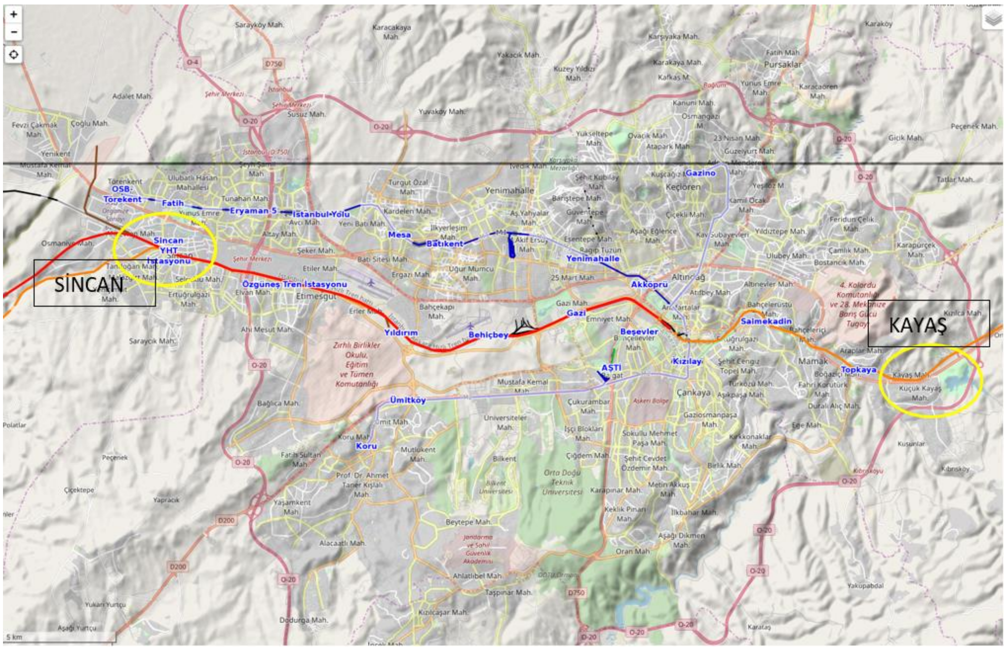

Figure 34. Demonstration of the Sincan-Kayaş Line [60]

Kayas is in the territory of Mamak and its climate type is defined as Csb. The average annual temperature and precipitation are measured as 11.1 °C and 399 mm respectively in long-time period. On the other hand, Sincan is classified as Csa type and the average annual temperature and precipitation are measured as 11.6 °C and 385 mm respectively [71]. Because of both types are sub-climate types of Type C, we suggest infrastructure manager to choose the lubricant and lubrication types for Type C as defined in Annex III.

In spefic examination, sincan-kayas line is near Ankara that is located in the Central Anatolian region. During the summer period, the weather is hot and dry where the maximum temperature can reach near to 40°C. The precipitation is very low comparing to spring season. On the other hand, in the winter season, the average temperature is nearly 11.7°C. The lowest temperature detected during the winter seasons was -24.9°C. The gap in temperature difference is rather higher compared the other regions. In the winter duration, the weather is foggy and snow amount is high. The precipitation during the winter seasons is 389,1 mm annually. The number of the frosted days is changing from 60 to 117 depending on the climate variation. The wind becomes an important parameter for this line because the type of line is high speed. In most cases, northern winds blow over the line and the winds are getting stronger especially in spring time [61].

For high speed lines, the specific lubricants are suggested by the suppliers. These lubricants commonly consist of synthetic and ester base oils where silicate or calcium-sulfonate used as a thickening agent. As high speed can be concluded as burning of the lubricant, the high-speed lubricants should have a high flash point and drop point values and large operating temperature range, in most cases the operating temperature range is from -40°C to 120°C. The on-board lubrication systems should be preferred for high speed lines.

3.3.3.2 Malatya Divriği

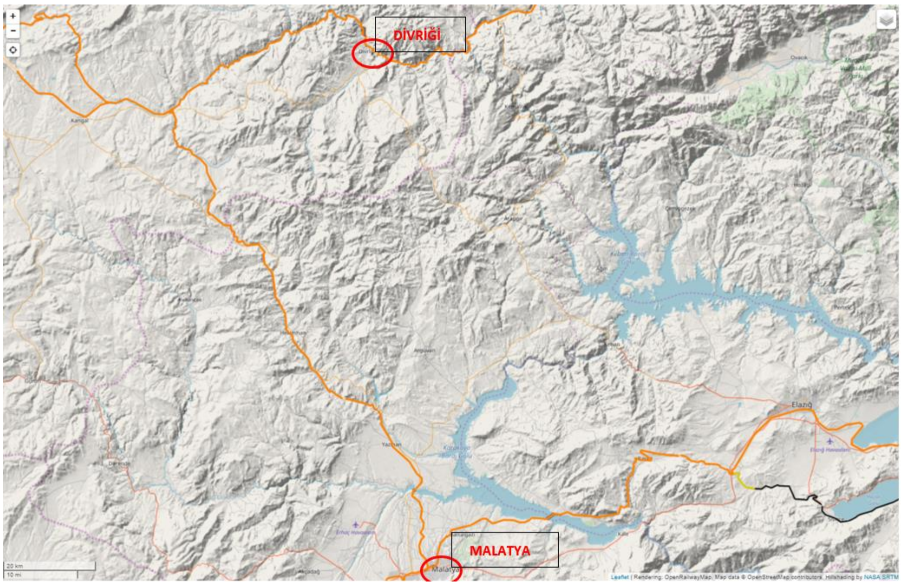

Figure 35. Demonstration of the Malatya-Divriği Line [60]

Divriği is in the territory of Sivas and its climate type was defined as Csa although Dsb sub-climate type is dominated in Sivas. The average annual temperature and precipitation are measured as 11.4 °C and 455 mm respectively [72]. On the other hand, Malatya is classified as Dsb type and the average annual temperature and precipitation are measured as 7.9 °C and 437 mm respectively [73]. As understood, there is climate transition through the line. Based on Annex III, as seen, Type D represent very harsh weather condition comparing to Type C. Hence, we suggest infrastructure manager to select their lubricant and lubrication types with respect to Type D.

As described in D2.7., the weather for this region differs very slightly from the previous region. Because the line is close to East Anatolia, the weather is cold and snowy during the winter season. The snow height is higher than Central Anatolia. The winter season, the average temperature is around 0°C which is very low. The coldest time average temperate was estimated as -4°C, however, in some regions, this value drops to -36°C. Contrary to this harsh winter season, the summer is rather mild where the average temperature is above 19°C and can be able to reach nearly 38°C. As expected, the gap between the temperatures is large which is approximately 74°C annually. The number of days having a temperature below 0°C is calculated as 132. In addition, annually average precipitation is 420 mm. The winter and spring seasons have the higher precipitation amounts. The number of rainy days and snowy day annually calculated as a 105 and 30 respectively. The estimated average elevation snow height is 20 cm. This region opens to strong winds where the 54,2 % of them is northern winds and the remain is various winds [61].

Considering the weather situation of this line, snowing, icing and heavy rain will have a significant impact on the lubrication. As stated in previous evaluations, it depends on the railway operator to use lubrication during the winter time. For this case, on-board lubrication type with a spray or solid can be an option during the spring and autumn seasons. For the winter times, only specific lubricants which have low temperature tolerances should be preferred and if possible combine with icing agents. The lubricant types to overcome these harsh weather conditions have synthetic base that high tolerance in case of freezing issue. The thickening agents or additives can be lithium-calcium soap, silicate in some cases paraffinic oil. The operating temperature range is larger than the traditional ones that can exceed -55ºC to 170ºC. Most of them also have high drop point and water resistance. In point of the lubrication system, the maintenance of wayside lubrication systems for this region will be rather difficult because of the high elevation and rough terrain.

3.3.3.3 Malatya -İskenderun

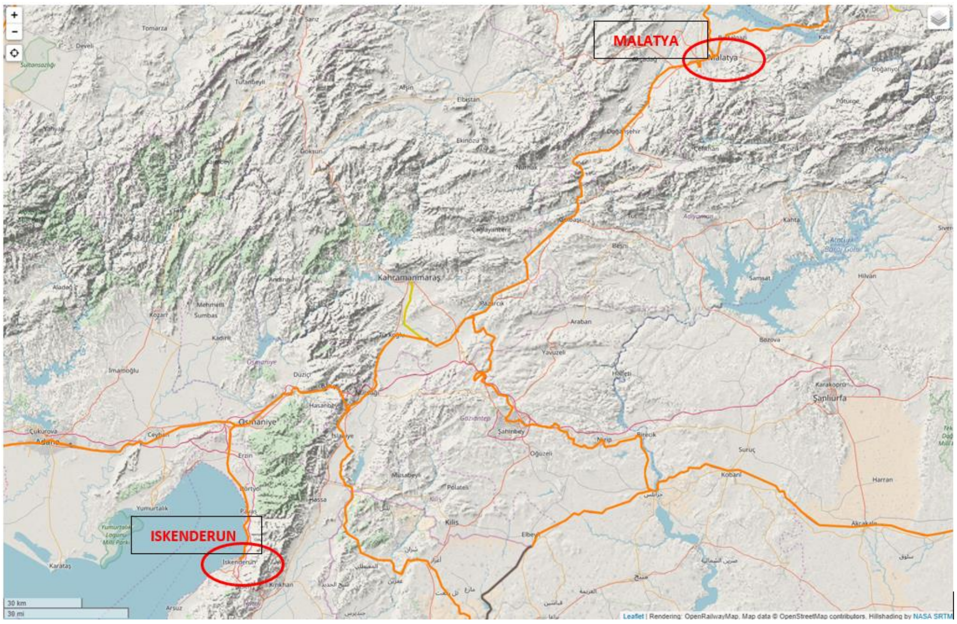

Figure 36. Demonstration of the Malatya-İskenderun Line [60]

Malatya was classified as Dsb type and the average annual temperature and precipitation are measured as 7.9 ºC and 437 mm respectively [73]. The dominated sub-climate types in Kahramanmaras are Csa and Dsb where we approach to Hatay, we see a transition from Dsb to Csa. Because of the study line passes through different locations, we cannot give exact values about average temperature and precipitation, but approximate values are as 10.4-14.1 ºC for temperature and 505-648 mm for precipitation [74]. As predicted, for Iskenderun (Hatay) region, Csa sub-climate type dominates the other sub-climate types. The average annual temperature and precipitation for study line last station are 16.4 ºC and 982 mm respectively [75]. As understood, there is climate transition through the line from Type D to Type C. Based on Annex III, as seen, although type D represent very harsh weather condition comparing to Type C, through the line more than 50% of the line, Type C characteristics are observed. Therefore, we suggest infrastructure manager to select their lubricant and lubrication types with respect to Type C. The reason to choose Type C instead of Type D is that Dsa sub-climate type characteristics are similar to Cfb and Cfc sub-climate types.

The line passing through three different type region that has varied weather characteristics. As stated in the previous examination performed by Malatya-Divriği Line, the weather conditions are excessively harsh and snow and icing become a serious problem during the winter. In summer conditions, the temperature can rise to 40°C. On the other hand for Kahramanmaraş, the climate is milder than the Malatya and the average temperature is estimated at 16.5°C annually. In winter season this average temperature can decrease to -3.7°C. The important parameter in here is the humidity rate which can vary between 50-60 % annually. The last region is Iskenderun. Iskenderun has the hottest climate regime. The average temperature varies from 32 to 34°C in the summer season. The average temperature during the winter is estimated as an 18°C annually. To see snow and icing problems are very rare. The number of the sunny days 88.3. The range of the precipitation is changing between 600 to 1000 mm due to wind conditions. The crucial parameters for this region are temperature and humidity [61].

Through the line, there are three different weather regime. To decide which lubricant is the best for the system, lubricant temperature range scale and their water resistance percentage should be examined. In fact, most of the lubricants whether applied on wheel/flange or rail flange, have an extended temperature rage from -55°C to 170°C. In addition their water resistance is higher than 90% which means that loss during high precipitation is low. However, with humidity and unexpected heat on the rail, few amounts of the lubricants can vaporize during the movement of the rolling stock. Therefore, using solid lubricants can be a solution for the loss amount of the lubricant due to the dissipated heat originating from the friction. During the selection, solid lubricant temperature range must be evaluated if it is so close to the ambient temperature, the solid lubricant should not be used, instead of this, liquid lubricants having higher temperature range should be preferred. Liquid lubricants are composed of synthehic or vegetable oil as base and Lithium or calcium-sodium agents can be preferred. It is necessary to emphasize that sodium (Na) based agents have tendecy to become more soluble under rainfall that can cause corrosion. For the lubrication systems, in terms of maintenance, as known, on-board lubrication systems have an advantage, however, depending on the choice of the infrastructure manager, wayside lubrication systems can also be efficient if they are managed correctly. The lubrication can be selected as rail flange or wheel flange lubrication type.

4 Conclusion and Remarks

The maintenance of the track has a direct relationship with the line specific characteristics, density, capacity, traffic, fastening systems, track geometry and also ballast. Every year, several operators have been paying an incredible amount to perform inspection, maintenance and renewal of track infrastructure. The aim of this deliverable was, first of all, to provide a general view about the relationship between maintenance, lubrication and track deformation (wear and damage) and then reduce the content in more specific to lubrication impacts. To describe the lubricant effectiveness on the rail or wheel/flange, it is important to understand the working mechanism of the lubrication system so that a detailed view including the pros and cons of the existing lubrication systems are covered in this deliverable.

After the detailed examination of the lubrication systems in perspective of their performance, environment, safety and health perspectives; the lubrication types and their behaviours supported by researches are analysed. In depth-in analysis about the impact of the extreme climatic conditions on the lubricants with the support, literature is performed and considering the results of tests applied in several countries and also feedbacks gathered through communication done with suppliers, the lubrication and its system selection was executed for the study lines in accordance with D2.7 outputs.

The main findings as a result of research performed during the preparation of this deliverable are:

1) Although the suppliers recommend their products in a simple way by looking at the line type and lubricant basic characteristic as well as their customer demands, most of them discarded the weather conditions and track situation.
2) Most of the lubricants products have similar features, the majority of them are composed of synthetic and ester-based oils and few of them includes vegetable oils, therefore, for the railway sector, alternatives are restricted. These kinds of lubricants classified as a biodegradable and have extended range temperature range and durable to extreme weather conditions if they supported with thickening agents.
3) Climatic conditions have a significant impact on the selection of the lubrication that affects their effectiveness, durability and consumption amount which indirectly influence the maintenance cost of the track and decrease to track wear and damage.
4) In this study, track situation, line specification such as speed and the existing fastening systems are not considered, the selection of the lubricants and the related systems only made according to climate conditions, line densities and the usage area (line type) of the lubrication systems. During the selection, FM and TOR application are also ignored because of the restricted information collected from the suppliers where their usage commonly preferred in specific conditions such as needing additional friction in curve sections or minimizing the rail head deformation and cracks. However, as stated before, to address the FM or ToR applications, the track status must be known because if the friction is sufficient

on the rail and FM applied, in high possibility it may lead to damage by creating unnecessary friction.

5) Through written and/or verbal communication with suppliers, it is realized that although suppliers in Europe have been providing the necessary information about environmental, safety and health impacts of their products and related the protection measures in case of exposure of the lubricant, in Turkey, majority of the suppliers have not informed their customers about lubricants' potential negative impacts on human health and environment.

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Annex I: Forms

Form 1 - Product Characteristics

The form is based on the sample safety data sheet, thereof, if you are planning to send the safety sheet data of your product(s), you do not need to fill this form. However, please check "**Section 7 – Physical and Chemical properties**" part if anything is missing in your product(s)' safety sheet data(s) and complete the **"Identification"** part for your product(s). To complete our research, ***we also need information about pour point, flashpoint, base oil viscosity (@40°C) and viscosity index parameters of your product(s)***.

1. Identification	
Product name	
Product type	
Supplier's details	
In which countries and cities, you are exporting your product(s)?	
2. Hazards Identification	
OSHA / HCS Status	
Classification of the substance or mixture	
GHS Label elements:	
Signal word	
Hazard Statements	
Precautionary statements:	
General	
Prevention	
Response	
Storage Disposal	
Hazards not otherwise classified	
3. Composition /Information about Ingredients	
Substance / Mixture	
Other means of identification	
CAS Number / other identifiers	
CAS Number	
Product Code	

Ingredient Name (if possible please give % and CAS Number)	
4. Accidental Release Measures	
For non-emergency personnel	
For emergency responders	
Environmental precautions	
Methods and materials contaminated and cleaning up	
Small Spill	
Large Spill	
5. Handling and Storage	
Protective measures	
Advice on general occupational hygiene	
Conditions for safe storage including any incompatibilities	
6. Exposure Controls / Personal Protection	
Occupational exposure limits	
Appropriate engineering controls	
Environmental exposure controls	
Hygiene measures	
Eye/face protection	
Skin protection	
Hand protection	
Body protection	
Respiratory problem	
7. Physical and Chemical Properties	
Physical state	
Colour	
Odor	

Odor threshold	
pH	
Melting point	
Boiling point	
Flashpoint	
Pour point	
Base oil viscosity @40°C (mm^2/s)	
Evaporation rate	
Flammability (solid, gas)	
Lower an upper explosive (flammable) limits	
Vapor pressure	
Vapor density	
Relative density	
Solubility	
Partition coefficient: n-octanol / water	
Auto-ignition temperature	
Decomposition temperature	
Viscosity	
Viscosity Index	
Volatility	
8. Stability and Reactivity	
Reactivity	
Chemical stability	
The possibility of hazardous reactions	
Conditions to avoid	
Incompatible materials	
Hazardous decomposition products	
9. Toxicological Information	
Acute toxicity	
Irritation /corrosion	
Sensitization	
Carcinogenicity	

Specific target organ toxicity (single exposure)	
Acute toxicity estimates (ATE value)	
10. Ecological Information	
Damage to the environment (please, describe if it as minor, moderate or major)	
Mobility in soil	
Soil/water partition coefficient (K_{oc})	
Other adverse effects	
11. Disposal Considerations	
Disposal methods	
12. Certification and Regulation	
If the product has certification(s) please state in here such as ecolabeling etc.	
13. Specific Comments	
Please state in here if you have any comments about your products.	

Form 2 - Product Preference according to Climatic Conditions and Line Densities

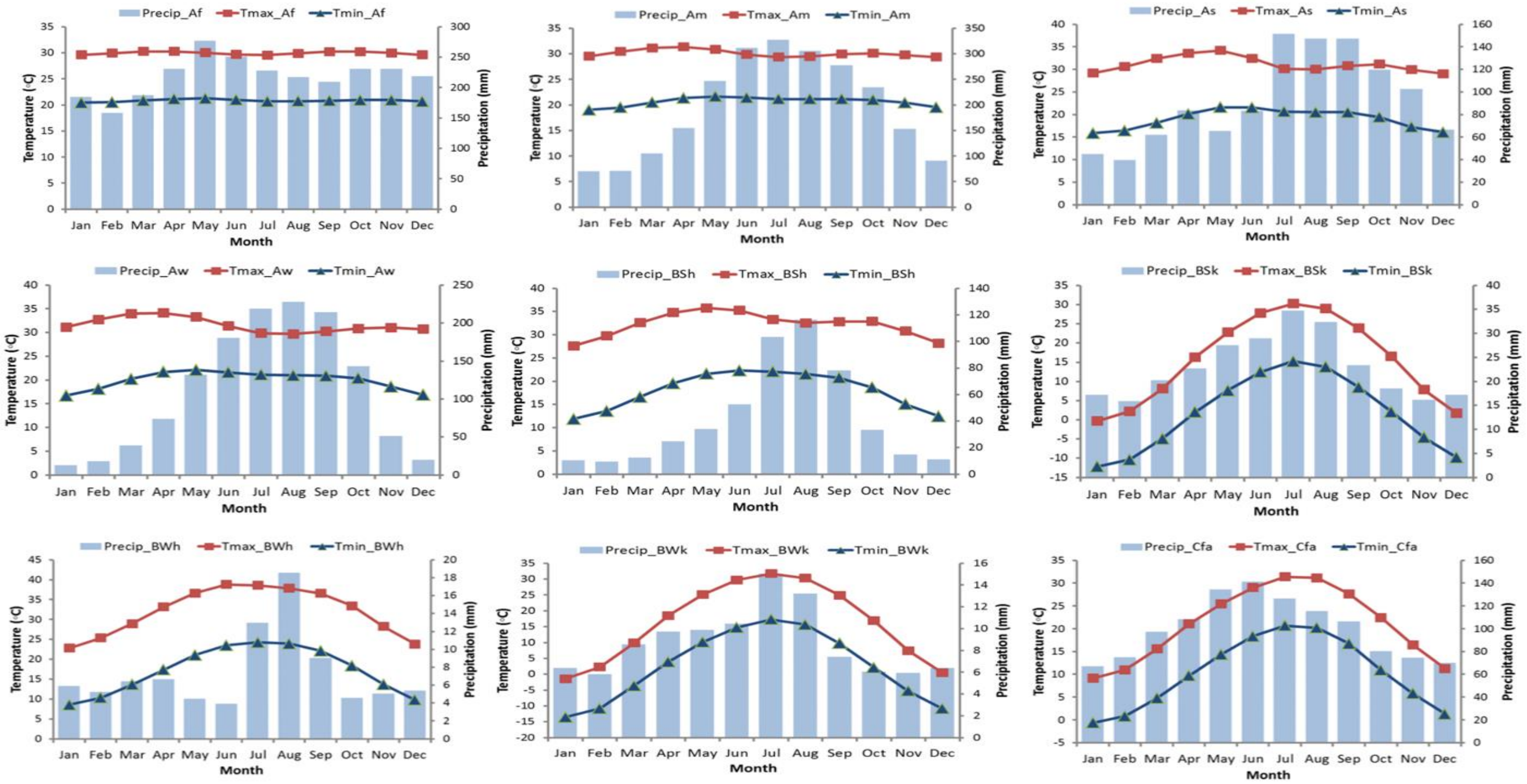
The form is designed to define which lubrication type(s) or characteristic is better with respect to specific climate conditions and line densities. **The information you give to us will be input for GIS mapping**. Hence, please identify your product characteristics according to given questions.

1. Identification	
Product name	
Product type	
In which countries and cities, you are exporting your product(s)?	
If possible, please state your product cost or cost range.	
2. Climatic Conditions	
While suggesting your products depending on the customer needs, do you recommend your products considering climatic conditions of the district/region/city?	
If your answer is "YES", what kind of parameters do you consider while choosing the right product?	
For extreme low or high temperatures /humidity/precipitation/icing/snow/wind, do you suggest your customer change their lubrication type? If your answer is "YES", please give a detail information.	
If your answer is "NO", what kind of methods do you recommend to your customers? For instance, do you recommend to dilute the current product with additives?	
3. Line Density Conditions	
While suggesting your products depending on the customer needs, do you request any information related to line density from your customers?	
If your answer is "YES", what kind of specific parameters do you consider while choosing the right product?	
For low-density line, which of your product is giving the best results?	
For high-density line, which of your product is giving the best results?	

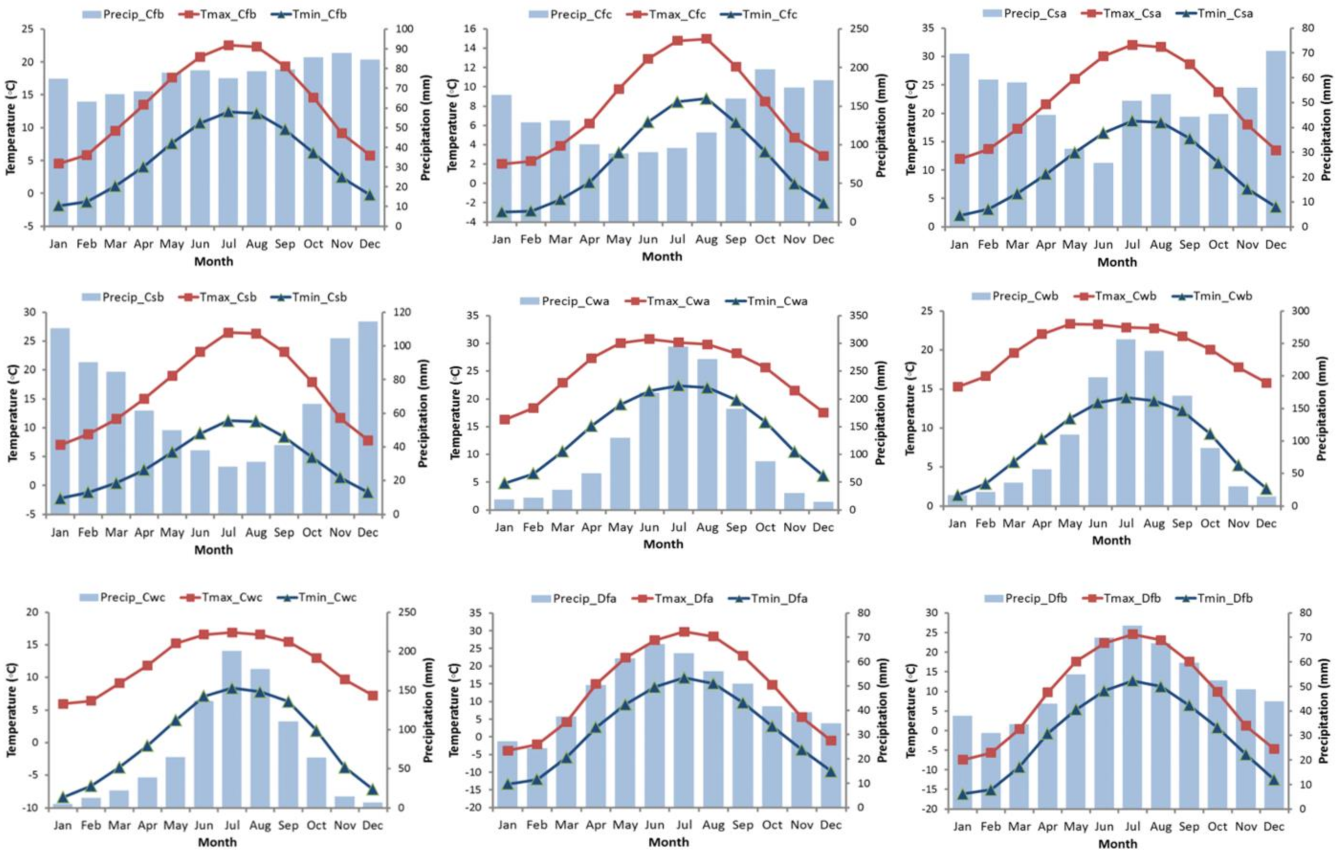
4. Safety Conditions	
Do you inform your customers about the safety conditions of your products? For instance, storage, usage methods etc.	
Have you ever tested your product toxicity or measured hazard range to the environment?	

Annex II: The average monthly pattern of rainfall and temperature for Köppen-Geiger zones [76]

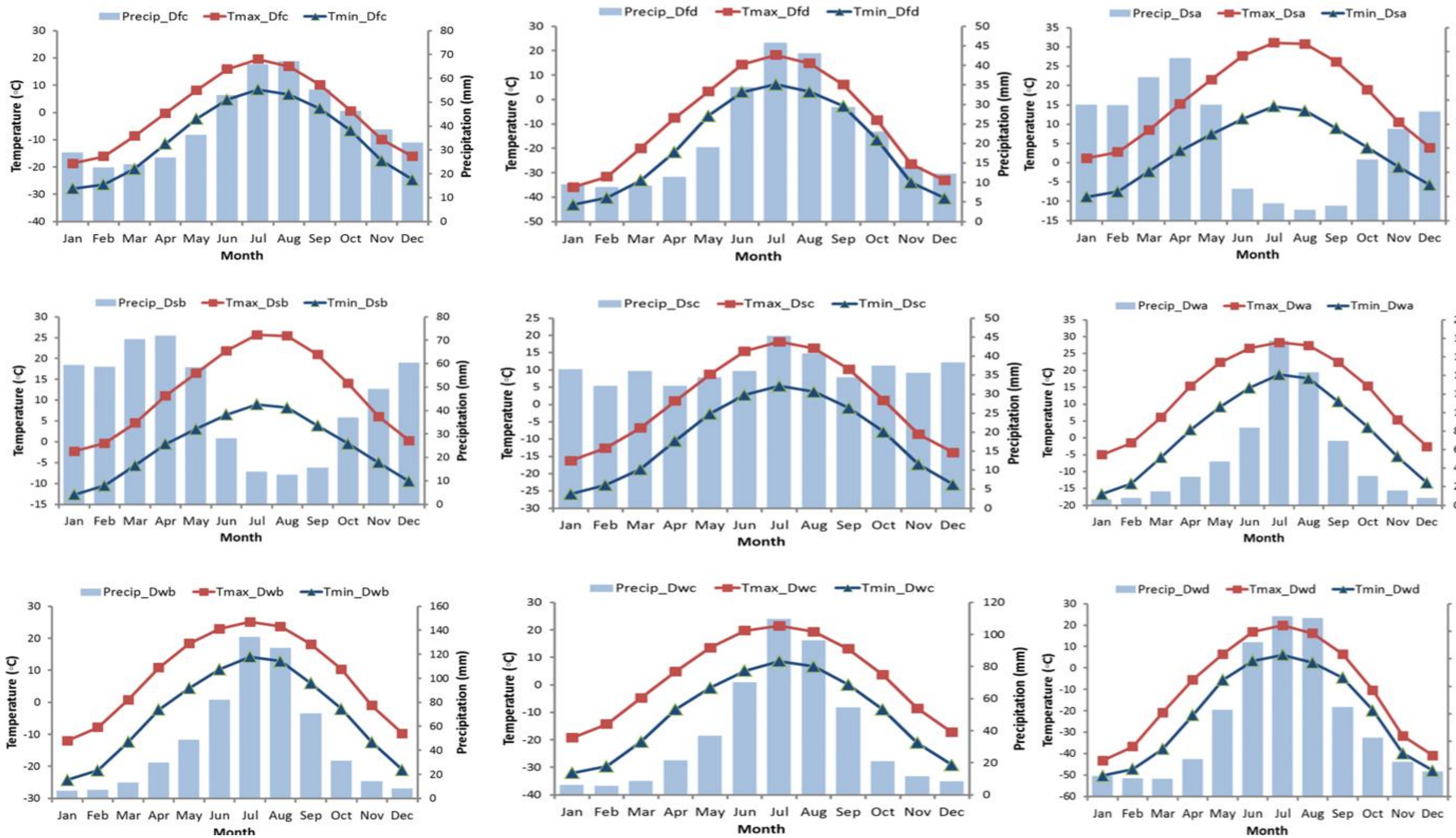
For the Northern Hemisphere



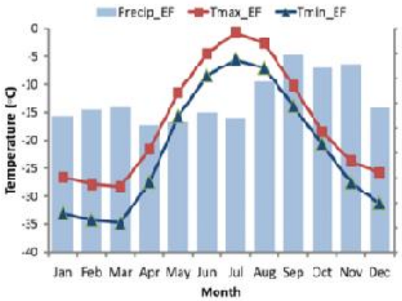
For the Northern Hemisphere

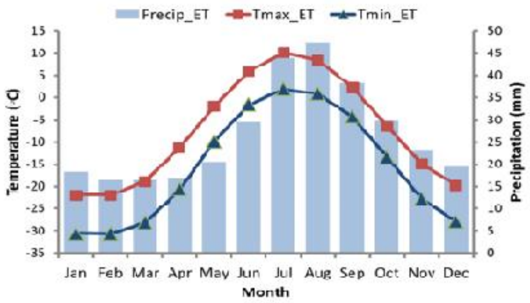


For the Northern Hemisphere

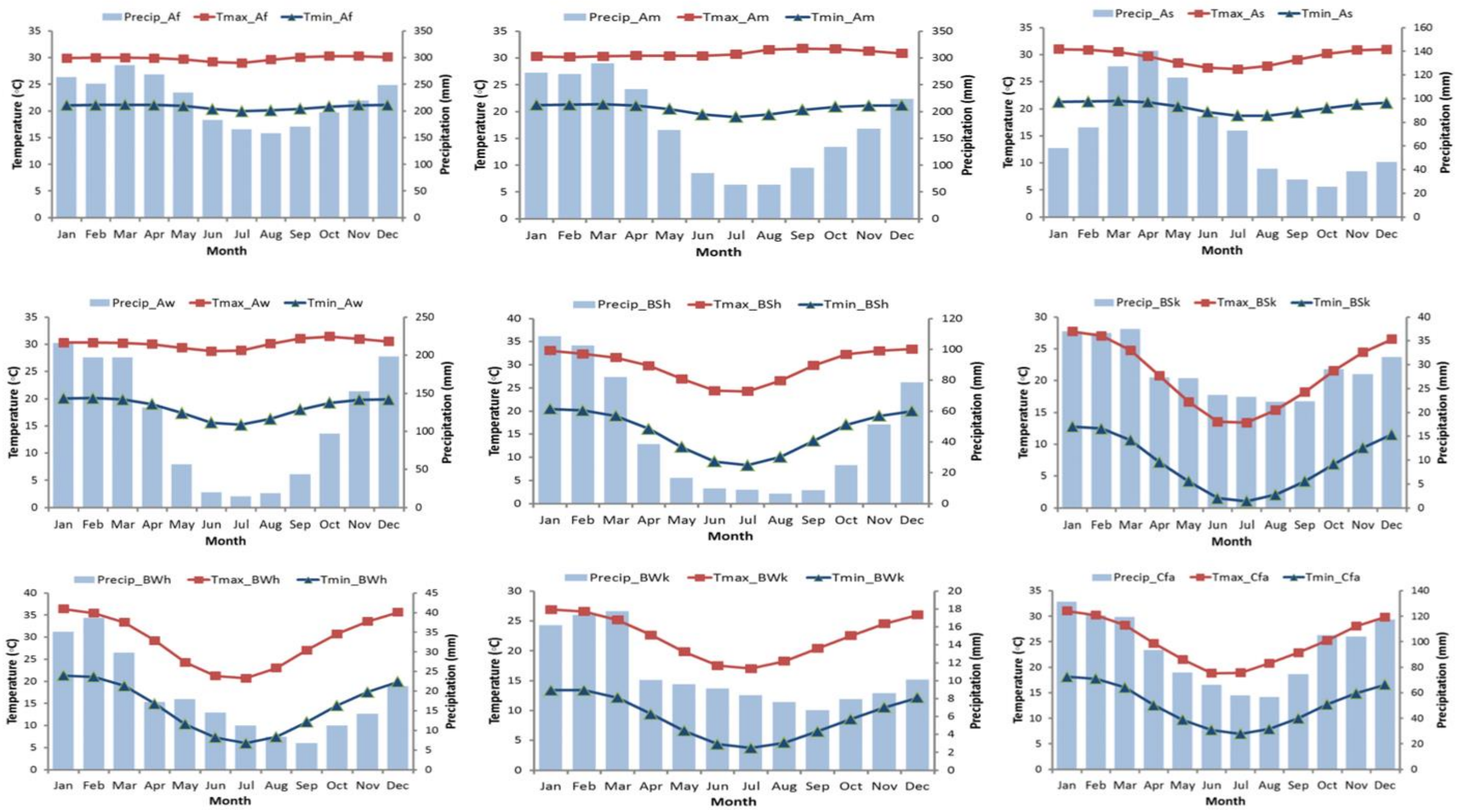


For the Northern Hemisphere

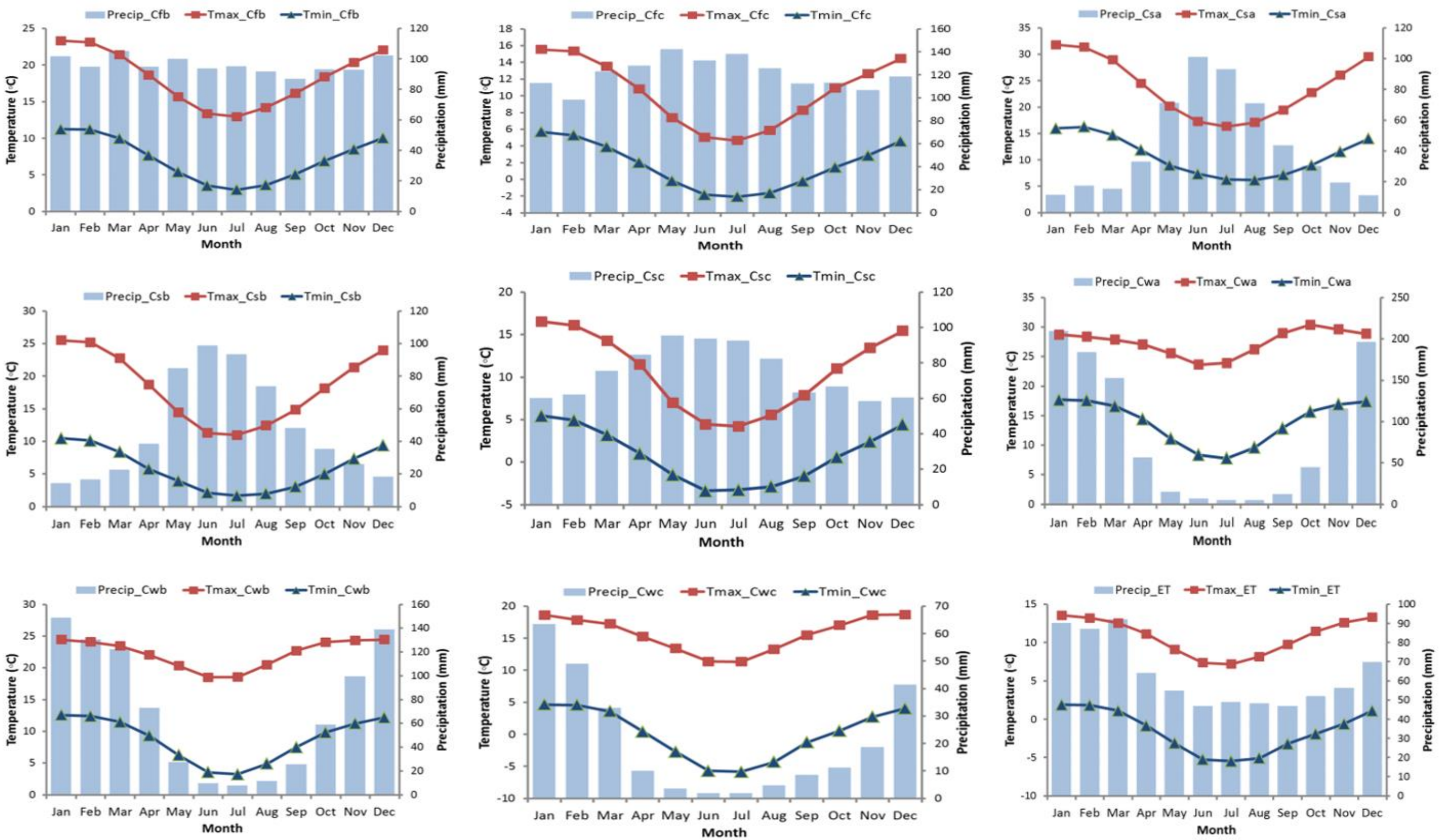




For the Southern Hemisphere



For the Southern Hemisphere



Annex III: Selection Methodology – Flowchart