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Project Report:

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Underground pipelines and railway infrastructure - Failure consequences and restrictions

Swedish Title:

Underjordiska rörledningar och järnvägsinfrastruktur – Konsekvenser och begränsningar av ledningsbrott

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Executive summary

Underground pipelines are an essential part of the railway and road infrastructure. The structural deterioration of pipelines crossing railways and their subsequent failures are critical for society and industries resulting in safety, direct and indirect costs and various risks for all the related stakeholders. Therefore, a continuous and accurate condition assessment is critical for the effective management and maintenance of pipeline networks within transportation infrastructure. The main goal of pipeXrail is to improve the operability and functionality of transport infrastructure at the pipeline - railway cross sections. An essential development to reach this goal is to have a better understanding of failure mechanism and related failure modes and their consequences at such a physical location. This report gives a summary of condition assessment of pipeline and its assets from pipeline, soil and railway perspectives. Furthermore, different statistical and predictive analytical models for diagnostic and prognostic modelling have been discussed for pipeline asset. Due to low availability of pipeline condition assessment data for PipeXrail, a hybrid prediction methodology has been described in the report for better performance prediction of the asset condition status. The aim of hybrid modelling approach is to integrate physical models and data-driven models including knowledge-based model in a systematic way.

The study is based on qualitative condition assessment. Inputs from expert opinion has been collected through two sets of questionnaires and interview with water and wastewater departments at municipalities, utility companies and Trafikverket databases. Questionnaires have been distributed to the 291 municipalities in Sweden. The Failure Mode and Effect Analysis (FMEA) have been performed to identify dominant failure modes at cross-sections with railway infrastructure. The FMEA analysis revealed that pipe deformation has higher impact followed by pipe rupture at the cross-section with railway infrastructure. Furthermore, for underground pipeline under railway infrastructure, aging and external load gets higher ranks among different potential failure causes to the pipeline. Finally, the risk priority number (RPN) has been evaluated. Severity, occurrence, and detectability are three main factors for evaluation of RPN. Our analysis shows the PRN index for erosion/corrosion has the highest value which means if the resources are limited this hazard should be treated first.

In PipeXrail study, two approaches for risk assessment were developed. The developed risk assessment approach involves estimating the current status of pipelines as well as determining the consequences of failure. In the first approach, economy, safety & health and environment were considered as the main key factors for the estimation of the failure consequences. In the second approach, direct costs, indirect costs, and social costs have been divided into several subfactors and multi-criteria matrix has been evaluated of the consequences of the failure. The result shows that pipe rupture and crack falls in the area with the highest consequences of the risk matrix. The risk assessment approach presented in this work provides valuable information for municipalities to prioritize the inspection process.

Based on our investigation and literature review, we found that few water utilities in Europe are trying to implement preventive maintenance for pipeline rehabilitation policies. The majority following in corrective maintenance strategy and there are only a few cases that are concentrating on rehabilitating strategy for maintaining pipelines before they wear out. This is

in opposite for Trans European oil and gas pipelines even water and wastewater infrastructure may have similar importance to the local stakeholder. In Sweden, most of the municipalities are aware of the advantages of predictive-based maintenance. In addition, we found that unavailability of data is not restricted to the pipelines at cross sections with railways. Maintenance managers are also challenged with poor availability and quality of data for the buried pipeline in an urban area due to the old pipeline network structure and its connected facilities. Hence, there is a need to use new condition monitoring tools in terms of hardware such as sensor-based technologies, software & data management tools. The success of implementing a proactive approach obviously depends on the criteria used for rehabilitation planning. This strategy should be integrated into the prediction of future pipe failures, the reliability of the water network serving the customers and the cost of improvements. If this information is available, it will be possible to optimize the rehabilitation programs.

During the course of PipeXrail study, we have faced with poor availability and quality of condition assessment data at cross-sections. This issue can be explained via less penetration of advanced condition assessment tools for health assessment of pipeline networks. Furthermore, lack of data integrity is also an important issue leads to small databases. Each municipality has their own reported system and acting in an individual form which restricts comprehensive data analysis, future prediction and remaining useful life estimation of the pipeline at the cross-section and pipeline in the urban area.

There were less amount of interest and investment toward operation and maintenance of pipeline by advance condition assessment tools and related technology, which leads to the creation of a big gap between required level and the actual level of maintenance characterized by so-called “maintenance debt”. Hence, extra efforts are required to close the gap and reach to the state where required maintenance of pipeline network coincide with the actual status of pipeline maintenance. In addition, implementation and utilization of digitalization and artificial intelligence (AI) techniques can convert the current pipeline/infrastructure maintenance engineering to smart infrastructure maintenance. We believe that maintenance debt can be reduced through smart infrastructure maintenance via installation of sensors for collection and analysis of a new set of data for condition health monitoring of buried pipeline. Smart infrastructure maintenance will enable pipeline maintenance to be more efficient, aligned with current and future maintenance technology.

Pipelines degradation at cross-section with railway may be affected by pipe feature, soil properties, and railway interaction, hence in the last section, recommendation for maintenance and construction of a pipeline under railway infrastructure from a different perspective have been discussed.

Utilization of the proposed approach will lead to better services to the customers, for instance, all municipalities that have railway infrastructure in their vicinity, Trafikverket, and Water supply and construction companies. The proposed framework can be extended for developing maintenance technology solutions of underground pipelines network crossing road and railway.

Keywords: Pipeline, Operation maintenance, pipe failure mode, Pipe crossing railway, Remaining useful life of pipeline, Pipe prognostic

Sammanfattning:

Underjordiska rörledningar är en väsentlig del av järnvägs- och väginfrastrukturen. Den strukturella försämringen av rörledningar under järnvägarna och deras efterföljande fel är av stor betydelse för samhället och industrin, vilket medför direkta och indirekta kostnader för alla intressenter. Därför är kontinuerlig och noggrann bedömning av tillstånd kritiska för effektiv hantering och underhåll av rörledningsnät inom transportinfrastrukuren. Det övergripande målet med pipeXrail är att förbättra driften och funktionaliteten hos transportinfrastrukturen för avgränsningen rörledning – järnväg. En viktig utveckling för att nå detta mål är att få en bättre förståelse för felmekanismen och relaterade misslyckanden och deras konsekvenser vid sådan fysisk plats. Denna rapport ger en sammanfattning av tillståndsbedömningen av rörledningar och dess tillhörande utrustningar sett utifrån ett från rörlednings, mark och järnvägsperspektiv. Vidare har olika statistiska och prediktiva analysmodeller för diagnostisk och prognostisk modellering diskuterats för rörledningstillgångar. På grund av den låga tillgängligheten av pipeline-tillståndsbedömningsdata för PipeXrail har en hybridprediktionsmetod beskrivits i rapporten för bättre resultatprestation av statusen för tillståndet hos dessa anläggningar. Huvudsyftet med hybridmodelleringsmetoden är att integrera fysiska modeller med datadrivna modeller, inklusive kunskapsbaserad modell på ett systematiskt sätt.

Studien bygger på kvalitativ bedömning av tillstånd och expertutlåtanden har samlats in genom två uppsättningar av enkäter och intervjuer med vatten och avloppsvattenavdelningar i kommuner, vatten- och avloppsföretag samt Trafikverket databaser. Frågeformulär har delats ut till de 291 kommunerna i Sverige. Failure Mode and Effect Analysis (FMEA) har utförts för att identifiera dominanta haverier vid dessa avgränsningar (tvärsnitt med järnvägsinfrastruktur). FMEA-analysen visade att rördeformation har högre felpåverkan följt av rörbrott i tvärsnitt med järnvägsinfrastruktur. För underjordiska rörledningar under järnvägsinfrastruktur får åldrings- och yttre belastningar dessutom högre rang bland olika potentiella fel på rörledningarna. Slutligen har riskprioritetsnummer (RPN) utvärderats. Allvarlighet, förekomst och detekterbarhet är tre huvudfaktorer för utvärdering av RPN. Vår analys visar PRN-indexet för erosion/korrosion har det högsta värdet vilket betyder att om resurserna är begränsade bör denna fara behandlas först.

I PipeXrail-studien utvecklades två metoder för riskbedömning. Den utvecklade riskbedömningsstrategin innebär att man bedömer rörens nuvarande status samt bestämmer konsekvenserna av fel. I det första tillvägagångssättet betraktades säkerhet och hälsa och miljö som huvudnyckelfaktorerna för uppskattning av konsekvenserna av felen. I det andra tillvägagångssättet har direkta kostnader, indirekta kostnader och sociala kostnader delats upp i flera delfaktorer, och flera kriterier har utvecklats för utvärdering av konsekvenserna av felen. Resultateten visar att rörbrott och sprickor faller i området med högsta konsekvenser. Den riskbedömning som presenteras i detta arbete ger därmed värdefull information för kommunerna att prioritera inspektionsprocessen.

Baserat på vår granskning och litteraturbedömning fann vi att få vattenföretag i Europa försöker genomföra förebyggande underhåll för rörledningar. Majoriteten av genomförda strategier definieras i re-action-strategin och det finns endast några fall koncentrerat på rehabiliterande

strategi för att upprätthålla rörledningarnas status innan de slits ut. Detta står i motsats till transeuropeiska olje- och gasledningar, även infrastruktur för vatten och avloppsvatten kan ha liknande betydelse betydelse för den lokala intressenten. I Sverige har de flesta kommuner varit medvetna om mottagaren av utnyttjandet av förutsägbart baserat underhåll. Dessutom fann vi att otillgängligheten av data inte är begränsad till rörledningarna vid tvärsnitt med järnvägs- och underhållsansvariga. Dålig tillgång och kvalitet av data för nedgrävda rörledningar i stadsområdet är också ett problem. Andra orsaker är den gamla ledningsnätstrukturen och dess anslutna anläggningar . Därför behövs nya krav för övervakning när det gäller hårdvara som sensorbaserad teknik, programvara och datahanteringsverktyg. Framgången med att genomföra ett proaktivt tillvägagångssätt beror självfallet på de kriterier som används för återställandeplanering. Dessa kriterier bör kopplas till förutsägelsen av framtida rörfel, tillförlitligheten i vattennätverket som betjänar kunderna och kostnaderna för förbättringar. Om denna information är tillgänglig kommer det att vara möjligt att optimera rehabiliteringsprogrammen.

Under PipeXrail-studien har vi konstaterat dålig tillgänglighet och kvalitet av tillståndsbedömningsdata i ovan nämnda avgränsning . Dessa resultat kan förklaras genom otillräcklig förmåga hos bedömningsverktygen för rörledningsnäten tillstånd. Dessutom är brist på dataintegritet också en viktig fråga som leder till små databaser. Varje kommun har sitt eget rapporterade system och handlar i en individuell form som begränsar omfattande dataanalys, framtida förutsägelse och återstående nyttjandeperiod av rörledningen vid den aktuella avgränsningen och rörledningen i stadsområdet.

Det fanns mindre intresse och investeringar av drift och underhåll av rörledningar med hjälp av förhandsbedömningsverktyg och relaterad teknik vilket leder till skapandet av ett stort gap mellan den önskade nivån och den faktiska underhållsnivån som kännetecknas av så kallad "Maintenance Debt" .Därför krävs extra insatser för att stänga klyftan och nå till status där det erforderliga underhållet av rörledningsnätet sammanfaller med den faktiska statusen för pipelineunderhåll. Dessutom kan implementering och utnyttjande av digitalisering och artificiell intelligens intelligens (AI) -teknik omvandla den nuvarande rörledningen / infrastrukturunderhållstekniken till smart infrastrukturunderhåll. Vi tror att underhållsskulden kan minskas genom smart infrastrukturunderhåll via installation av sensorer för insamling och analys av en ny uppsättning data för tillståndsövervakning av jordgrävning av nedgrävda rör. Genom underhåll av smarta infrastrukturer kan underhållet av rörledning bli effektivare, anpassat till nuvarande och framtida underhållsteknik.

Rörledningarnas nedbrytning i tvärsnitt med järnväg kan påverkas av rörfunktion, markegenskaper och järnvägssamverkan. Därför har rekommendation om underhåll och konstruktion av en rörledning under järnvägsinfrastruktur från ett annat perspektiv diskuterats.

Utnyttjande av föreslagna tillvägagångssätt leder till bättre service till kunderna, till exempel alla kommuner som har järnvägsinfrastruktur i närheten, Trafikverket och Vattenförsörjning och byggföretag. Det föreslagna ramverket kan utökas för att utveckla underhållsteknologilösningar av tunnelbanelinjer för nätverksöverföring av väg och järnväg.

Nyckelord: Rörledning, Driftunderhåll, Rörsviktsläge, Rörkorsningsjärn, Återstående livslängd för rörledning, Rörprognos.

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Glossary of terms

Pipeline Failures, Faults, and Errors

The term failure is sometimes confused with the terms *fault* and *error*. Hence, it is important to have a clear understanding of these terms. These terms have been defined according to IEC50(191) [1].

Error: an ***error*** is a “discrepancy between a computed, observed or measured value or condition and the true, specified or theoretically correct value or condition.” An error is not a failure because it is within the acceptable thresholds of deviation from the desired performance.

Failure: Failure is the event when a required function is terminated (exceeding the acceptable limits),

Fault: Fault is “the state of an item characterized by an inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources” IEC50(191) [1]. A fault is hence a state resulting from a failure. For instance, it is supposed that the pipeline flow rate is 5 m/s however due to failure this rate decreases to 2m/s.

The relation between these terms (Error, Failure, and Fault) have been depicted in Figure 1.

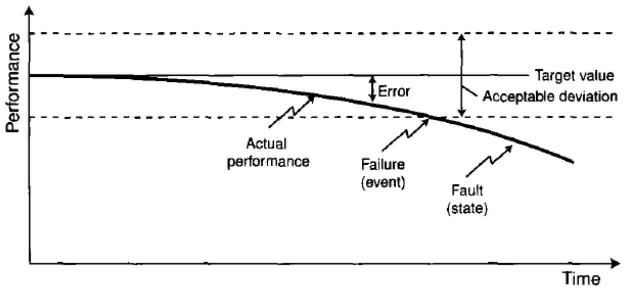


FIGURE 1: DIFFERENCES BETWEEN ERROR, FAULT, AND FAILURE [2]

Generally, pipe failures can be classified based on the type and size of the pipe. Pipe failure occurs when the pipe cannot withstand the fluid internally within the pipe–either the strength is too low (from wrong material selection, fatigue, stress corrosion, etc.) or the stress is too high (overloads due to increasing axle load, increase traffic frequency, loss of wall thickness etc.) resulting in an interference zone between loads and strengths.

It is important to note that municipal pipeline systems like water and wastewater and even natural gas distribution systems tolerate some amount of leakage (unlike most transmission pipelines). Therefore, they might be considered to have a failure in the system only when the leakage becomes excessive by some measure. Due to the railway transport system impact on the pipeline at the cross-section, the definition of the failure at such location depends on the health of rail, means that the leakage itself may not pass the threshold but railway infrastructure has been affected by such leakages.

Failure rates

A failure rate is defined as a number of failures over time. Investigation of failure rate over the previous period of the time can provide some insight about the prediction of the number of failures expected in the specific period in the future. Failure behavior can be categorized according to the behavior of the failure rate over time. Figure 2 illustrates the well-known “bathtub shape of failure rate changes over time. This general shape represents the failure rate for many manufactured components over their lifetime.

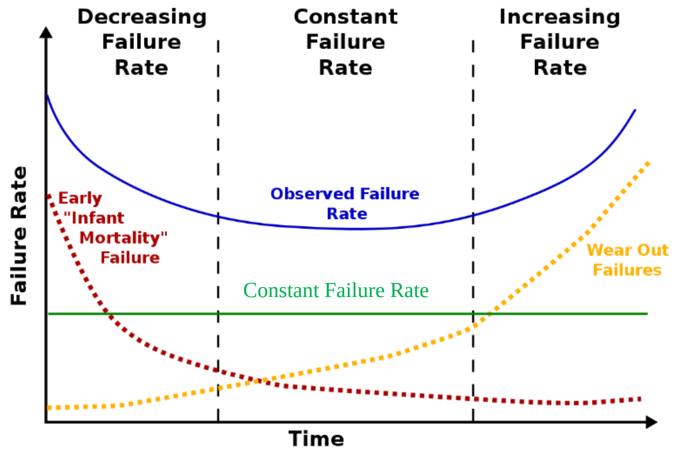


FIGURE 2: FAILURE RATE & BATHTUB CURVE

Some of equipment or installations have a high initial failure rate. As given in Figure 2, the first portion of the curve is called the burn-in phase or infant mortality phase. Here failures are mainly due to defects in the manufacture of a component (material, design) or installation of pipes. The high failure probability drops to the lowest when the construction completed and pipes begin their normal operation. This decreasing failure rate typically lasts several weeks to a few months.

In the second portion of the pipeline life, the pipeline failure rate remains constant. Note that pipeline like other long-life assets spends most of their lifetimes operating in this flat portion of the bathtub curve. After a specific period of time, the failure rates may tend to increase which is the beginning of the wear-out zone (third phase). When pipes are considered in wear out zone rehabilitation or replacement should be carried out.

The relation between the failure rate and failure mechanisms of the pipeline are shown in Table 1:

TABLE 1: FAILURE MECHANISMS & FAILURE RATE

Failure Mechanisms	Failure Rate	Nature of Mechanism
Cracking	Increase	Age, Usage
Material degradation	Increase	Age, Usage
Corrosion	Increase	Age, Usage
Material defect	Increase, Constant	Age, Stress

Pipe rupture	Increase	Age, Usage
Deformation	Increase	Age, Usage

Pipeline *failure causes:* Failure cause is "the circumstances during design, manufacture or use that have led to a failure" IEC50(191) [1]. Investigation of failure cause leads to have a better understanding of the failure mechanism and to mitigate similar failures in the future. In general, failure causes may be classified as a design failure, manufacturing failure, aging failure, misuse failure, mishandling failure [2].

Reliability: According to Standardization [3] definition, the reliability of a system is defined as "The ability of the system to perform a required function, under given environmental and operational conditions and for a stated period of time".

Minimal repair: When the reliability of the repaired pipeline is exactly the same just before and immediately after the corresponding repair. The situation is termed *minimal repair*.

Predictive model: The models used for prediction of future failures & remaining life estimation.

Rehabilitation: All methods for restoring or upgrading the performance of an existing pipeline system. The rehabilitation term includes repair, renovation, renewal, and replacement.

Renewal: Construction of a new pipe, which fulfills the same function in the distribution system but does not necessarily have an identical path as the pipe is replacing.

Renewal process: A failure process for which the times between successive failures are independent and identically distributed with an arbitrary distribution. When a component fails, it is replaced by a new component of the same type, or restored to "as good as new" condition.

Renovation: Methods of rehabilitation in which all or part of the original fabric of a pipeline are incorporated and its current performance improved. Relining is a typical example of pipe renovation.

Acute Repair: An unplanned maintenance activity carried out after the occurrence of a failure. After the repair, the system is restored to a state in which it can perform a required function (e.g. supplying water). (Rectification of local damage).

Repairable system: Repairable systems are those systems that can be restored to a fully satisfactory performance by a method other than replacement of the entire system.

Availability: The availability, $A(t)$ at time t is the probability that pipeline networks are functioning at time t. The average availability $A_{av}(t)$ denotes the mean proportion of time the asset is functioning. If we have an asset that is repaired to an "as good as new" condition every time it fails, the average availability is

$$A_{av} = \frac{MTTF}{MTTF + MTTR}$$

where MTTF (mean time to failure) denotes the mean functioning time and the MTTR (mean time to repair) denotes the repair time of the asset. The average availability, $A_{av}(t)$ is used in network reliability analysis.

Qualitative trend analysis approaches: Trend analysis is an important step in process monitoring and supervisory control. Trend modelling can be used to explain the various important events that happen in a process, to diagnose malfunctions and to predict future states.

Support vector machine (SVM): This model is one of the supervised machine learning models for data analyzes used for classification and regression analysis.

Principal component analysis (**PCA**): PCA is a dimensional reduction approach to convert a set of observations of possibly correlated variables (entities each of which takes on various numerical values) into a set of values of linearly uncorrelated variables.

RAMS: is an acronym for Reliability, Availability, Maintainability, and Safety and is a well-known method of estimating the operational availability of a system by assessing failure modes, frequencies and consequences.

AHP: Analytical Hierarchy Process.

GRNN: General Regression Neural Network.

MLP: Multilayer Perceptron.

RWT: Remaining Wall Thickness.

MLR: Multiple Linear Regression.

VA: Water and wastewater, “Vatten och avlopp”.

1. Introduction

1.1. Background

Underground pipelines are an essential part of the road and railway infrastructure globally and in Sweden. The structural deterioration of pipelines, in general, and in crossing railways and their subsequent failures are critical for society and industry resulting in direct and indirect costs for all the related stakeholders. Pipeline failures are complex processes, which are affected by many factors, both static (e.g., pipe material, size, age, and soil type) and dynamic (e.g., traffic load, pressure zone changes, and environmental impacts). These failures have serious impacts on the public due to safety, disruption of traffic, inconvenience to society, environmental impacts and a shortage of resources. In addition, there will be huge cost of renewal of pipelines and hence maintenance of these pipelines has been of major importance. Therefore, continuous and accurate condition assessment is critical for the effective management and maintenance of pipeline networks within railway and road infrastructure. Furthermore, the accessibility of buried pipelines under railway infrastructure is a practical challenge for the health assessment of pipeline network regardless of the type of pipe. This project is going to identify the failures from railway, soil and pipeline perspective to provide a comprehensive assessment of pipeline condition.

1.2. Project Consortium

The proposed research project has been carried out in close cooperation between the divisions of Operation and Maintenance (DUA); Architecture and Water (AVA), Geotechnical & Mining (GEO) at Luleå University of Technology, Stormwater&Sewers consortium at LTU, Swedish Water and Wastewater Association and Aarsleff Rörteknik AB. The project members collaborated with more than 100 municipalities in Sweden and construction companies for data collection and identification of issue and challenges of pipeline rehabilitation at cross-section with railway infrastructure. Based on the communication and data analysis, maintenance and construction solutions have been recommended to enhance the reliability and to reduce the risk and operating costs of the pipelines with special reference to the crossings of pipelines with railway infrastructure.

1.3. Interaction of railway, cities development and infrastructure

1.3.1. The need for developing railway transport

The condition of the land transport infrastructure (rail, road, and pipe) has a big social and economic relevance since constraints result in service disruptions. The next 20–30 years will see unprecedented demand for growth in transport. European railways have to deliver increased productivity to fulfill growth demands across all modes in freight and passenger services by 80% and 50% by 2050, respectively [4].

Besides, for the aging infrastructure will be required more maintenance interventions which infer normal traffic operation. Therefore, one way to increase the capacity of transportation infrastructure is to optimize the performance of the existing infrastructure to fulfill an increasing transportation demand [5].

In addition, Shift2 rail roadmap[4], aims for the "Smart, green and integrated transport" and to boost the competitiveness of European transport industries and achieve the European transport system that is resource efficient, climate and environmentally friendly, safe and seamless for the benefit of all citizens, the economy and society. Demands for increasing the transport infrastructure results in more cross section with the currently established pipeline network. Furthermore, demand for increasing axle load can create new challenges on the reliability of the old transport infrastructures that have not been designed to fulfill the new society's demand.

1.3.2. The need for cities development and infrastructure

Pipelines are an essential part of the transportation infrastructure in urban habitats as well as in developed industrial areas. The crossing of pipelines with traffic infrastructure is of ongoing concern to all stakeholders and the various interactions (building of rail tracks above existing pipelines and incorporating or crossing of new pipelines through existing rail tracks) should be a major concern in design, building and maintaining of both rail tracks and pipelines [6, 7]. Nevertheless, pipelines are often regarded as small and secondary structures of large infrastructure where the underground work is often neglected and leads to failures interrupting both traffic systems as well as infrastructure guaranteed by the pipelines. For instance, uncased pipes that cross under major freeways, highways, and railways, and those suspended from bridges represent some of the highest quantified consequence of failure events as disruptions to major roads or railroads may result in significant triple bottom line impacts [8-10].

From urbanization perspective, railways going through towns and cities are often entering the city centers with build urban areas on both sides of the railway. Therefore, pipelines for e.g. water, sewage and stormwater at some points must go under the railways to connect these areas with drinking water and wastewater treatment plants as well as to the receiving waters to be able to drain the cities. With increased urbanization and densification of cities, the underground pipelines crossing railways are increasing near future.

With the change in the climate, there will be a change in rain patterns and more intense rainfalls [11]. Depending on topography, the railway embankments in urban areas function as dam constructions. With increased the rain intensity, the risk of urban flooding will increase [12]. Therefore, it is likely that existing drainage pipes through/under railway embankments need to be exchanged to larger dimensions and new cross sections (drainage pipes- railway embankments) are needed to avoid urban flooding in the future. Gould, Boulaire [13]found that seasonality exists in the pipe failure rate database and indicated that pipe failures occur due to the complex interaction of different factors including pipe attributes, soil properties and weather conditions. Furthermore, Rajeev and Kodikara [14] also identified the relationship between climate change and expansive soil volume variation, which results in the majority of the pipe damage in shrink-swell soil.

1.4. Problem statement

The main observed problems due to the interaction between the pipeline and railway infrastructure are shown in Table 2. Accordingly, there is a need to study the pipeline failure modes and its consequences related to the crossing of pipelines in railways corridors to reduce the potential failures in the future transport system [12, 15, 16].

TABLE 2: PROBLEM DEFINITION AND ITS DESCRIPTIONS

Problem	Description
1. Railways act as Dams	Railway construction acts as water dams in city zones. Once the railway construction acts as a water dam, it is difficult to build drainage and other piping across the railway without disruption to the train traffic. Costly solutions exist (press in tunnels) but are rarely used for smaller-scale projects and pipes.
2. Increased dynamic load affects existing pipelines	LKAB and TRV attempt to increase the axial load from 30 to 32.5 tonnes in iron ore line, which may affect old piping designed for a lower axial load. The plan is to increase load for more than 40 tons.
3. New pipes vs old rail infrastructure	Installation of new piping across the railway or modification of the existing piping.
4. Cross-sections of railways and pipelines	If a failure/maintenance action happens at the cross-section, this can obstruct both the infrastructure.
5. Failures prior to maintenance schedules	Due to the cross-correlation, both assets can fail prior to the scheduled.

1.5. Project aim

The aim of this study is to identify failure modes and their consequences related to the crossing of pipelines in railways corridors. For this study, several data-driven methods for diagnosis and prognostics are needed to be investigated for condition assessment of pipelines and railway infrastructure. In addition, it is also required to assess and optimize the reliability, availability, maintainability, safety, and risk to maintain the transport infrastructure in the healthy condition.

1.6. Project objectives

The objectives of this project are as follows:

- To investigate the scale of the problem and identifying failures modes at pipeline-railway cross sections.
- To identify failure consequences and investigate the root cause of failures.
- To identify the appropriate tools and techniques for monitoring, diagnostic and prognostic of the pipeline using data-driven methods for mitigation of failure consequences of current and future transport infrastructure.

- To suggest technical solutions to overcome the problems of building and maintaining pipelines under railway embankments.

1.7. Scope and limitation

The scope of this study includes the operation and maintenance of the pipeline network under railway infrastructure. This study focuses on the understanding of failure modes at cross section and the identification of critical failure modes that could provide better information for condition assessment, operation, and maintenance of the pipeline under rail embankments.

This study considered only the areas connected to the pipeline and railway and did not consider the operation and maintenance of pipelines and railways in general. Furthermore, the study and related analysis built upon qualitative studies due to unavailability of pipeline failure/condition data at the cross-section.

2. Condition Assessment of Pipeline Network

For the condition assessment of pipeline network, a preliminary analysis is to identify failure modes & failure causes of the pipelines. Base on the literature[17, 18], the structural deterioration of the pipeline network can be categorized into four groups; structural parameter, environment issues, hydraulic factors and maintenance variables. The parameters under each variable have been presented in Table 3.

For condition assessment, there is a need to characterize and standardize failure modes in pipelines that are more prone to damages when pipelines are crossing rail tracks. This can be achieved by obtaining experience from geotechnical models in tunneling, pipeline engineering, and maintenance engineering. Thus, the different type of data such as traffic and load conditions, the angle of the pipeline with the railway at the cross section, pipe embedment conditions, production and installation procedures are needed to be collected.

Today the condition assessment of water pipelines mainly depends on the information from operational disruption reports. The only time you can inspect pipeline is when digging them, which becomes too expensive to use as a method of status assessment. Internal condition assessment of pipe is not practical since the pipes often have coatings along the walls that hide cracks and corrosion and there are not reliable, time and cost efficient method for pipeline condition assessment.

Furthermore, the relation between age and leakage rate is not straightforward and there may be several co-variants that might affect the leakage rate. For instance, previous leaks, pipe loads, construction work, construction period, pipe length and pipe material and geographical location [18-20]. For instance, gray pipes installed during the 50's and 60's have been shown an increased leakage rate. This is most likely due to the transition from digging by hand to excavators, as the pipes were dropped into larger pipes with poor support from surrounding soil. Similarly, road salting increases the risk of external corrosion. Due to needs for developing urban area during 1960s, a construction rush took place where installed pipes had a worse facility. On the various geographical locations, different soils can increase external corrosion of the pipeline. The soils that are especially corrosive are clay soils with a high sulfur content. In a British study, it was seen that clay soils had almost twice as much leakage as pipes in sandy soils [19]. Loose soil can cause sedimentation, even pressure conditions change and pressure drops can be induced and several consequential leaks can occur on nearby pipes. According to Sundahl [21], it was seen that leaks tend to come group-wise, close to each other physically and temporally.

The traffic load on the pipelines and the degree of pressure is an important covariant mainly at cross section where the pipeline and transport infrastructure have intersection area. Pressure by axial load causes the types of circular fractures known as beam fractures. Transverse voltages are caused by land and traffic pressure. When the ground becomes cold, it expands and the pressure may create longitudinal cracks for the pipe. The quality of the construction work also varies from period to period, hence different failure rate may occur in the different areas of the pipeline network.

Temperature also has been considered as an important factor for leakage frequency in the several studies [22, 23]. The connection between increased leakage in winter and the temperature in the outgoing water from the waterworks have been studied by Swedish Water [23]. When its temperature goes below zero and the ambient temperature in the ground is warmer, this process may lead to the leakage. This process creates the tensile stresses in the outer surface of the tubes and ring pressures in the inner surface [23]. The falling temperature can increase the number of circular cracks in the gray iron pipes which may occur between the diameters 76 mm to 203 mm. In addition, gray iron pipes are sensitive to rapid falls in temperatures and by leveling the water temperature, leaks can be reduced [22].

In addition to the above, internal corrosion can also cause pipe leakage. The internal corrosion rate may be affected by the water quality and flow rate. Corrosion results in the reduction of pipeline wall thickness and deterioration of hydraulic function. Alkaline pH in drinking water reduces corrosion rate [23].

Today, most of the assessments of pipelines at cross section are performing on the bases of interruption reports and these are the main resource for obtaining information about the water management status. Other types of information, for instance, possible failure mode, pipeline pressure, environmental condition, and related inspection & maintenance date and time, etc. will help to understand the underlying causes. In addition, there is need to use new condition monitoring tools in terms of hardware such as sensor-based technologies, software & data management tools, and utilization of digitalization infrastructure to have a more accurate pipeline health status estimation. Based on the interview with experts, we found that most of the users have difficulty to use data collection/management tools. These tools should be designed user-friendly and the failure reporting system must be easy to fill the data in a short period of time. The tools should be able to capture more feature of pipeline failure, and related causes for documentation of how the actual damage looks.

2.1. Pipe failure cause under railway infrastructure

Røstum [18]categorized the most important variables for the structural deterioration of pipeline into four (4) categories as structural or physical variables, external or environmental variables, internal or hydraulic variables and maintenance variables as given in Table 3. The external or environmental effect and maintenance variables are the two dominants factors for a pipeline under railways. Pipelines at the cross section with railway infrastructure are prone to fail before the expected life of the asset due to exogenous factor receive from the railway, for instance, axle load, traffic frequency, and eddy current to the metal-based pipes.

TABLE 3: FACTORS AFFECTING STRUCTURAL DETERIORATION OF PIPES UNDER RAILWAY[18]

Structural variables	External/ environmental variables	Internal variables	Maintenance variables
Location of pipe	Soil type	Water velocity	Date of failure
Diameter	Axel Load& Traffic frequency	Water pressure	Date of repair
Length	Groundwater	Water quality	Location of failure
Year of construction	Direct stray current	Water hammer	Type of failure
Pipe material	Bedding condition	Internal corrosion	Previous failure history

2.1.1. Effect of a culvert on tamping and railway maintenance: A case reported in a railway system

Availability and safety of track are two main feature for railway infrastructure manager to operate the rolling stock on the track. Hence continues monitoring of the track geometry has been required to provide a safe and functional railway track. The quality of the track geometry deteriorates with time giving rise to the need for intervention to restore it to the design specifications or the allowable threshold for maintenance and safety. Tamping aims to restore the geometry to its original state to ensure an efficient, and safe railway track. Furthermore, due to non-homogeneity of soil condition and other assets in railway corridors, an effective tamping strategy is needed to achieve the track design capacity.

Installation of pipelines under rail track is increasing non-homogeneity of the infrastructure. Pipeline crossing railway can create both concavity (bump) and convexity (settle down) rail tack shape depends on the soil condition. Khouy [24] identify that in some railway sections the failure occurs repeatedly. For instance, in one case, 39 times longitudinal level faults were detected over only 45 m of a 1000 m track segment from 2004 to 2010 over kilometer 1218 as illustrated in Figure 3.

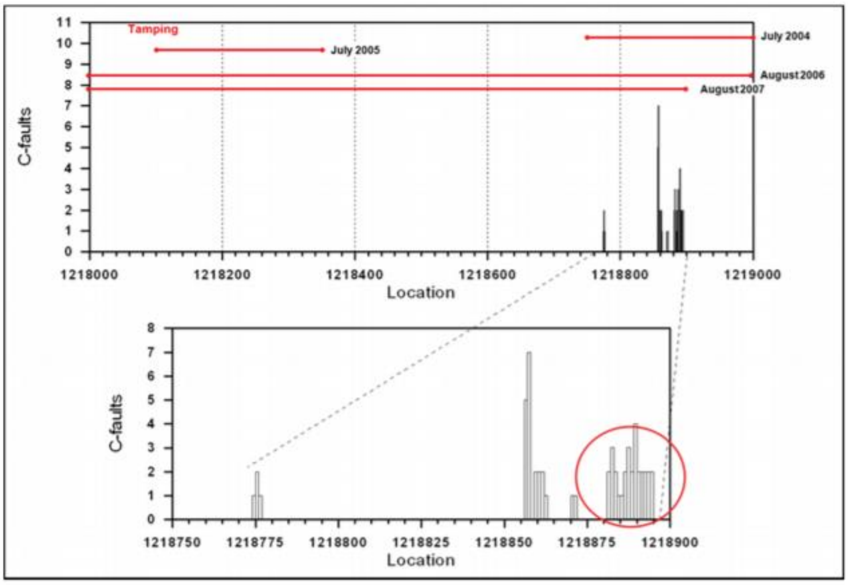


FIGURE 3 LOCATIONS OF LONGITUDINAL LEVEL FAULTS OVER KILOMETRE 1218, [24]

More investigation shows that tamping is not an effective solution to remove the root cause of failures since the failures repeatedly recur. Physical inspection of track reveals that a culvert has been installed under rail track Figure 4. This culvert creates non-homogeneity of the substructure, which has an effect on the track stiffness, can be a root cause of the high failure rate on this segment of the track. Figure 5 shows a clear bump on the track over the culvert. In such cases, more investigation on the soil mechanic is required to avoid any bump or settlement of rail track.

	
FIGURE 4: CULVERT UNDER THE TRUCK	FIGURE 5: THE EFFECT OF A CULVERT ON THE TRACK

2.2. Pipe deterioration process

Like other engineering structures, culverts, stormwater pipes, and drinking water pipes, drainage pipes deteriorate with time and stress results in a reduction of the useful life. The effects of pipe deterioration at cross section can sometimes be observed on the railway corridors with consequences of rail settlement or rail bump, traffic disruption or a pipe blockage with consequences of flooding to neighborhood environment and environmental pollution. Therefore, managing and maintaining the performance of buried pipes is a critical task for infrastructure managers and owners. This task entails the information on the current and future condition of the pipeline at the cross-section.

The structural deterioration of sewers and stormwater pipes are characterized by structural defects that directly reduce the structural integrity, i.e. shape and load-bearing capacity of pipes. WRC's[25] identified the main structural failures such as crack, fracture, deformation (shape distortion) and hole. The WRC also explained the process leading to the collapse of rigid sewers by following the three-phases of structural deterioration.

- First phase: in this phase, some minor deficiencies such as cracks or leaking joints that are possibly caused by poor handling and improper construction methods will appear. Identifying the initiated defects in this period is difficult and even costly. Hence, in most of the cases, the ongoing failures remain hidden.
- Second phase: initial deterioration of the first phase extends with different rates, which is depending on a combination of attacks such as external loads (both static and dynamic), chemical corrosion, erosion and ground loss [26, 27]. Particularly, the ground loss happens when surrounding soil is washed/drawn into pipes due to crack or pipe rupture. This would lead to the poor structural support of pipes and may lead to the other types of failures which was not considered as potential failures in advance. Furthermore, due to the low access to the buried pipe at the cross section and difficulty to have proper information through condition monitoring tools and unavailability of prior information of pipeline installation/constriction failures will remain hidden in the most of the cases.
- Third phase: most of the pipeline failures occur in this phase and the consequence of the failures could create a different type of hazards for transport infrastructure and the environment. These failures may create a hazard for passengers due to the rail settlement and the possibility of derailments. Although the determination of pipeline remaining useful life considering different factors are a difficult task but it is possible to estimate the possibility of failure occurrence by the pipeline maintenance experts during pipe inspection.

Davies, Clarke [28] and Kleiner and Rajani [29] described the above three-phase degradation by a 'bath-tub curve' (See Figure 2) for the health status of sewers and water pipes respectively. Tran [30] and Micevski, Kuczera [31]assumed that the rigid stormwater pipes also experience similar properties of deterioration and collapse processes and validate their hypothesis using data analysis of Newcastle City in Australia. Micevski, Kuczera [31] described the structural deterioration of stormwater pipes using a stochastic process via developing a multi-stage transition between four development stages from perfect to collapse. In addition, they found that the current deterioration intensity could affect the deterioration intensity of the next period. Duchesne, Beardsell [32] developed a survival analysis model to predict the state health of structure of a sewer network based on camera inspection data.

2.3. Pipeline leakage management

In section 2.1, we have briefly look at what causes pipe failure and leaks. Fatigue cracks, material manufacturing error and external force are three main causes. Leakage is a symptom of pipeline failure and can be managed as active or passive strategies. Active leakage control techniques can further be divided into two groups [33] :

Inspection: Inspection task for leakage detection can be planned and performed in the regular time intervals or the time that may need to put more attention due to season's changes. The inspection involves checking the whole or a part of the system to assess the level of leakage and finding leakages that are already taken place.

Monitoring: Continuous failure monitoring is used for detection of leak events in real-time. A monitoring system can be installed on a pipeline or in the network permanently for checking new leakages, continuously. In addition, in some monitoring systems can perform leak checks, periodical (non-continues).

In this regards, Misiūnas [33] classified the different approaches shown in Figure 6. Details description of leakage inspection techniques can be found in the ref.[33]

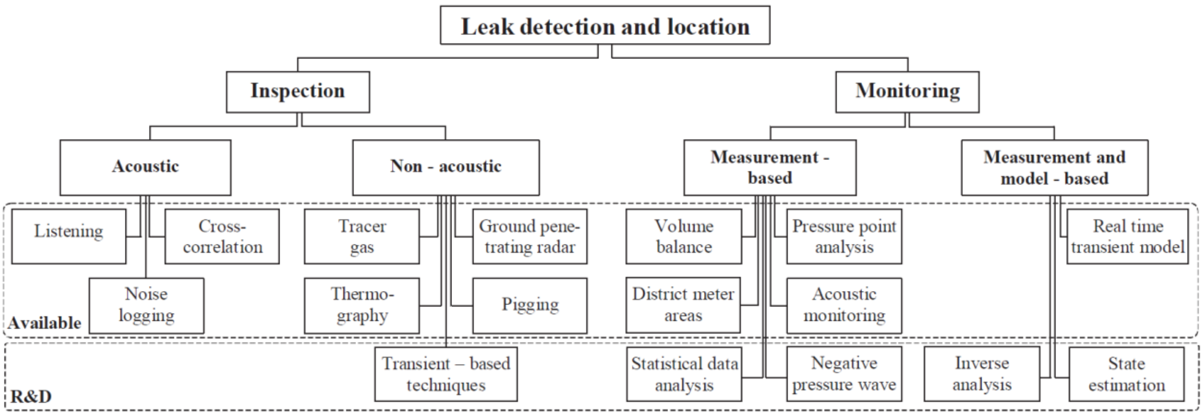


FIGURE 6: ACTIVE LEAKAGE MANAGEMENT TECHNIQUES

Leakage inspection of pipelines under railways infrastructure plays an important role for early fault detection to mitigate the possible risks that lead to the disruption of railway traffic and surrounding stakeholders. Lack of pipeline installation documentation and improper data collection are the two main barriers for developing a data-driven model to estimate inspection interval.

Furthermore, there is no leak detection system/technique that can be used all the time. Selection of right leakage diagnosis technique depends on the different features of pipeline or location. Furthermore, the cost of installation, operation, maintenance and servicing of the leak detection system and the installation conditions (such as if a pipeline has to be excavated or uncovered) are other criteria that should be considered in advance [34]. Due to the railway embankment condition, limitation & their specific features make it difficult or in several cases impossible to utilize leak diagnosis techniques for the old pipeline under cross sections.

2.4. Potential soil perspective causes of failures for pipeline crossing

Pipelines are lifelines for transportation of water, oil, gas, sewage or heat. Due to urbanization, increase in population and safety, most of the pipelines are buried underground and crossed railroads or roads. In buried pipelines, ground plays a major role in providing safe and sound conditions around pipelines but soil also plays a vital role in pipelines failures due to lack of geotechnical knowledge during designing of pipelines. After literature study from past years, it has been concluded that there is limited data available, which determines the geotechnical parameters responsible for the failures of pipelines under railroad crossings. For most pipelines which are buried underground, little data is available about their failure modes [35] but geotechnical parameters, which are responsible for failures of pipelines crossing under railroads are presented and various preventive measures to avoid pipeline failures have been suggested.

In order to discuss various preventive measures for pipelines failures, the factors which cause these failures from a geotechnical perspective have to be discussed.

i) Type of Soil
ii) Moisture content in Soil
iii) Frost susceptibility of Soil
iv) Compaction/ Density of Soil
v) Overburden Stress (Surface Dynamic Load)

2.4.1. Type of soil

Soil is classified into four types i.e. Gravels, Sand, Silt, Clay. Pipes buried in fine soil or loose soil are mostly affected. Fine particles infiltrate into pipe cracks which creates pockets around the pipe and soil becomes loose and allows the pipeline to move[36]. On application of live load (Rail movement), the pipeline will be dislocated due to the creation of pockets. Also, clay with high organic content (Sulphur) can be another reason for corrosion of cast iron pipes and reinforced concrete pipes [37]. Clay with high Montmorillonite content is a very soft soil which has less strength and experience high settlements which affect the pipe alignments. Soils with high swelling potential are responsible for bending failure of pipes. Soil with large size particles can crack the pipe due to friction between the particles as well as due to high point loads while application of live load.

2.4.2. Moisture content in the soil

Degree of saturation mostly affects the Pipe material. As higher the moisture content in soil, more are the chances of corrosion of pipe material are given [38]. Also, if pipes are buried below the groundwater table, there is a possibility of loss of support due to the migration of particles and erosion (conveying by groundwater of finer particles into void spaces of coarser soils). There is more probability of soil migration if the soil is erodible and consists of poorly graded soil.

2.4.3. Frost susceptible material

In Sweden, due to seasonal temperature change (from 25℃ to -40℃), soil is subjected to freezing and thawing. Especially silt is a highly frost susceptible material [39]. During winters, ground freezes and expands as the water in the pores freezes. In addition suction of free water takes place if close to the groundwater table and ice lenses will be created causing segregational heave, which is under a road not constant so that bending of pipes crossing might occur. During summer, the frozen water is converted into water due to temperature change and if there is no drainage, the load will be taken by this water which decreases the strength of the system. If soil surface is free to move, it heaves and this force is large enough to lift or dislocate structures. If the weight of the pipeline and the uplift resistance of the depth cover are not large enough to hold the pipeline in place, then it will move upward during pipeline operation.

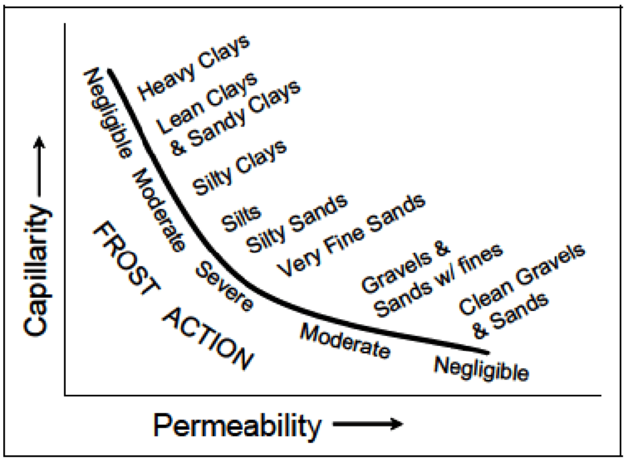


FIGURE 7: THE RELATIONSHIP BETWEEN FROST ACTION AND HYDRAULIC PROPERTIES OF SOILS[39]

2.4.4. Compaction/ density of soil

If the soil is not properly compacted, the size of voids is larger. On application of live load (dynamic load conveyed by trains/ vehicles) movement of soil particles take place which affects the sides support strength provided by soil to pipes. Also, fines particles can infiltrate through pipe cracks resulting in loss of material which leads to failure of infrastructure at crossings (rail beds, highway, and pipeline system).

2.4.5. Overburden stress

Overburden stress on the pipe is due to applied external loads such as soil mass, the dynamic load due to vehicular movements at the crossing (Trains/ vehicles), old installed pipelines were designed according to live loads as per previous system. Due to the increase in speed and/or load, there is more stress which is transferred to the soil-pipe system. If this stress is greater than the strength of the pipe, there will be a rupture in the rigid pipe and more bending stresses in flexible pipes which leads to infrastructure failure[35, 40, 41].

3. Methodology

Different performance indicators such as reliability, availability, and safety (RAMS) can be used to evaluate the condition of each asset considering their interconnectivity within transport infrastructure. Since pipeline degradation rate varies according to environmental impact, hence it is important to consider these effects on the pipeline degradation process. As can be seen in the "impact on infrastructure" block in Figure 8, different factors such as traffic, weather, etc are considered as inputs to the condition assessment block. Expert knowledge-based approach or statistical-based modeling are the two appropriate approaches to describe the failure characteristics of the pipeline at the cross-section. In this study, the expert knowledge-based approaches have been selected to identify the potential failure modes and their related consequences.

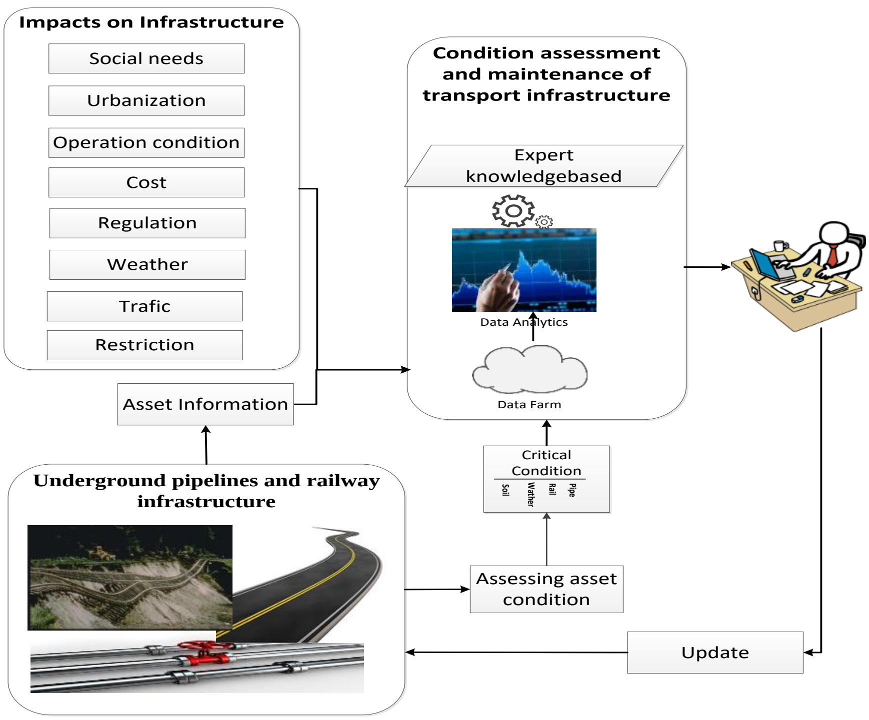


FIGURE 8:THE INTERACTION OF PIPELINE WITH TRANSPORT INFRASTRUCTURE AND DECISION PROCESS

3.1. Data harvesting

3.1.1. Questionnaire and interview study

The initial step of this project is to collect historical failures data of maintenance records of both railways and pipelines where these structures are crossing each other. This study aims to identify the bottlenecks within organizations link to installation, renovation, and repair of the pipeline under railway corridor. The physical mechanisms that lead to pipeline failures are often very complex and not completely understood. The fact that most pipes are buried and relatively little data are available about their failures modes which contribute to this incomplete knowledge (the comprehensive details can be seen in section 4). Hence, two questionnaires and one interview study have been conducted to collect the required information and knowledge connected to the problems at cross-sections. The details of the procedure and the outcomes have been summarized in the following subsection.

In addition to the above investigation, the Ofelia database (failure database from Trafikverket) has been analyzed to find the related incident from railway lines, from Kiruna to Stockholm for the years 2001 to 2017. The records from Ofelia database have been used as support for questionnaires and interview studies. It may note that this study is more dedicated toward society and municipals perspectives to identify the related risks and possible consequences.

3.1.1.1. First Questionnaire

First questioners have been distributed to 291 municipalities and two general questions were considered about the possible experience of the pipeline failure within railway and road infrastructures. Essentially these questionnaires have been distributed to collect information from the water and wastewater experts at municipalities, see Appendix I. The questions are as follows:

- During the last 10 years, have you been working on the installation or renovation of pipelines in the railway's infrastructure?
- Have you been working on the installation or renovation of pipelines in the roads infrastructure for the last 10 years?

The questions concern primarily high-traffic routes and apply to both planned activities and emergency measures.

The outcome of the first questionnaire:

In total, we have received 100 responses from the first questionnaire. Although, we knew that some of the municipalities found the first question irrelevant due to unavailability of railway infrastructure in their area. The comprehensive analysis of this questionnaire has been presented in section 4.

3.1.1.2. Second Questionnaire

In addition to the above activity, based on the second work package titled “Investigate the scale of the problem”, the second questionnaire has been designed and distributed to those municipalities in Sweden that reported cross-sectional failure under railway infrastructure from the first questionnaire. This questionnaire has been sent to 63 municipalities. The target of the second questionnaire was to identify the pipe failure modes and failure causes in the railway infrastructure from the municipality perspective.

In this questionnaire, 8 questions had been asked. In some of the questions, for instance, questions 2.1-2.3 experts should select only one option, however, in other questions, there were with multiple selection options. The questionnaire was validated and Cronbach's alpha is in the acceptable range. In addition, a formal expert judgment process can be followed, which consists of three main phases, namely, expert selection, elicitation of expert opinions, and aggregation of expert opinions [7].

Furthermore, we have asked about risk parameters and current methods for the installation or renovation of the pipeline under the railway. For more details, please see Appendix II.

The outcome of the Second questionnaire:

From the second questionnaire, we have received 25 responses out of 63 municipalities. The data of this study were analyzed and four failure modes have been studied. In addition, some of the experts provide a short description of their experiences and possible alternative solution that has been reflected in Section 4.

3.1.1.3. Interview study

Interviews survey were carried out with infrastructure managers to obtain qualitative data to analyze and classify the failure modes related to the rail-pipe-soil interaction. This study built on the expert based knowledge approach for analyzing the failure mode and consequences of the pipeline at the cross section within railway infrastructure. Generally, based on the TRV report and complementary information from questionnaires, 7 municipalities have been selected. In all 7 municipalities (one of them being Roslagsvatten AB covering water & wastewater service to 5 municipalities north of Stockholm) and 2 private companies were investigated by telephonic interview. The summaries of the findings have been grouped into 7 specific questions.

3.1.2. Railways database

The initial step of this project was to collect historical failures and maintenance records of both railways and pipelines where these structures are crossing each other. TRV utilizes a different type of databases for operation and maintenance of railway and brief description of the databases are provided in Table 4.

TABLE 4: DESCRIPTION OF RAILWAY DATABASES

TRV databases	**Description**

Basun	Traffic information system. One of its applications is registration of faults in the railway track
BESSY	The program used for registration of safety and maintenance inspections in track with the possibility to use a PDA (Personal Digital Assistant) or a mobile phone
BIS	Railway engineering assets register. Every time an asset is changed in some way it has to be registered in BIS, e.g. component replacements
Duvan	Duvan is a tool for maintenance analysis. It is possible to search for reports with data assembled from Ofelia, BESSY, BIS, and train delays
LUPP	LUPP is the successor to Duvan, it has the old functions as Duvan, plus some additional ones, like searching data of train delays and the reasons for the delays
Ofelia	Ofelia is used for following up reported faults, i.e. handling of corrective maintenance work orders. All work orders initiated by faults found in the track are found in Ofelia. Work orders started in Basun is followed-up and closed in Ofelia
Optram	An online Java-based software for analysis of data from track measurement cars. It has data from both track geometry cars and ultrasonic testing cars, which is put together with the asset structure from BIS.
Rufus	Used for registration of measures taken due to scheduled inspections or maintenance actions

After more investigations, we have found that Ofelia, Basun, and BIS were the three possible databases which may useful for the PipeXrail project. In the next step, we met with TRV experts Arne Nissen and Matthias Asplund to verify our previous database selection. Based on their investigation, they were not able to find the related records for the pipeline in the Basun and BIS databases. They mentioned that these databases are quite new compared to the age of the installed pipeline on the railway corridors. Based on their suggestions and feedbacks, we verified the Ofelia database and have found some records related to pipelines.

In order to access the Ofelia database, JVTC communicated with TRV for agreement. Thanks to TRV to support us by providing access to the Ofelia database and Veronica Jägare at JVTC facilitating the administration process and agreement documents. The following information can be found through this database.

3.1.2.1. Ofelia failure database

Ofelia failure database records the disruptions in infrastructure plants due to any fault/failure in the railway corridor. A failure report is divided into symptoms and documents. This database is recording any maintenance activities including fault detection, track actual cause & what action is performed, the time of appearance and finally closing the failure report.

Ofelia graphical user interface called Ofelia analysis provides several features for the analyses, for example:

- Search capabilities using predefined statistical reports and powerful queries with a free search.

- Several different search criteria, such as the failure rate on the track pieces, facility types.
- All search criteria can be saved for easy repetition of previous searches.
- Portability of search results to Excel for further assessments or presentations in diagram form.
- Charts and tables can be produced for presentations.

These analyzes can be used to:

- Budgeting (information about errors and delays)
- Operation and maintenance / replacement / upgrade
- Activity statistics.

The Screenshots of Ofelia user interface and some output data are provided in Figure 9 and Figure 10.

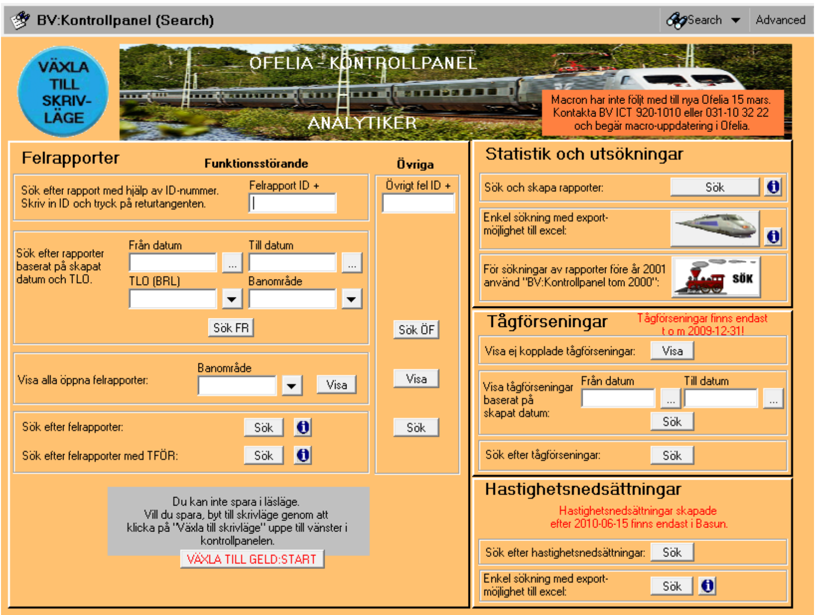


FIGURE 9: OFELIA USER INTERFACE

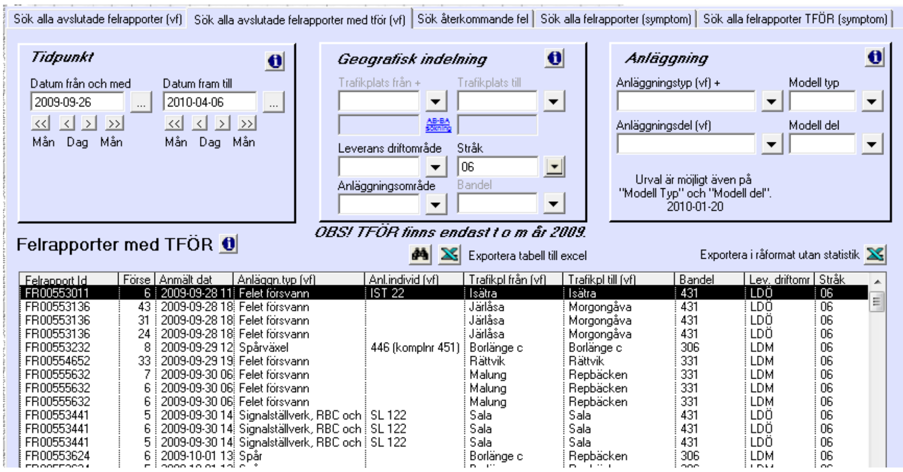


FIGURE 10: OFELIA MAINTENANCE RECORDS

Pipelines under railway can fail rarely due to their long life design expectation. However, the likelihood of pipeline failure is increasing due to the age, soil factors and stresses received from railway infrastructure. In the other hand, although the likelihood of pipeline failure is relatively less, it may have high consequences to the society and needs to be addressed all associated risk.

To identify the possible incidences, the Ofelia database has been analyzed for the lines between Kiruna till Malmo as depicted in Figure 11 for a period of period of 17 years from 2001-2017.

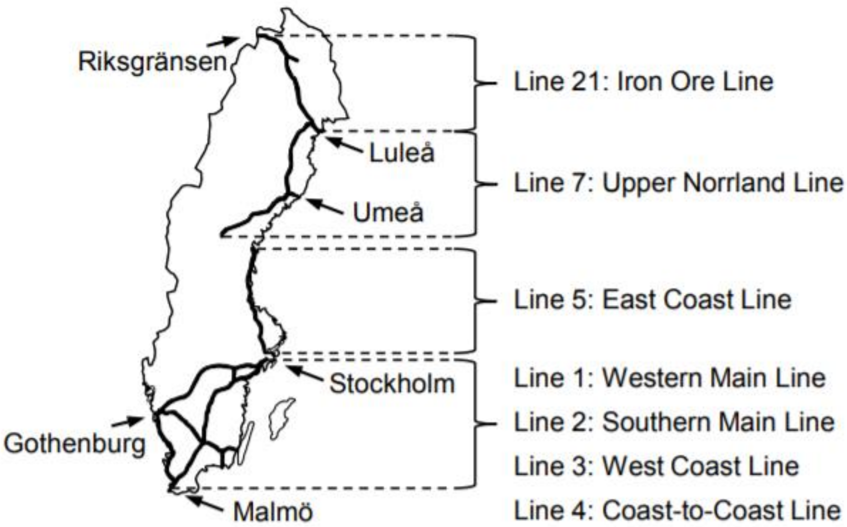


FIGURE 11: SWEDISH RAILWAY NETWORK

Unfortunately, pipeline incident under railway except for Calvert & railway drainages are not recorded in a proper way. It seems that municipal pipeline (regardless of the types) failure modes have not been defined on the Ofelia database. In some cases, TRV experts described the pipeline failure in the fault description field of the Ofelia database. In such cases, looking for the pipe related failure is not possible by searching tools in the Ofelia analysis to extract the records.

Hence, to extract the pipeline related failure different type of filtering has been implemented to identify the possible records via text mining techniques. To achieve this purpose, we have created special software and module to be able to extract the possible pipeline recorders.

Several issues such as following cases have been reported in related to Culvert in Ofelia database.

- ❖ The deep hole next to the track down
- ❖ Train felt that it was swinging firmly
- ❖ Warm high tide pressure drum under rail for Risån risk undermining
- ❖ Risk of undermining bad drum and slippers
- ❖ The drainage under the railways does not work and causes swallowing
- ❖ Drainage pipes at the crossroads are clogged. The property owner gets water on the plot.
- ❖ Drainage pipes (well pipes) have broken.
- ❖ Under the railway pipes clogged and risk of flooding.

In most of the cases, the culverts need to be inspected regularly to avoid water flooding to the neighborhood and instability of substructure of railway track.

3.2. Statistical analysis and predictive analytics: Pipe rehabilitation management under the railway

The statistical methods for analyzing pipeline maintenance management have been reviewed for the water pipelines under railway corridors. Pipeline under railway withstands under a different type of loads during lifespan.

The objective of studying statistical analysis and predictive analytics is to identify the appropriate tools and techniques for monitoring, diagnostic and prognostic using data-driven methods. The analysis of failure modes and their associated consequences including observable or measurable signs are carried out to highlight the dominant failure modes and deterioration mechanisms. Analyst in some of the models is able to evaluate the significance of the covariates, or explanatory variables affecting the deterioration process. In general, based on the pipeline features, we can consider the pipelines as a repairable asset and repairable based methodology can be used for pipe rehabilitation process. Repairable systems are those systems that can be restored to a fully satisfactory performance by a method other than replacement of the entire system [42, 43]. In the most cases, the pipelines are expensive to replace, and it is not cost-efficient to replace a pipe after the first failure hence the repair of the pipeline at the failure spot are the most optimized decision. Furthermore, replacement of pipeline under railway infrastructure may not be possible due to higher cost and severe disruption to the traffic network. Hence, we believed that the repairable system is a suitable methodology for such pipelines and condition location.

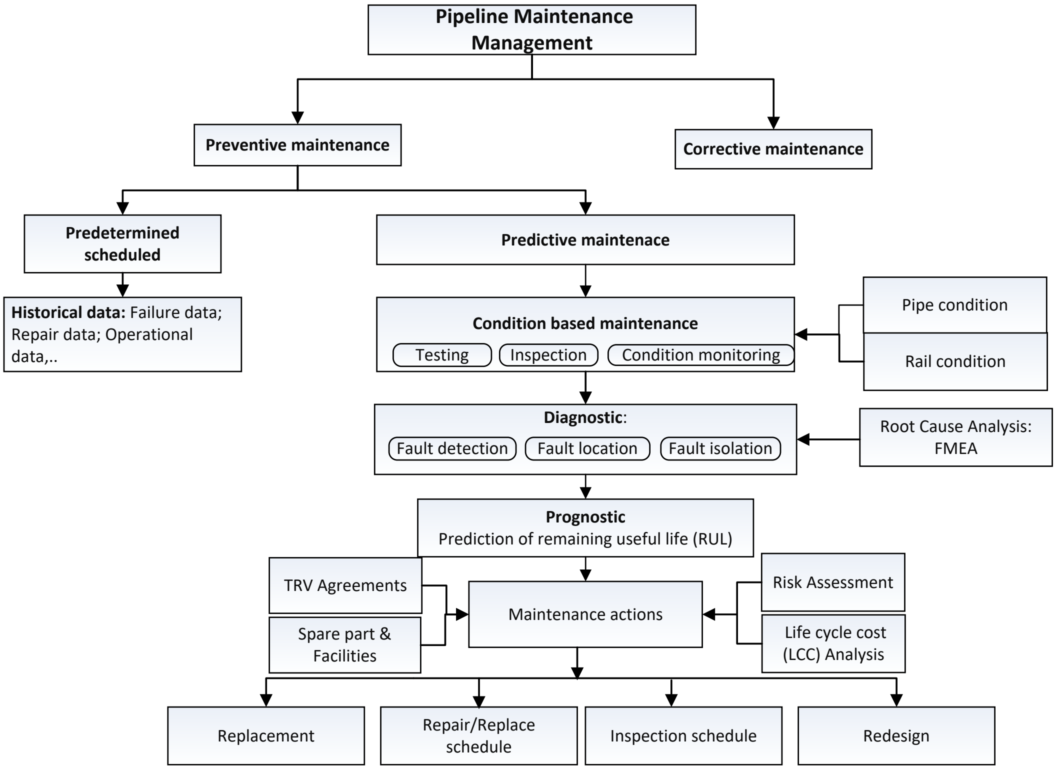


FIGURE 12: PIPELINE MAINTENANCE FRAMEWORK AT CROSS-SECTION WITH RAILWAY

3.2.1. Diagnostics, prognostics and maintenance model for pipeline under rail infrastructure

This section discusses briefly the role of predictive models for improving maintenance decisions. Few water utilities in Europe are trying to implement preventive maintenance for their rehabilitation policies [18]. The majority of policies is defined in re-action strategy and there are a few cases are concentrate on rehabilitating strategy for maintaining pipelines before they wear out. Most of the time, pipes are rehabilitated only when the failure rate is higher than an arbitrary value or when other works in the street are planned. In Sweden, most of the municipalities have been aware of the advantage of predictive-based maintenance. The utilization of predictive models is a step towards a proactive maintenance strategy, and replacement/renovation can be carried out where failures are most likely to occur. A proactive or preventative rehabilitation strategy should be more cost-effective than the reactive strategies used today.

The success of implementing a proactive approach obviously depends on the criteria used for rehabilitation planning. These criteria should be linked to the prediction of future pipe failures, the reliability of the water network serving the customers and the cost of improvements. If this information is available, it will be possible to optimize the rehabilitation programs. The overall picture of the pipeline rehabilitation program has been depicted in Figure 12. The detail description of each item is discussed in the subsequent sections.

3.2.1.1. Corrective maintenance vs preventive maintenance

As given in Figure 12, maintenance can be divided into two categories as corrective and preventive maintenance. Corrective maintenance (CM) is carried out after the occurrence of the failure, i.e. all maintenance activities intended when the asset failed. In other words, this strategy can be utilized when other types of maintenances policies can create more cost or when the asset is not critical for the whole pipeline network.

Planed based maintenance is the methodology that makes arrangements of all tools, skills, etc. in advance results in a more cost-efficient solution for the infrastructure manager compare to corrective maintenance. Figure 13 shows different involved activities for the planned maintenance.

FIGURE 13: PLANNED MAINTENANCE COMPONENTS

Preventive Maintenance (PM) is carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of failure or the degradation of items. Furthermore, the aim of PM is to provide maximum system reliability and safety with a minimum of maintenance resources [6, 44].

Selection of a right maintenance strategy depends on a number of factors, including downtime cost, redundancy, reliability characteristics, safety, and criticality. Therefore, based on the above features a balance between the number of PM and CM for minimizing operation and maintenance cost needs to be performed in advance. It may note that, when the PM fails to prevent the failure, the CM should be performed with higher cost and consequences. A pipeline maintenance management framework is presented in Figure 12.

Since pipelines under the railway corridor being aged by time and loading, the probability of failure occurrence is increasing. The PM based modeling aimed to reduce the occurrence of an unplanned failure. These failures may have serious impacts on the public due to safety, disruption of traffic, inconvenience to society, environmental impacts and a shortage of resources. Based on the literature review and interview, we found that the number of municipalities that practiced PM as pipe failure management techniques is not large.

Predetermined schedule and predictive maintenance are the two main categories of the preventive maintenance program. The details of each category are as follows:

- ***Predetermined Schedule:***

Predetermined maintenance/inspection is maintenance activity carried out on the regular bases at predetermined time/usage intervals. The maintenance actions are performed periodically in order to prevent degradation and mitigate the occurrence of the failures. The effectiveness of scheduled maintenance can be greatly influenced by the length of the predetermined maintenance interval. Since the pipes have a life length of about 40-years the maintenance intervals will be performed yearly or every second year. Pipelines under rails are under stress of weight and vibration hence the pipeline failure may appear before the estimated life of asset recommended by pipe manufacturer.

3.2.1.2. Predictive maintenance

Predicted maintenance can be considered as an integration of condition-based maintenance and other features that may affect the decision, for instance, the market price of the asset or product, environmental factors, etc. Condition-based maintenance (CBM) is a maintenance methodology which has been built on condition assessment of the pipeline asset. Condition assessment of the pipeline is a technique that can be used to evaluate the current state of the pipeline. The outcomes of condition assessment can be utilized to estimate the failure probability, the residual lifetime and trend of degradation of the pipeline.

CBM offers a variety of benefits that finally may lead to improving sustainability in terms of society, financial and environment. Furthermore, CBM can increase system reliability of pipeline, and the availability transport infrastructure. Prognostics is one of the main activity that needs to be performed for predictive maintenance. The main task of prognostics is to calculate future health status and estimate the remaining useful life (RUL). RUL can be defined as the length of time from the current time to the end of the useful life [45-47]. RUL is very useful when the lifetime of the asset is a random variable and difficult to predict. Diagnostic and prognostics are the key activities for health assessment of the pipeline[45, 48]. The next section reviews the data-driven tools and techniques for diagnostic and prognostic.

3.2.2. Data-driven diagnostic methods for pipeline under railway corridor

Data-driven diagnostic techniques have a close relationship with pattern recognition, wherein one seeks to categorize the input-output data into normal or faulty classes. The most notable techniques for quantitative data-driven diagnosis includes principal component analysis (PCA) [49], Fisher discriminant analysis [50], partial least squares (PLS) [51], and support vector machines (SVMs). Furthermore, the diagnostic process can be performed via qualitative approaches as given in Figure 14. Generally, diagnostic of an asset can be performed via three steps as fault detection, fault isolation and fault identification which have been defined as follows:

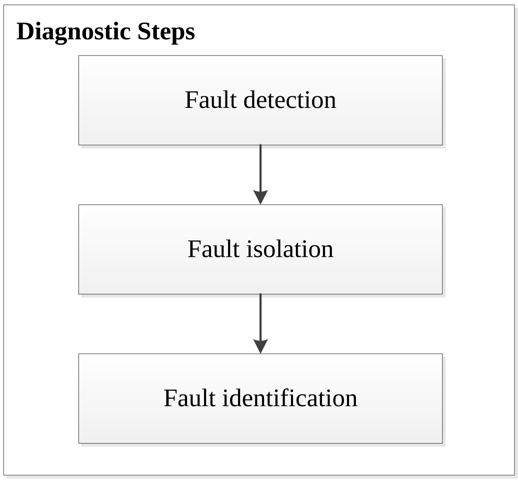


FIGURE 14: BASIC STEPS FOR DIAGNOSTICS

- Fault detection: Detecting and reporting an abnormal behavior of the system as soon as possible.
- Fault isolation: determining which component has failed and finding the root cause of the failure by isolating the system component(s) whose operation mode is not nominal.
- Fault identification: estimating the size and type or nature of the fault. Which failure mode has caused the degradation and what is the severity?

Different categories of fault detection techniques have been studied in the literature. For instance, Dai and Gao [52] classified these techniques into three categories: (i) physical model-based methods; (ii) signal-based methods; and (iii) knowledge-based, historic data-driven methods. Alzghoul, Backe [53] categorized based on the model-based methods and data-based methods. Figure 15 illustrates the data-driven based methods in different categories.

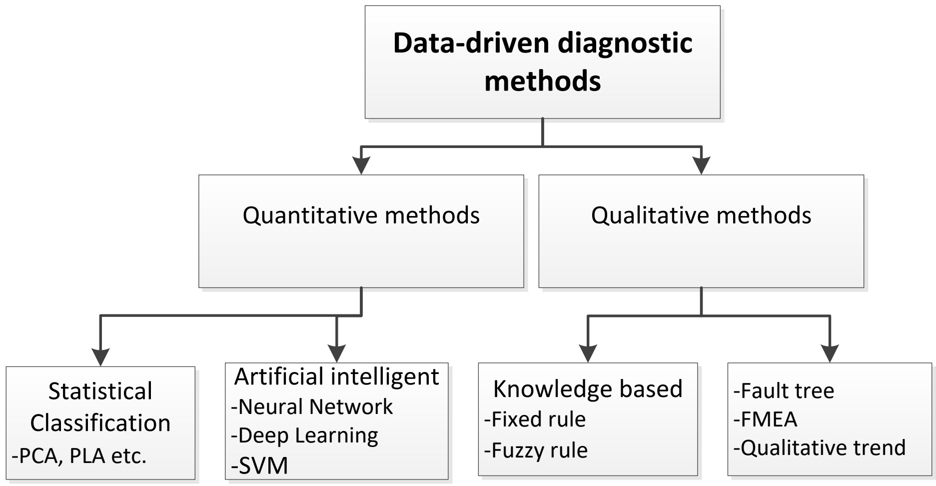


FIGURE 15: DATA-DRIVEN DIAGNOSTIC METHOD, ADAPTED FROM[53]

It may note that some of the other methods given in the prognostic section can be used for diagnostic also.

3.2.3. Data-driven prognostic methods for pipeline health estimation

There are different types of prognostics techniques as per the principle of modeling as shown in Figure 16 [45, 54]. Life expectancy, artificial intelligent and knowledge-based modeling can be considered as data-driven approaches that rely on condition monitoring and historical data to identify the behavior of the system.

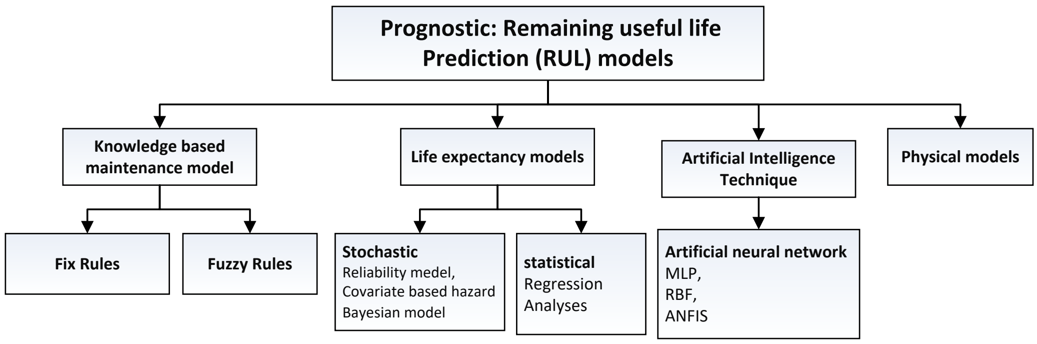


FIGURE 16: DATA-DRIVEN PROGNOSTIC METHODS ADAPTED FROM [54]

3.2.3.1. Knowledge-based maintenance models

Knowledge-based models assess the similarity between an observed situation and a database of previously defined failures and deduce the life expectancy from previous events. The knowledge-based model can be categorized into (i) rules-based expert system and (ii) fuzzy rules-based expert system.

Expert Systems (ESs) are designed to support users in the decision-making process. One of the most important features of an ES is the capability to make automated inference and reasoning.
An expert system is capable to simulate the performance of human experts in a particular field. It generally consists of an experience knowledge database from experts and a rule database for applying that knowledge to particular problems. Rules can be designed based on heuristic facts acquired by one or more experts in the form of IF-THEN. To have more accurate inferences a knowledge base databases should be able to cover as much as possible the cases[55]. The knowledge base will be required to be updated and maintained when new knowledge has been experienced or process configurations have been changed. These problems can be partly alleviated by incorporating fuzzy logic as described in the next section.

- *Fuzzy rule:*

The dearth of data is the greatest acknowledged obstacle to the deterioration modeling of the linear infrastructure assets. In such cases, fuzzy rule-based models can be interpreted as a knowledge-based system. Rules are formulated as precise IF-THEN statements; these are often based on facts acquired from experts over several years (Biagetti & Sciubba, 2004). The use of fuzzy rule-based system and fuzzy techniques help to incorporate the inherent imprecision and subjectivity of the data, as well as to propagate these attributes throughout the model, yielding more realistic results. Some of the possible input & output of fuzzy expert systems are summarized in Table 5:

TABLE 5: KNOWLEDGE-BASED APPROACHES FOR PROGNOSTIC MODELLING OF LINEAR ASSETS

Method	Advantages	Disadvantages	Input	Output
Fuzzy Expert Systems	Simple to develop; easy to understand, flexible, - and are often robust, in the sense that they are not very sensitive to changing environments and erroneous or forgotten rules.	Not accurate, ie. it provides approximate output data; lack of exact mathematically description; Domain experts required to develop rules.	Maintenance knowledge; Maintenance experience; quality before maintenance; quality after maintenance; Training; environmental condition, etc.	Output is a number within [0,1] which can be used solely or combined with a closed form of degradation model.

Fuzzy expert systems use empirical relationships described by a linguistic variable which may not rely on statistical or mathematical relationships. For example, a linguistic variable for the quality of maintenance task can be categorized as high repair quality, moderate repair quality, and low repair quality. The modelling process begins by collecting as much initial system information as possible. In addition, work orders and maintenance reports, handwritten by maintenance crews and interviews can be used. Maintenance crews can provide valuable verbal information; however, this information needs to be processed before further

investigation. Different defuzzification method can be used to convert the fuzzy output to crisp data based on the decision maker attitudes. The process of fuzzy inference system has been illustrated in the
Figure 17.

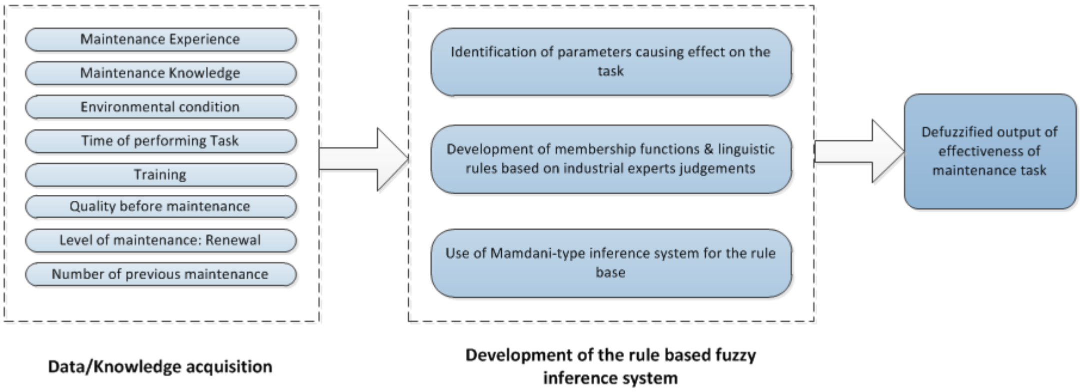


FIGURE 17: FUZZY INFERENCE SYSTEM

In addition to facing imprecise data, the knowledge-based approach can be used for life estimation of pipeline under railway due to facing small data, and improper failure reports.

3.2.3.2. Life expectancy models

Life expectancy models can be used to estimate the remaining useful life of the asset with respect to the expected risk of deterioration under known operating conditions. Two categories of Life expectancy models are statistical models (e.g. regression and autoregressive models) and stochastic models (e.g. reliability and covariate based hazard models and Bayesian methods). A summary of the data-driven methods and its advantages and disadvantages is shown in Table 6.

- ***Statistical Methods***

There are few studies that utilize the regression-based models in linear assets[56]. Davies, Clarke [28] explored the multiple factors such as length, size, location, material, etc., affecting the condition of a sewer in London using logistic regression. Ariaratnam, El-Assaly [57] investigated the sewer pipes from Edmonton, Canada and have found that age, diameter, and waste type were significant variables by predicting the probability of a sewer system. Sun, Fidge [58] proposed multiple failure characteristics with mixed failure distributions of linear assets using hazard predictive method. Ting [59] predicted the likelihood of failure of underground linear assets using the survival analysis. Other works in linear assets are for distributed pipeline assets [60], electricity transmission[61], civil infrastructure [62], rail breaks [63] and geometry degradation [64]. Chughtai and Zayed [65] developed a multiple regression model on the basis of historic condition assessment data for predicting existing operational condition rating of sewers. They considered the following regression-based model based on age, pipe diameter, pipe length and slop as an independent variable for status estimation of operational condition.

$$Operationa\ Condition = \left[\frac{0.308 + 0.567 \times (\frac{Age}{Diameter^{n}} 0.63) \times (Lenght^{Slop})}{Age^{0.63}}\right]^{\frac{1}{0.63}}$$

Recently Bakry, Alzraiee [66] proposed a model to predict the structural and operational conditions of CIPP rehabilitation on the basis of pipe's diameter, material, inspected length, rehabilitation date, and rehabilitation method.

$$Structural\ Condition = 0{,}258 - 0.00071 \times Diameter + 0.663 \times Depth + 0.03 \times \frac{Age}{5} - 0.38 \times Service\ Type + 1.025 \times Road\ type$$

- **Stochastic models**

Stochastic models provide reliability-related information, such as Mean Time to Failure (MTTF) as probabilities of failure with respect to time. They are based on the assumption that the times to failure of identical components can be considered statistically identical and independent random variables and thus be described by a probability density function.

- ***Reliability models***

Based on statistical models and reliability data (for instance, time to failure and time to repair) the probability of failure with respect to time e.g. mean time to failure, can be provided. Reliability analysis of repairable units can be classified into parametric and non-parametric methods. Among the parametric methods, stochastic point processes, e.g. the homogeneous Poisson process (HPP), renewal process (RP), trend renewal process (TRP), branching Poisson process (BPP), and non-homogeneous Poisson process (NHPP) can be used for data analysis.
When the failed unit is replaced or restored to an as good as a new condition then usually time between failures of the repairable unit are independent and identically distributed. In such cases, homogenous Poisson process and renewal process are a common model to analyze the reliability of a system. From the probability density function, the remaining life can be calculated as the time remaining before a certain failure are expected to occur by conditional reliability function (R) as:

$$MRL(t) = \int_0^{\infty} R(x|t)dx = \frac{\int_t^{\infty} R(x)dx}{R(x)} \quad 10$$

Various distributions can be used to model failure data, including the Exponential, Normal, Lognormal, and Weibull functions. In reliability engineering, the Weibull distribution function is performed well due to its ability to describe many different types of failure mode. Furthermore, in the case of having deterioration, Weibull process is one of a successful model to estimate the reliability of the item and consequently remaining useful life of the asset [42]. When the failed unit is replaced or restored to an as bad as old, considering HPP or RP may lead to the wrong calculation. In such cases, the systems exhibit a trend (i.e. a tendency for failures to occur more closely). In such situation, considering NHPP process is a suitable alternative for modeling the degradation process.

- ***Covariate hazard based***

In real case situations, several factors called as covariates may have an effect on the degradation process. For example, the wear-out process of the pipeline at cross section can be affected by temperature, material properties, axle load and running speed, cross angle and these factors can be considered as covariates to the degradation process. Proportional hazards model (PHM) is one of the most reported covariate-based models for prognostics. PHM is applied in different application due to its generality, flexibility, and simplicity (Cox, 1972). Thus, PHMs have been widely used to relate the system's condition monitoring variables and external factors to the failure of a system and hence have been applied in different areas of life data analysis, nowcasting and forecasting.

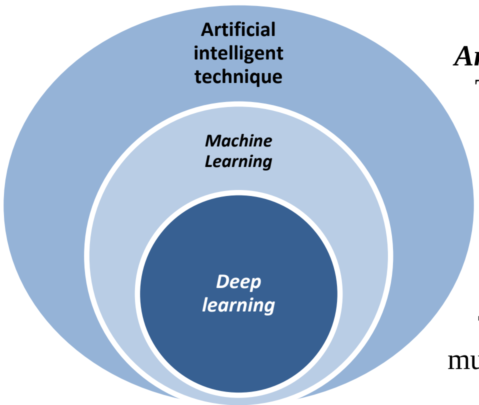
TABLE 6: DATA-DRIVEN METHODS FOR PROGNOSTIC MODELLING OF LINEAR ASSETS

Method	Advantages	Disadvantages	Input from	Output
Regression-based	Due to the availability of data, forecasting can be updated, checked and validated for multiple variables.	There is no understanding of the physical system	Condition data	Performance parameters (as defined) and error measures
Reliability	Simple and works well with time to failure data	The is no information about the condition. Can be complex with multi-state system or for continuous degradation modelling.	Failure data	Survival function, Mean Time to Failure (MTTF).
Markov models	Well establish approach that can model several failure mode scenarios.	Can only model previously known faults. Assumes a single monotonic failure degradation. Large volume of data required for training.	Statistically correlated data of node states (or expert knowledge) Prior distribution of parameters	Probabilities of next conditions

Covariate hazard	PHM with time-dependent covariates over the other statistical approaches is that covariate information can be easily combined with a baseline hazard function. Thus, the effect of different covariates on the total hazard can be easily evaluated.	(1)The models mixed the casual relationship of different covariates. (2)When the evolution of covariates is stochastic, another process (mostly a Markov chain) must be used for describing the covariate process. (3) Strict (albeit implied) assumptions regarding nature of underlying process	Event time, Covariate parameter,	Reliability estimation, RUL estimation, nowcasting and forecasting in this project

3.2.3.3. Artificial intelligent technique

The hierarchy of artificial intelligent techniques have been depicted in Figure 18 with a short description of each item. *Artificial Neural Networks* (ANNs) are a successful tool in many application setting as machine learning tools. The brief details of the ANN have been provided in the next section.



Artificial intelligence
The science of making machines smarter which in tum augments human knowledge and capabilities.
Machine Learning
Machines take data and begin to learn for itself. Machine learning algorithms are programmed to learn and improve based on the patterns
Deep learning
The next generation of machine learning that employs multiple layers of learning from massive data-sets.

FIGURE 18: ARTIFICIAL INTELLIGENT TECHNIQUE HIERARCHY

- *Artificial neural networks*

ANNs are parallel information processing system and are powerful tools/method to estimate the remaining useful life of the asset. ANNs can perform the computation via a mathematical representation of the asset which has been derived from the features data or based on the physical understanding of the failure processes. Artificial Neural network based technique is effective for modeling complex systems when a number of different features have an effect on the process, for instance, condition monitoring data, asset characteristic, maintenance history, etc.

ANNs methods have been implemented for pipe health prediction. For instance, Achim, Ghotb [67] was developed a Multilayer Perceptron (MLP) model and to enhance the accuracy of pipe failure prediction. This result has led to the development of a computational model integrating Analytical Hierarchy Process (AHP) and ANN by Al-Barqawi and Zayed [68]. Later on multiple regression, MLP, and General Regression Neural Network (GRNN) have been studied to predict the remaining useful life of cast iron water mains [69].

Degradation of the pipeline is due to complex interaction of different factors (including pipe attributes, soil properties, external load and weather conditions) and in most cases, finding a closed form physical model (mathematical or statistical model) may not possible. In such cases, the data-driven model, for instance, ANNs based model can be considered as an alternative. For instance, ANN can be utilized for identification of crack and tracking of crack propagation or corrosion process in the pipeline system under different effects e.g. stress received from railway track/rolling stock. Furthermore, ANNs can be implemented for the identification of maintenance/inspection interval or estimation of remaining useful life of the asset. It may note that when less amount of data is available or data is symbolic, ANNs cannot perform to estimate the parameter.

Although the availability of data in many areas is increasing at a higher rate but in the pipeline at cross-section with the railway, we faced with limited data. This scenario is also valid for the pipeline network in an urban area due to lack of proper data collection system or difficulties of collection data from buried pipes.

3.2.4. Physics-based models

Physical models (also known as physics of failure or behavioral models) quantitatively characterize the behavior of a failure mode using physical laws (i.e. from first principles). This implies a thorough understanding of the system behavior in response to stress, at both macroscopic and microscopic levels[54]. When the material is subjected to heavy loads it deforms and the deformation depends on the magnitude of the stresses and/or strains the material is exposed to. The physics base modeling can be performed at component level mainly and deriving a closed form mathematical formulation at the system level is a complex task. In addition, empirical data are necessary for physics-based approaches. Therefore Physics-based models are mainly considered for design purposes[70, 71].

From physics based prognostics models, failure mechanisms can be categorized into two group [72]. (i) Overstress failures. Overstress failures occur when experienced load exceeds the strength of the material; for instance brittle fracture, ductile fracture, yielding and buckling [73]. (ii) Wear out failures. In contrast with overstress failure, these failures are characterized by irreversible, i.e. the accumulated damage will not disappear when the load is removed, such as fatigue [74], corrosion, stress-corrosion cracking [73, 75], wear and creep. Once the allowable tolerance for the particular damage mechanism has been exhausted, normal operating loads will exceed the remaining strength and an overstress failure will occur [76]. A physical prognostic model for wear out failure modes needs to be able to track aggregated damage and its rate of progression under any/all operating conditions.

The main advantage of physics-based models is incorporating existing understanding of the physical mechanisms of failure to the model structure, directly, which in many cases subjected to the extensive and exhaustive empirical testing (e.g. Paris–Ergodan crack propagation laws). When physical understanding of the system matured, the model can be adapted to improve its accuracy which may tend to significantly outperform other types of models [77].

3.2.5. Hybrid model

Health assessment of pipeline network is often modeled by data-driven, Knowledge-based or physics-based approaches separately; only a very few studies have been reported on the combination of these approaches. Recently Cheng and Pecht [78], Liu, Wang [79] implemented a hybrid based model for remaining useful life prediction of electronic products. Galar, Palo [80] proposed a method for integration of disparate data sources to perform the maintenance prognosis and optimal decision making. The selection of the most suitable approach depends on the characteristic of the asset/system/item, nature of the problem, the purpose of the prediction, resources available, available domain knowledge about the system, type and level of the asset within the linear infrastructure etc.

Accurate health prognosis is a challenging task in the condition-based maintenance of the linear asset. This is necessary for assuring equipment reliability, maximizing the useful life of the system/components, effective maintenance decision making. Separate implementation of the mentioned approaches has some drawbacks and regarding the demand for higher accuracy prediction model. Hence there is a need to consider a combination of different techniques for the health assessment of pipeline network under the railway. This combination is referred to as an integrated or hybrid prognostic method. The definition of hybrid method of condition prognostics can be perceived in different ways. The main aim is to fuse physical models and data-driven or knowledge-based models in a way that all relevant physical laws and mathematical/statistical hypotheses are respected. A comprehensive schematic of models application in different infrastructures is depicted below.

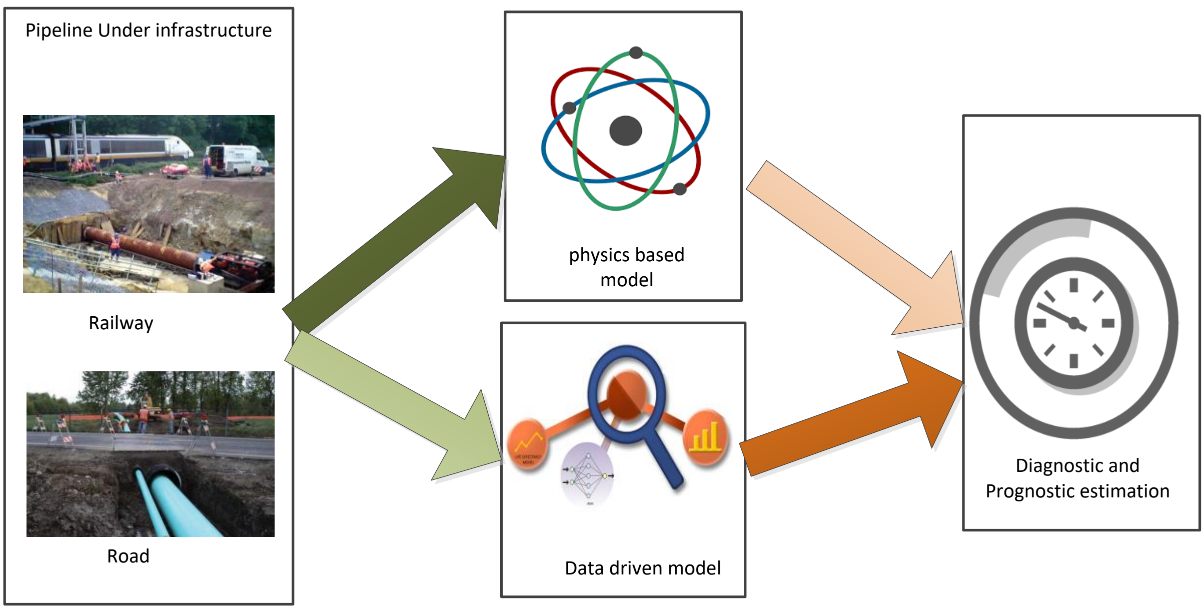


FIGURE 19: A HYBRID MODEL FOR PIPELINE HEALTH MANAGEMENT

There are several challenges to implement the perfect hybrid methodology approach, specifically:

- Unavailability of the physical information/ degradation model for the system due to the complexity
- Lack of conditional data over a longer period
- Storing of different types of data (heterogeneity) located in several databases
- Difficulty in extracting relevant information due to heterogeneity within existing data
- Difficulty in obtaining the symbolic information due to data quality and data cleaning issues
- Fusing relevant physical information with a data-driven approach
- Complexity in algorithm development to manage regular tuning of models for accuracy and precision.

To overcome these issues, there are several ways of implementing the hybrid methodology without involving all types of models. Some of them are as follows:

- Implementing the physical/data-driven/Knowledge models at different process steps in the modelling approach
- Tuning physical, data-driven model and incorporate the knowledge-based model wherever necessary.
- Physical information assisting in supervising the data-driven models.

Hybrid model entails the integration of simple prognostic approaches. The selection of the approaches to be integrated depends on the amount of data available, the existence of domain knowledge, level of known physical theories or model etc. Figure 20 shows the possible combinations of different prognostic approaches based on the quantity of data and the strength of the physical model.

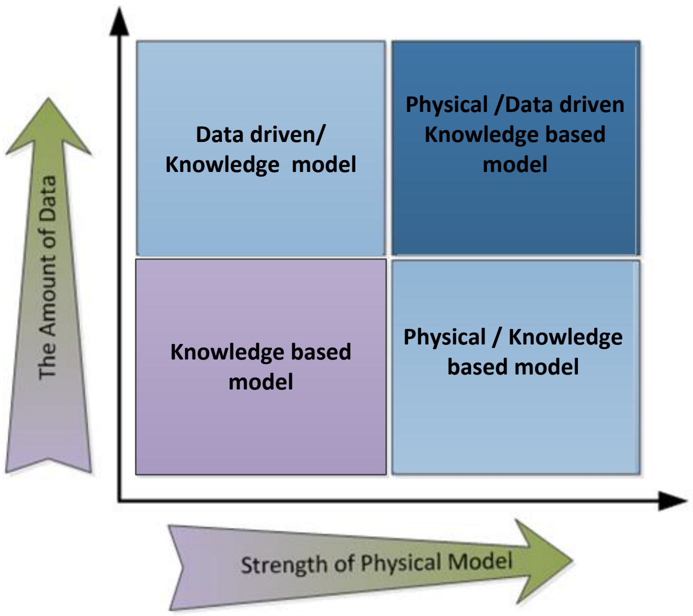


FIGURE 20: COMBINATIONS OF SIMPLE PROGNOSTIC APPROACHES

3.3. Risk assessment

Risk assessment of a pipe network is part of proactive maintenance management, to achieve an optimal balance between maintenance cost, and performance indicators [81]. Hence, risk assessment is an essential step for the selection of suitable maintenance activities e.g. pipe inspection, rehabilitation, and replacement. Pipe risk analysis consists of pipe condition prediction and pipe failure consequence analysis. Generally, risk has been defined as the probability of an event that causes a loss and the potential magnitude of that loss. By this definition, risk index can increase when either by growth for the probability of the event or by increasing the consequence of the potential events. Pipelines under railway may suffer a different type of risk, for instance, the probability of the pipeline failure due to railway effect, frequency, and axle load., releasing its contents, and causing damage (in addition to the potential loss of the product itself). It is important to make the distinction between a *hazard* and a *risk* because we can change the risk without changing a hazard.

To have a clear understanding of risk management it is important to answer the following questions:

1. What can go wrong?
2. How likely is it?
3. What are the consequences?

Linear assets like pipelines are considered to be low risk/high consequence meaning that incidents are relatively rare considering the total mileage of pipelines and the volume of product transported, but when incidents do occur, they often have catastrophic consequences. Globally, Over 50% of the nation's pipelines were constructed in the 1950's and 1980's and some pipelines were built even earlier. The age case in Sweden can be higher due to noninvolvement to World War I, II. Over 12% of the nation’s cross-country gas transmission and hazardous liquid pipelines were built prior to the 1950's [82]. The figure below depicts the most contribution of failure events/frequencies related to pipelines in different mechanisms.

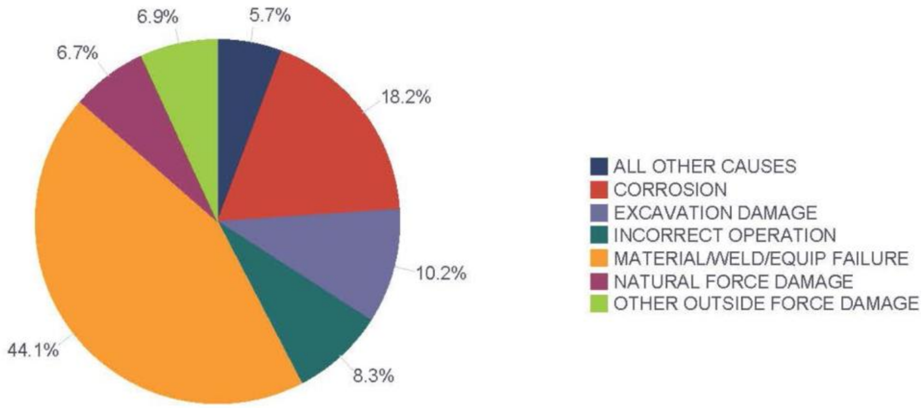


FIGURE 21: FAILURE PERCENTAGE OF PIPELINES FOR DIFFERENT MECHANISM[82]

To assess the related risk, evaluation of the different stresses to the pipelines under railway could provide better insight to understand the associated hazards. Section 2.1 summarized the most important factors affecting the pipeline health. This includes internal and external coating and soil condition, corrosion potential and welding problem and related connecting system as well. Risk assessment and management can be performed in the following phases and each phase can be performed separately or can be performed by aggregation of all factors gives as:

- Design and construction phase
- Operation and Maintenance
- Human factor

Design and construction phase is one of important phase for risk assessment. The municipalities do not keep details of the design and planning process of the old pipeline construction at the cross-section. In addition, due to the changing demand and new expectation (more frequent traffic and more axel load for freight train), the old construction need to be inspected and evaluated the pipeline health more frequently in connection to new society expectation demand. Hence, the design-based hazard must be clearly understood before carried out the risk reduction approach. In this phase having a clear understanding of different failure modes of the pipeline at cross sections is more remarkable [83].

Material selection also can play a critical role in this design and construction phase. Installation/utilization of the same material could not be an optimal material selection when different parameters, for instance, soil type and axle load, traffic frequency, etc. is changing.

Operational factors: failure and inspection history, pipeline renovation, repair, rehabilitation age, and rehabilitation methods can be considered as factors in the operational category.
Operational and maintenance factors analysis yield to have a better understanding of pipe infrastructure failure rates, the current status of the pipeline (Nowcasting) and remaining useful life of the pipe(prediction). In that direction, the main factors include failure and inspection history, pipeline renovation, repair, rehabilitation age, and rehabilitation methods. As we mentioned earlier, most municipalities do not keep detailed operation and maintenance records, hence reliability analysis based on historical records is rarely possible to perform.
Human error is one of the most important aspects of risk assessment and always it is difficult to quantify due to the complexity of the process, and availability limited approach to capturing associated risk. Here in this study, we are mainly focusing on the factor related to construction and operation & maintenance for pipeline network considering cross-section.

3.3.1. Brief information regarding risk assessment

Risk assessment in most standards and guidelines can be divided into three main steps as:

1. Risk identification
2. Risk analysis
3. Risk evaluation

In a literature study, several *risk identification* techniques have been identified. For example, ISO [84] provides a detailed overview and a comparison of risk identification techniques. The following techniques were found as the most suited to deal with risk identification at the cross section of pipeline network and railway infrastructure:

- Risk profiling
- Structured or semi-structured interviews
- Fault tree analysis
- Hazard and operability analysis (HAZOP)
- Failure mode and effects analysis (FMEA)
- Failure mode, effects, and criticality analysis
- Event-tree analysis
- Delphi based method
- What if analysis

Each of the above approaches has been defined for specific issues. Figure 22 shows a procedure for selection of the right approach.

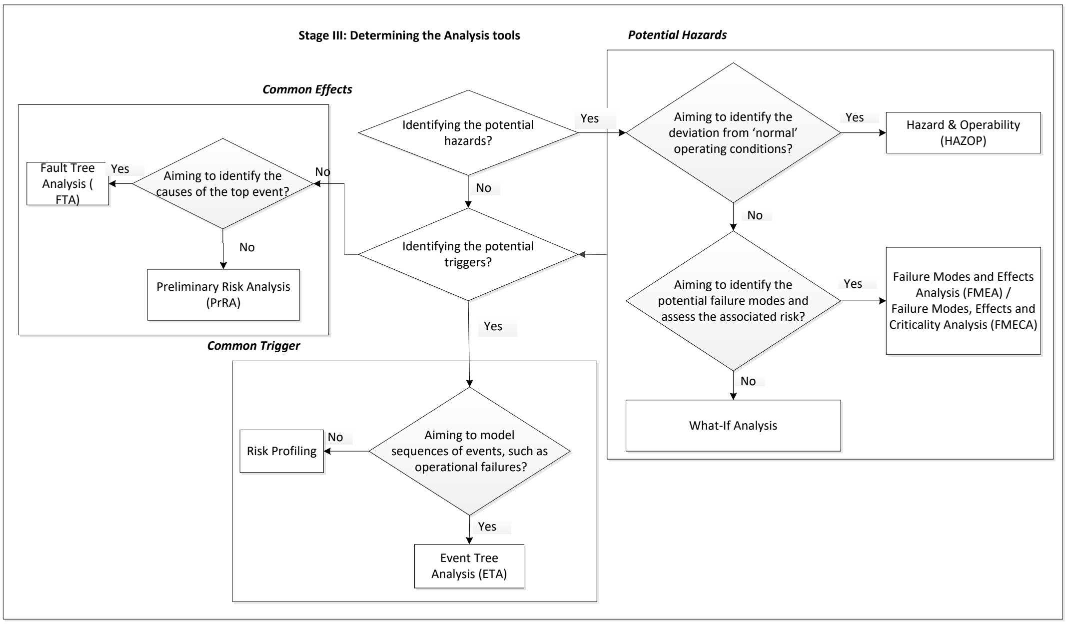


FIGURE 22: DIFFERENT CRITERIA FOR MODEL SELECTION.

In addition, a description of the above methods can be found in the Refs [85-87]. Each of these approaches has strengths and weaknesses, and selection of the method including costs, availability of data, complexity if the system, location, and type of the task, etc. For instance, HAZOP model and failure modes and effects analysis (FMEA) technique are appropriate tools while the risk assessments are involving the complex facilities under different effects of the process. Fault-tree and event-tree analyses are tracing the sequence of events backward of a failure propagation through a fault tree diagram. In an event tree, the process begins from a basic event and extends forward through all possible subsequent events to determine possible failures. Probabilities can be assigned to each branch and then combined each other to calculate all event probabilities. Finally, the probability/likelihood of event and risk analysis process could be carried out

Due to unavailability of measurement data, a qualitative approach have been selected for the aim. Questionnaires and interview approach have been designed to collect the related data through the expert's knowledge and their experiences. Questionnaires were validated and experts provided details on the failure location and the type of contraction performed for installation or maintaining pipelines under railway embankments. For this purpose, a formal expert judgment process can be followed, which consists of three main phases, namely, expert selection, elicitation of expert opinions, and aggregation of expert opinions [88]. Firstly, a number of experts should be selected based on a set of criteria (e.g., knowledge on VA technology, railway maintenance expert, and the equipment unit or the case of interest); Once expert opinions are elicited, an aggregation method is chosen to combine expert data and thus to obtain a single solution (e.g., single distribution function) that will be used by the decision-maker.

Among different mathematical methods to combine expert data, weighted-arithmetic and weighted-geometric averaging techniques are the less complex ones, which are widely used in different applications of expert opinions [89]. However, such methods require some weighting factors to be defined for experts, which is a challenging task. Several techniques such as equal-weighting, performance-based weighting, and computation of experts' weighting factors based on a set of predefined criteria are suggested in several studies [9, 10]. In addition, we found that the selection of weight factor based on the expert's opinion will reduce the quality of the analysis. Here we request experts to only rank the attribute weights' based on importance or criticality of the asset instead of assessing quantitatively (also qualitative term such as high, moderate or low, etc. is not used). Hence, the new approach to the selection of weight factors is presented in this research project.

Finally, *risk evaluation* is the phase where the risk analysis results are collected and put together. For the representation of the result, the risk matrix tool is select to evaluate the risk due to the qualitative nature of the study. Figure 23 represents different steps for the risk assessment of pipeline under the railway.

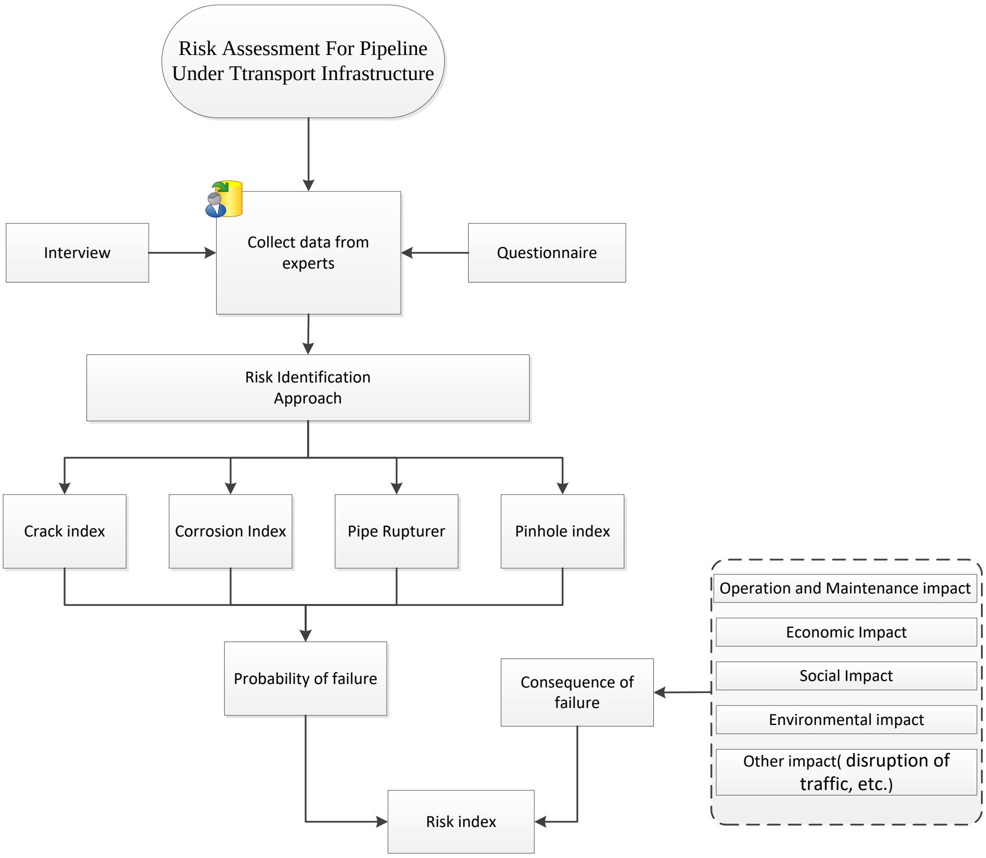


FIGURE 23: QUALITATIVE RISK ASSESSMENT OF PIPELINE UNDER INFRASTRUCTURE

3.3.2. Pipe failure consequences (PFC)

3.3.2.1. First approach

Evaluation of pipe failure consequences index is quite straightforward and beneficial for infrastructure managers. Failure consequence analysis is a subjective modeling procedure due to the determination of weights factor. Here pipe failure consequences have been categorized in terms of environmental impacts, social, economic as well as operation and maintenance costs as given in figure 19 [48]. Eliminating and managing this kind of failure consequences play a critical role to achieve the high-performance efficiency and productivity towards pipeline sustainable perspectives.

The economic impact is linked with the pipe material, diameter, and physical features, as well as buried depth. Pipe material determines the price of replacing or maintaining pipes, while also playing a role in the selection of methods used for underground pipeline inspection. Hu, Yang [90] shows that the costs have a direct relation with diameter, means larger diameter incur a heavier cost. Furthermore, buried depth has an economic impact and needs to be considered. It is logical that by increasing the depth of buried pipeline the operational difficulty for instance rehabilitation and repair will increase and incur more cost for maintenance and/or replacement activities.

Regarding the operational and maintenance impact, pipe segmentation and connection type and dependency between pipe networks can be considered as operational impact. For instance, the high dependency can be found in the series system which makes network high level of risk. Furthermore, water damage to the surrounding infrastructure and properties can be categories as operational and maintenance impacts, for insurance, water flooding due to pipeline failure or inadequate drainage system, rail settlement/bump and other structural damage that may influence traffic.

From an environmental perspective, leakage of industrial wastewater will result in an environmental hazard. The risk associated with safety & health and environment can be categorized based on the different consequents that has been shown in Table 7.

TABLE 7: PIPE FAILURE CONSEQUENCES

	Consequences			
	Negligible	**Low lost**	**Medium lost**	**High lost**
Economy	10000SIK	10000-100000SEK	100000-1000000SEK	More than1000000 SEK
Safety and health	Injuries or ailments not requiring medical treatment Minor injury or first aid treatment case	Serious injury causing hospitalization or Life-threatening	Life-threatening injury or multiple serious injuries causing hospitalization	Death or multiple life-threatening injuries
Environment	Minor adverse effects on living organisms and the environment	Moderate adverse effects on living organisms and the environment	Moderately high adverse effects on living organisms and the environment	High adverse effects on living organisms and the environment

3.3.3. Second approach

Here in this section, pipe failure consequences at cross section can be analyzed based on the different type of costs. For this aim, different cost, for instance, direct costs, indirect costs, and social cost can be expected for pipe failure or inadequate drainage in the railway corridor. Losses as a result of pipeline failure at cross-section may be higher than losses in other location due to its impacts to the railway network. Here some of the cost/losses in each category have been summarized as follows:

1. *Direct costs*

(i). Repair or installation cost. The cost of pipeline failure and repair under railway embankment is more costly compared to other pipeline failures.
(ii). Cost of water lost that depends on the size of the pipeline and failure severity.
(iii). Loses due to water damage to the surrounding infrastructure and property for insurance, water flooding due to pipeline failure or inadequate drainage system, rail settlement/bump, and other structural damage.
(iv). Injury, accident due to pipeline failure can be a two important issue at cross-section with the railway. If the probability of such failure is considered as less but it can create expensive consequences.

2. Indirect costs

(i). Costs of supply interruption (loss of business due to the water outage) that depend on the isolation time of the failure;

(ii). Losses due to unavailability of rail transport infrastructure including passenger and freight train.

(iii). Cost of increasing deterioration rate of affected surrounding infrastructure and property;

3. Social costs

(i). Cost of water quality degradation due to contaminant intrusion caused by de-pressurizing;

(ii). Decreasing trust of the railway transport system due to delay, unavailability, and punctuality.

(iii). Decrease in public trust to the asset owner and manager.

(iv). Cost of disruption of the traffic and business

(v). Cost and risk of disruption of the water supply to special facilities (hospitals, schools, etc.)

Table 8 shows more detailed criteria to determine the failure cost consequences index. The total cost associated with the main factors have been divided to its sub-factors and multi-criteria matrix has been developed for evaluation of consequences of the failure. In addition, the following equation has been used for the weight aggregation of the activated criteria.

$$PFC = \sum_{i=Main\ feature} W_i \left(\sum_{j=sub\ featuer} w(p\_value_j) \times w_j \right)$$

$$\sum_{Main\ feature} W_i = 1$$

TABLE 8: FAILURE COST ESTIMATION INDEX AT CROSS-SECTION

Main factor	Weight for main factor	Sub-factor cost	Sub-criteria	P-value	Weight factor
Direct costs	0.40	Repair or installation cost	>100000 <10000 and 100000> 10000<	3 1,5 0	0.2
		Cost of water leakage	Diameter >200 100 <Diameter <=200 Diameter <=100	3 1,5 0	0.2
		Damage losses to surroundings due to water leakage	High Medium	3 1,5	0.2

			Low	0	
		Losses due to Injury, accident	High Medium Low	3 1,5 0	0.4
Indirect costs	0.30	Costs of water supply interruption	Maximum Medium Minimal	3 1,5 0	0.4
		Losses due to unavailability of rail transport	High cost Medium cost Low cost	3 1,5 0	0.3
		Cost of increasing deterioration rate	High rate Medium rate Low rate	3 1,5 0	0.3
Social costs	0.3	Losses due to water quality degradation (dust particles)	Higher ppm of contamination Medium ppm of contamination Lower ppm of contamination	3 1,5 0	0.3
		Decreasing trust to the railway transport	Loss in long-term trust Loss in medium-term trust Loss in short-term trust	3 1,5 0	0.1
		Cost of disruption of the traffic and business	Higher cost Medium cost Lower cost	3 1,5 0	0.3
		Cost and risk of disruption for the public (hospitals, schools, etc.	High risk Medium risk Low risk	3 1,5 0	0.3

It may note that the weight should be selected by experts and selection of the weight depends on the location, type of construction and condition of the pipeline and railway infrastructure and assessing unified weights to cover all the cases are not an optimal solution. The factors with minor impact can be removed from the above assessment. The above pipe failure consequence index can be used for the selection of maintenance policies also. The maximum index value is 2.73 when all factors have an effect on the process with higher weight and the maximum value is estimated 0.12 when the only repair factor has been activated with moderate impact. The consequences of failure have been re-scaled in Table 9 to be used for developing a risk matrix.

TABLE 9: CONSEQUENCE OF FAILURE RATING

Consequence of failure index	**Consequence of failure rating**	**Description**
2.2-2.73	5	Very High
1.68-2.2	4	High
1.16-1.68	3	Moderate
0.64-1.16	2	Low to Moderate
0.12-0.64	1	Low

4. Result and Discussion

4.1. Analyses of questionnaires and interview study

4.1.1. Analyses of the first questionnaire

As mentioned in the Section3.1.1, the first questionnaire has been distributed to 291 municipalities and two general questions asked about the possible experience of the failure of the pipeline within railway and road infrastructure. Essentially this questionnaire has been distributed to collect the information from the water and wastewater experts at municipalities, see Appendix I.

We have received 100 responses from VA experts from the first questionnaire and participation rate is around 35%. The distribution of the responses has been plotted in Figure 24 for the railway cases. Furthermore, the experts who answered the questionnaire has been categorized into four groups, which are presented in Table 10.

TABLE 10: PARTICIPATION TYPE IN THE FIRST QUESTIONNAIRE

Participation Type	First questionnaire
VA and Road Head	41
VA Project Engineer	24
Grid manager/Municipal VA Manager	25
Operator/ Operation and Maintenance + Other	10
Total	100

FIGURE 24: RESPONSE RATE: 100 FROM 291 MUNICIPALITIES

Based on the responses of this questionnaire related to railway question, 63% reported “Yes” to the question, means they had such failure experience at pipe crossing railway and 37% report “No” to the question. It may note that the result of 37% included those cities that they don’t have railway infrastructure and a questionnaire distributed to all municipalities without filtering due to the mobility of experts between municipalities in the last 10 years. The details description of the answers has been analyzed and categorized into six group. The percentage of each group is calculated and presented in the pie form as given in Figure 25.

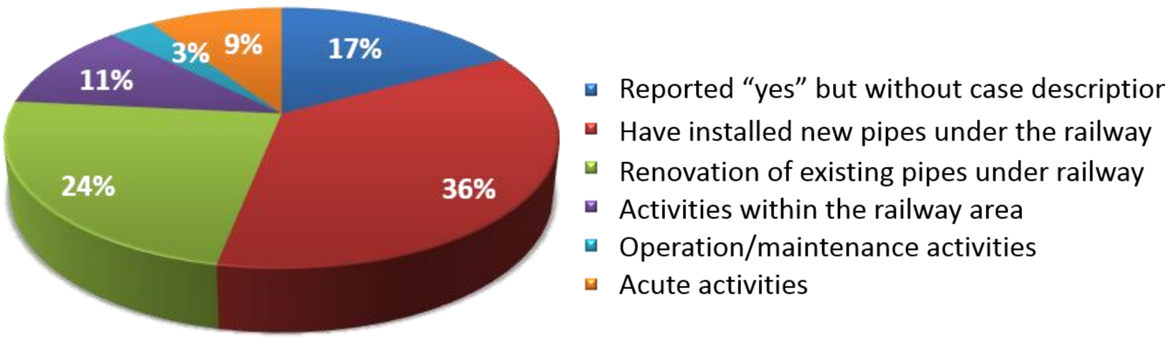


FIGURE 25: QUESTIONNAIRE RESPONSE FOR RAILWAY

In addition, 75% of responses had pipeline crossing road experiences in their experiences depicted in Figure 26. For instance, 34% had an installation of new pipes under the road and 24% have experience of the different type of pipe renovation in their last 10 year experiences.

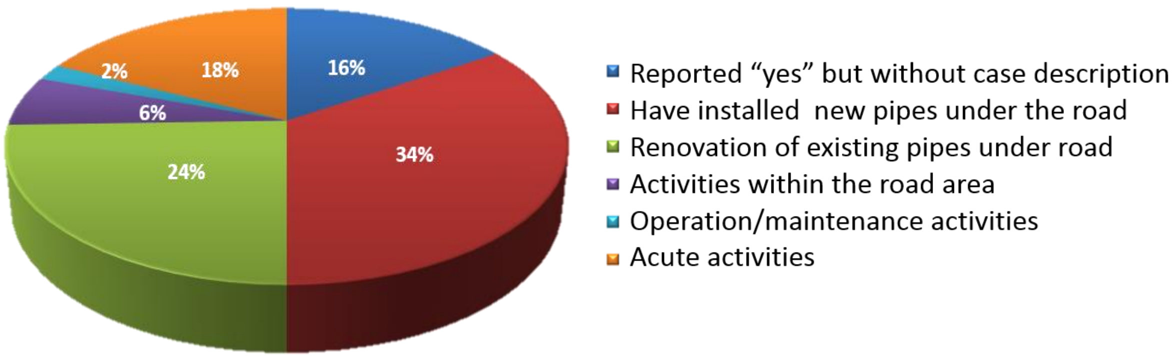


FIGURE 26: QUESTIONNAIRE RESPONSE FOR ROAD

Different colors have been selected for each group. The similar colors in the above figures (Figure 24, Figure 25 and Figure 26) have the same meaning to avoid any confusion. Some of VA experts reported different issues and we reflected such issues by different colors in column bars represented given in Figure 24. For example, VA experts in Gälve report acute activity, renovation, and installation of a new pipeline under railway embankments. These three groups have been depicted by the Orange-green-red bar on the Gälve map.

4.1.2. Analysis of the second questionnaire

The complimentary questionnaire has been sent to the municipalities directed to railway case only. The selection of municipalities for answering the questionnaire was based on some inputs that we have received from the first questionnaire. In total 63 municipalities in Sweden reported cross-sectional failure in their area’s. The target of the second questionnaire is to identify the pipe failure modes and failure causes from the municipality perspective.
As discussed in section 3.1.1.2, in total 8 questions had been asked. The details of questions are available at Appendix II.

TABLE 11: PARTICIPATION OF EXPERTS IN THE SECOND QUESTIONNAIRE

Participation Type	Second questionnaire
VA and Road Head	9
VA Project Engineer	6
Grid manager/Municipal VA Manager	7
Operator/ Operation and Maintenance + Other	3
Total	25

FMEA model results

Failure modes and effects analysis (FMEA) is one of the popular tools in the operation and maintenance engineering to analyze the potential failure effects and identifying the dominant failure modes as well as classify them according to severity and likelihood. Furthermore, the objective of FMEA is to provide feedback to the design phase for improving the performance of the system in terms of quality, reliability and availability. FMEA defines the term "failure mode" to identify potential or actual failure in a product design or operation, with an emphasis on those affecting the customer or end user. A "failure effect" is the result of a failure mode on the product or system operation. The study of consequences of identified failures is called effects analysis. FMEA prioritizes failures according to severity, occurrence, and detectability. Severity describes the seriousness of failure consequences. Occurrence describes how often failures can occur. Detectability refers to the degree of difficulty in detecting failures.

In this questionnaire, 8 questions have been for the aim. The first question of the questionnaire aimed to identify the type of the methods/technique for future investigation.

Question 1- How it has been found that there were problems with the VA pipelines under / near rail?

The result as given in Figure 27 reveals that most of the identified faults and failures are based on the visual inspection. This confirms the substantial needs of utilization of new condition monitoring technologies on the pipeline system especially at cross section due to load and traffic frequencies.

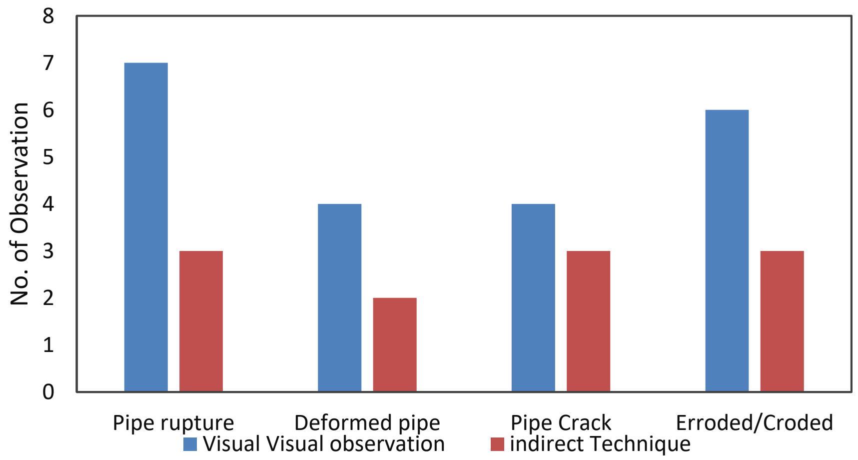


FIGURE 27: TYPE OF FAILURE DETECTION METHOD

In addition, based on the literature [18, 33, 83] and interview with VA experts the following four different failure modes and resulting effects from each failure mode given in Table 12 have been selected to be asked from VA expert.

TABLE 12: POSSIBLE FAILURE MODES AND EFFECTS FOR PIPE CROSSING RAILWAY

Failure mode	**Effects resulting from each failure mode**

Pipe rupture	Limited sanitation capacity
Deformation	Wastewater treatment
Eroded/corroded	Flooding
Crack	Sinkhole and rail settlement

In the second question “What types of pipe defects have been noted on pipes below / near rail?” we aimed to verify above identified failure modes. In addition, we have requested on the complementary information from the experts. The percentage of the observed failure modes have been plotted in Figure 28. It may note that some of the experts reported more than one failure mode.

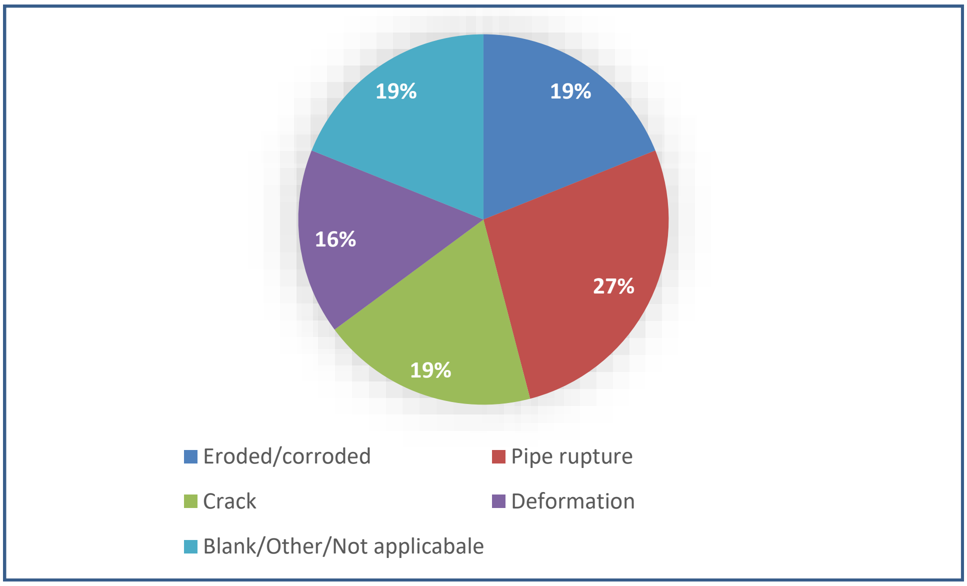


FIGURE 28: PERCENTAGE OF OBSERVED FAILURE MODE

In the next step, the effects of each failure mode on the above failure effect have been measured by the four-scale method as (1) there is no effect, (2) has little impact, (3) moderate impact and (4) has a severe impact. For converting the linguistic variable, we have used the numeric scale 1, 2, 3 and 4 respectively. Based on the additive weighting analysis, the temperature matrix has been evaluated and presented in Table 13.

TABLE 13: EVALUATION OF POSSIBLE FAILURE MODE AND EFFECTS

	Effect of pipe Rupture				Effect of deformation				Effect of Crack				Effect of errosion/corrosion					
	Limited Sanitation Capacity	Wastewater treatment	Flooding	Pinholes	Limited Sanitation Capacity	Wastewater treatment	Flooding	Pinholes	Limited Sanitation Capacity	Wastewater treatment	Flooding	Pinholes	Limited Sanitation Capacity	Wastewater treatment	Flooding	Pinholes	SUM	Average
Pipe Rupture	3,00	1,89	1,89	2,00	2,38	1,75	1,88	1,88	2,88	2,13	2,25	2,13	2,50	1,50	2,00	1,88	33,90	2,1
Deformation+All other	3,17	2,50	2,83	2,17	2,83	1,83	2,00	3,00	3,00	2,00	2,60	2,40	3,40	2,00	2,60	2,40	40,73	2,5
Crack	2,57	1,33	2,17	1,83	2,00	1,33	1,50	1,50	2,83	1,50	2,33	1,67	2,33	1,17	1,67	1,50	29,24	1,8
Eroded/corroded	2,44	1,29	2,00	1,71	1,29	1,29	1,14	1,29	2,00	1,43	1,86	1,57	3,13	1,57	2,29	1,57	27,86	1,7
Sum	8,74	5,72	6,89	6,00	7,21	4,92	5,38	6,38	8,71	5,63	7,18	6,19	8,23	4,67	6,27	5,78		
Average	2,18	1,43	1,72	1,50	1,80	1,23	1,34	1,59	2,18	1,41	1,80	1,55	2,06	1,17	1,57	1,44		

To visualize the effect of each failure mode in correlation with sides' effects radar chart have been utilized and depicted in Figure 29. The result given in Figure 29 reveals that limited sanitation capacity and flooding are two dominant effects resulting from failure occurrences.

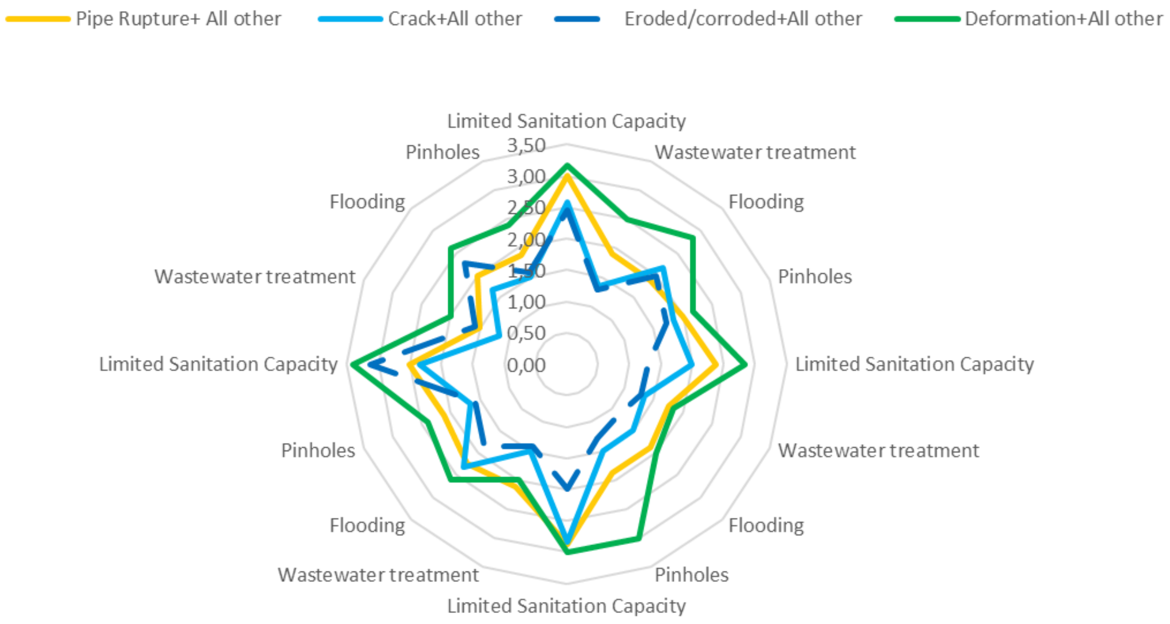


FIGURE 29: DISTRIBUTION OF FAILURE MODES IN CORRELATION WITH SIDES'

Based on the analyses, we have found that pipe deformation has higher impact followed by pipe rupture at cross-section with railway infrastructure. Figure 30 represents the level of impact for identified failure modes.

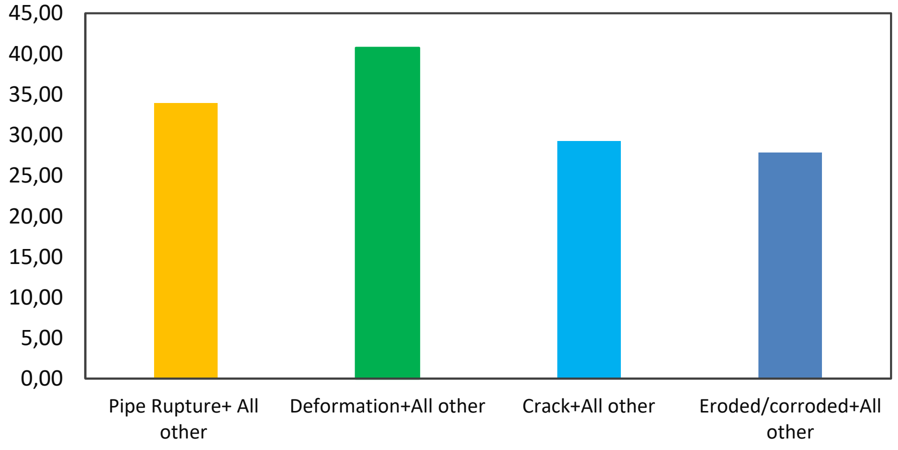


FIGURE 30: IMPACT LEVEL OF IDENTIFIED FAILURE MODES

Several covariate, for instance, maintenance action, installation period, aging, corrosion, nearby excavation, seasonal variation, pipe properties (diameter, pipe length, pipe material), soil condition, previous failure, pressure in the pipeline, external load stress (traffic frequency, axle load) which can be considered as failure causes to the pipeline network which have been reported by [18, 33]. The experts have selected these covariant as the most important failure causes to the pipeline at the cross-section. In this study, a question has been asked from VA experts to identify the factors that have the greatest impact to the pipeline failure at the cross-section. Figure 31 represents the impact of each defined causes. In this case, aging, external load, erosion/corrosion, and reduced pipe function have been received higher impact compared to other causes on pipeline failures.

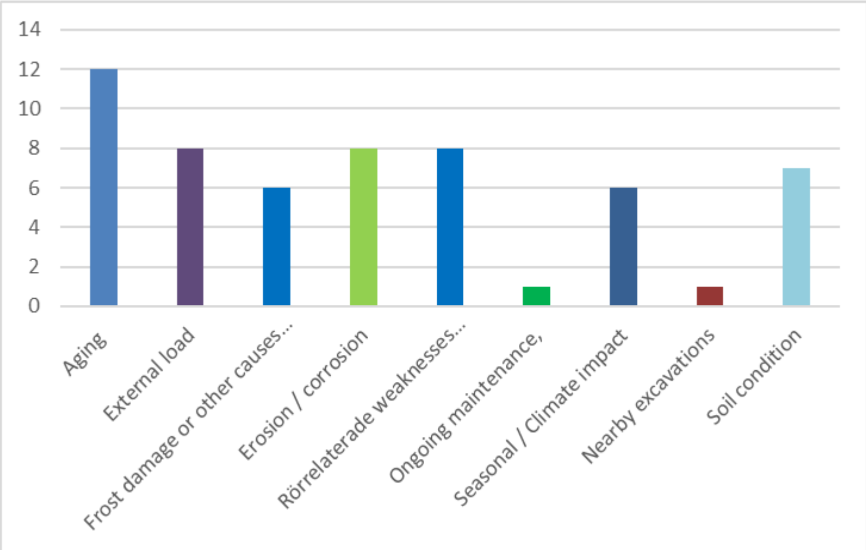


FIGURE 31: THE COVARIATE EFFECTS LEADING TO PIPELINE FAILURE AT RAIL-CROSS

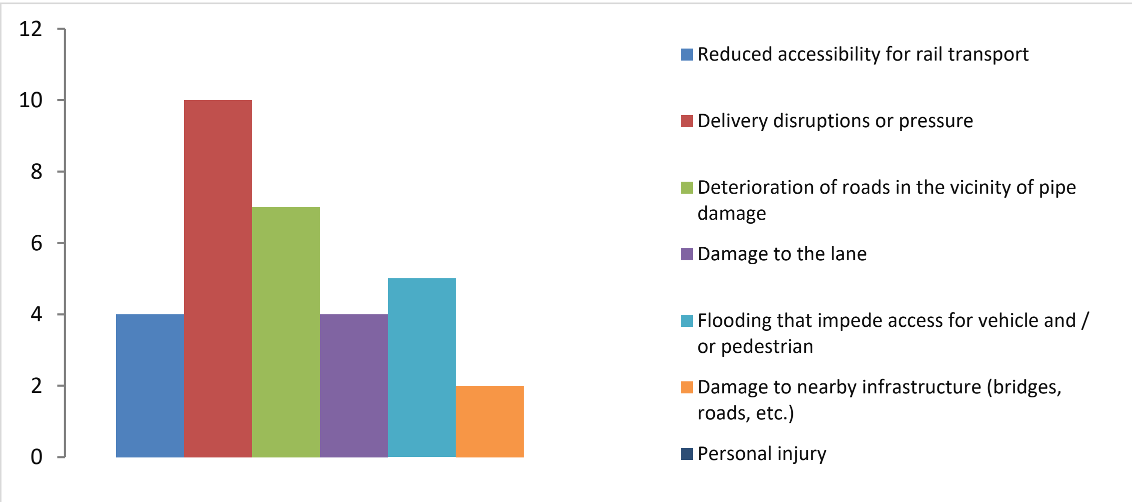


FIGURE 32: POSSIBLE CONSEQUENCES OF FAILURE AT THE CROSS SECTION

In the next step, we aim to identify the possible consequences by asking a question “what was the consequences of pipeline failure at the cross section with railway?” from the experts. Different alternatives have been extracted from literature and interview with VA expert. In addition, there was a possibility for the experts to describe their case in details. The result reveals that “Delivery disruption or pressure” gains higher impact followed by “Deterioration of road nearby to the pipeline failure”. Figure 32 shows the level of the possible consequences at the cross-section.

To identify the “greatest needs for installation of the new line under railway embankment” which directed to one of our research questions given in Table 2. In this question, five alternatives have been asked and the results have been presented in Figure 33. The result confirms that some of our hypothesis. Also, the result shows that replacement of the old pipeline and needs for increasing the capacity of the pipeline are the main demand for installation of a new pipeline under the railway. Furthermore, we were interested to know about the techniques that have been utilized for the installation of a new pipeline and there was the possibility to describe their case in more details. Here we have asked, “which technique has been used for the installation of a new pipe near/under railway corridor.” For this question, the higher grade captured by “No Dig” trenchless technology-steered drilling and trenchless technology with pipe pushing, see Figure 34. Steered drilling is a drilling technique used in wire mesh construction. The drill head is controlled from the ground and has a design that makes it possible to drill crooked, for example, under roads, railways, and rivers. Steered drilling works best if the ground is stone free and easy. The method can be utilized for the pipe with a diameter less than1200 mm and lengths up to 1500 meters.

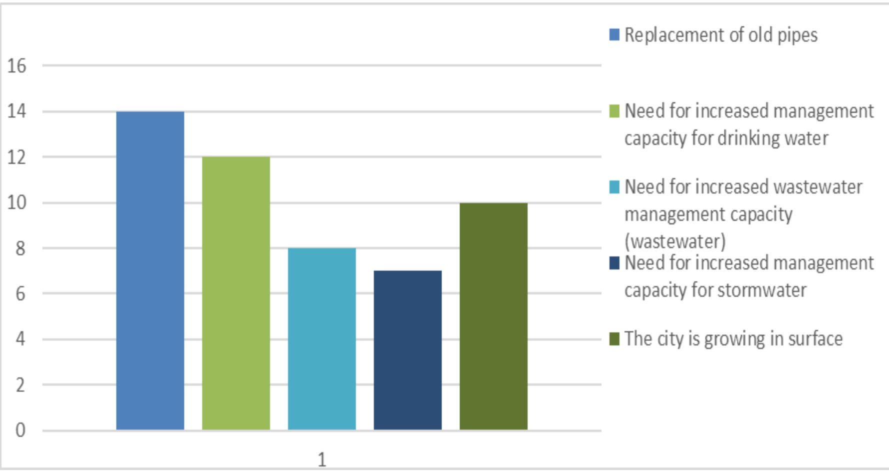


FIGURE 33: THE NEED FOR INSTALLATION OF A NEW LINE UNDER THE RAILWAY

It is important to note that in this survey, 26% of municipalities have used the open excavation for the installation of new pipe. This issue needs to be studied in more details to identify why 26% of municipalities had been used such an expensive solution. We have tried to find some relative answers through interview study presented in the next section.

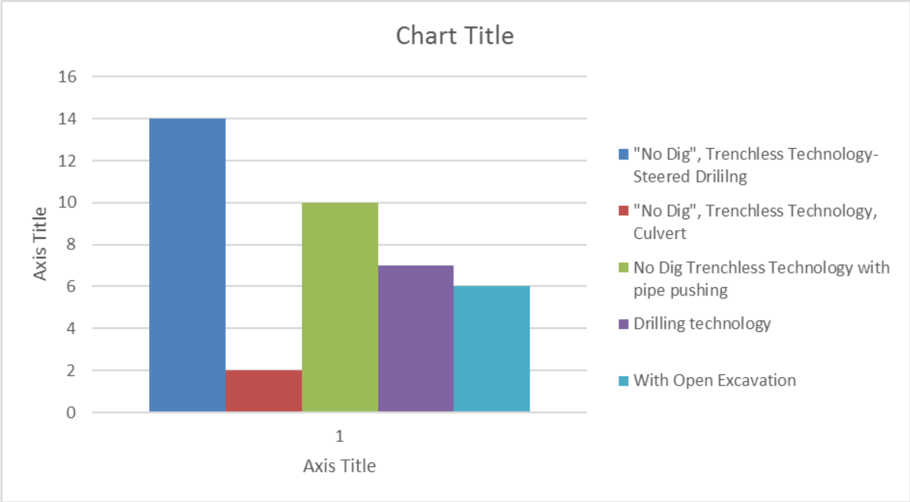


FIGURE 34: TECHNIQUE USED FOR INSTALLATION OF NEW PIPE UNDER THE RAILWAY

Furthermore, we differentiate between pipe renovation and new pipe installation technique to have a deeper analysis in the study. Several popular methods have been selected based on the literature and interview with the VA expert. As the result depicted in figure 10, trenchless technology with flexible pipe gains higher impacts follows by open excavation and No dig lining with a rigid tube. In this question, we have received some blank responses or other information provided by the expert. For instance, in one case have been reported drilled new pipe next to old ones.

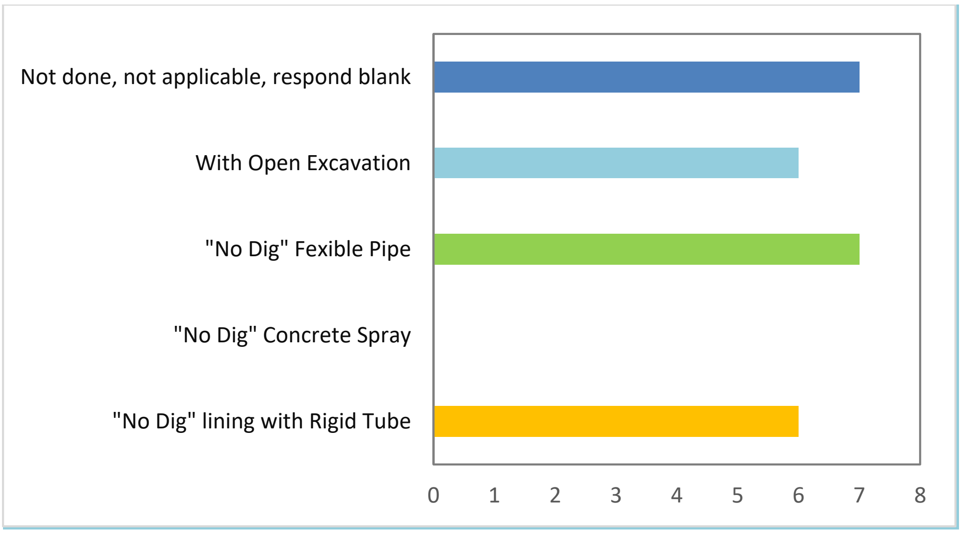


FIGURE 35: TECHNIQUES USED FOR INSTALLATION OF NEW PIPE UNDER THE RAILWAY

Risk priority number (RPN) estimation

As explained in chapter 4, severity, occurrence, and detectability are the key parameters in the evaluation of Risk Priority Number (RPN). RPN has been defined as a mathematical product of Severity (S), Occurrence (O) and Detection (D). It serves in fixing the priority for the process/item to focus on maintenance decision making. It may note that detectability scaled in the reverse form means it will take high rank when not likely to be detected and low rank when very likely to occur.

TABLE 14: DETECTABILITY SCALE

Rank	Likelihood of detection during diagnosis
1	Almost certain
2	High
3	Moderate
4	Low
5	The fault is undetected by Operators or Maintainers

Scaling Detectability parameter:

Detectability level ranged from 1 to 5 based on the linguistic variable as given in Table 14. In general terms water & wastewater pipe failures can be detected by (i) water flooding up to urban soil surface, (ii) sudden cracks/depressions of surface layers in streets etc, (iii) pipe capacity change as observed by rising level in manholes, (iv) loss of access to water service in flats/urban areas, (v) basement flooding – both wastewater and drinking water, (vi) sudden/unexpected change in water level in water reservoir,(vii) unforeseen capacity problems in waterworks, (viii)dramatic change of incoming flow to wastewater treatment plant, (ix) unexpected behavior when it comes to pumping stations operation hours/24 h day, (x) manual observations of sewer/stormwater overflow to recipients (even under ice/snow cover).

There are not dedicated SCADA system in most of the municipalities able to detect & alert to the operation staff for the above changes within the pipeline network. In some of the municipalities the general SCADA system is installed and running for more than a decade – but the software system for this purpose is not added.

- Pipe rupture detectability: Based on the result of expert judgment it will be in level 2.
- Deformed pipe detectability: estimated level 2. Deformation means mostly “near collapse” – detected either at once (soft PP pipes not laid down in soil properly) or when they start to break down in large pieces due to i.e. soil pressure during 30-50 years (I e concrete pipes missing steel reinforcement)
- Pipe crack detectability: estimated level 4. If water is transported by gravity the crack might be harder to detect – especially regarding small gravity systems.

- Eroded/corroded pipes detectability level: estimated 4. The problem with this kind of failure mechanism is that it is expected to be fairly spread and is a major factor for drinking water leakage – especially when it comes to customer service pipes made of galvanized steel (40-50% of all service pipes). Most damages connected to corrosion are hard to detect in time where they either result in deleterious water quality.

After evaluating the severity, occurrence and detection levels for each failure mode RPN can be calculated via the following formula. As given in Table 15 erosion and corrosion gets higher RPN value.

$$RPN = Severity \times Occurance \times Detection$$

TABLE 15: RPN EVOLUTION

	Severity	Occurrence	Detectability	RPN
Pipe rupture	2,1	0,31	2,00	1,31
Deformed pipe	2,5	0,18	2,00	0,9
Pipe Crack	1,8	0,22	4,00	1,58
Erosion/Corrosion	1,7	0,28	4	1,9

As this table shows the PRN for Erosion/Corrosion has the highest number which means if the resources are limited this hazard should be treated first.

4.1.3. Interview Study

Interviews study have been carried out with infrastructure managers to obtain qualitative data to analyze and classify failure modes related to the rail-pipe-soil interaction. This study builds on expert-based knowledge approach for analyzing the failure mode and consequences of the pipeline at the cross section within railway infrastructure.

Recent findings based on the two questionaries' 2017/18 at LTU survey raised a need to further deepen the knowledge of operation disturbances, caused by municipality water pipes buried in railroad beds. A rough estimation based on a selection of all reported roadbed damages (Ofelia database records) or disturbances between 2001 and 2017 is that only a minor number of all disruptions can be connected to water or wastewater pipe crossings railway embankments. The total number for 2001-2017 is estimated to a couple of dozens (< 50) out of a total damage railroad number exceeding 60 000 annually and 20% affects train movement (The statistics extracted from Ofelia database). A first rough estimate of the total domestic number of (municipal) water & wastewater pipe-railway crossing is on the level of 2000 – 4000 (based on the estimated number of crossing W&W piping per larger urban area) and with a total domestic crossing pipe length of 45000-75000 m (based on a sensitive pipe length of 15 m per crossing). The estimated frequency of water & wastewater pipe damages near (defined as within 15 m of perimeter of railbed areas) or inside railway/railbed areas is below the mean W&W general pipe damage level of 0,2 damages/km of pipe and year. This estimation is based on the Swedish estimated length of W&W pipes crossing the railway, the reported number of W&W related damages in the areas of interest - finally compared with total domestic figures/levels for municipal W&W piping length and pipe damages.

In order to further try to understand the driving forces and the potential for this damage number to increase in the future, more specific questions were addressed to all municipalities and companies, i e. those reporting some sort of interrelated damage as well as willing to take part of further research activities.

In all 7 municipalities (one of these being Roslagsvatten AB covering Water & Wastewater service to 5 municipalities north of Stockholm) and 2 private companies were investigated by telephone interview. The following is a summary of the findings, grouped to each of 7 specific questions.

Questions and answers

1. What kind of juridical agreements are there between the national Swedish Transport Authority and municipality Water & Wastewater service providers when it comes to water pipes crossing railroad beds?

   Results: In a rare number of cases (Olsson [91]; Sjögren [92], Evaldsson [93]) there exists a written document known as *avtal* (agreement). Others reports alternatives as *avtalservitut* (easement agreement), *ledningsrätt* (pipe entitlement) or *grävtillstånd* (dig permit) as the general administrative way to handle this kind of issues. *Grävtillstånd* as a permit is connected to the time when the pipe is to be taken through the roadbed or is to be repaired etc.
   All respondents reported having none (officer) allocated as responsible for or working deep with statistics of pipe disturbance. Usually, pipe damage are taken care as soon as they arise - prior on a scale depending on customer needs and environmental quality. But the collection, analyses, and reuse of valuable information in this sector are usually not performed to a decent degree - as it isn't demanded by regulations or law Evertsson [94].

2. Are pipes crossing rail beds protected by pipe-in-pipe technology or being put inside walkable reinforced concrete conduits?

   Results: Nearly all bed crossings are protected using 100% pipe-in-pipe technology, in all municipalities [91]. In multi-rail track areas, one can find reinforced walkable conduits Nilsson [95] large enough to handle output from a number of municipal service providers, i.e. district heating, water &wastewater, electricity, and digital information lines.

   Two municipalities (Evaldsson [93]; Evertsson [94]) reports that gravity flow (wastewater) pipes are not in all cases protected. It´s not clear if municipalities reporting not using 100% protective devices have done so in many cases, or if they still continue this habit.

3. When problems arise connected to pipes near or crossing rail beds – is there an implemented strategy at hand or has there been any discussions about the need? Or are they handled from time to time when they emerge?

   Results: as these cases are so rare and for most areas happens only a few times during a decade – or nil – municipality respondent couldn´t give an answer. Probably due to that they usually were/are responsible for daily operation/maintenance, short time planning and not staffed for long time planning/design. The latter in many cases is done by consultants, with no further responsibility after the project is finished [96, 97].

4. Is there a strategy decided how to plan and construct new pipe structures near rail beds and areas – or when new rail systems are needed in areas with gravity or pressure pipe systems?

   Results: the strategy reported is: (1) try to avoid crossings during pipe system design stage, (2) if necessary use natural openings in rail beds (traffic crossing viaducts) or other technical structures [98], (3) if bed crossing is necessary use conduit technology as well as inspection manholes on both side of rail bed [99], (4) regarding multiple rail bed areas (railroad station area) use walkable reinforced concrete conduits [95].
   Railway areas usually are connected to electrical converts, which generates current surges. This transformation can become a threat connected to galvanic currents in rail beds using metallic pipe materials [99].

5. What is your attitude regarding risks connected to pipes placed near rail beds – or in the case these structures together creates “shut-in” drainage areas?

   Results: risks connected to pipes near rail beds or even crossing rail beds must be addressed by proper design and operation. In most cases crossing design, measures focus is in pipe-in-pipe technology, in two cases with added inspection man-holes at each side of every pipe-in-pipe section ([93]; [99]). In some cases pipe-in-pipe technology was not used, usually connected to gravity flow sewers ([94]; [93]). Using a specific safety policy is probably often connected to consulting firm risk assessment results or consulting firm general standard.

   Entrepreneur/Contractor responsible for nationwide pipe repair and replacement reports that many pipe materials can be expected to have a very limited operational time left – i.e. reinforced concrete gravity flow sewers. Back in time (1980-ies) repair activities mainly focused wastewater pipes, the present focus lies on ductile iron, PVC and pipes made of GAP [100]

When it comes to enclosed areas and potential drainage problem it´s (very vague answers) considered an internal problem for the landowner (usually Järnhusen etc– not the municipality) to handle.

6. During recent pipe works crossing rail beds or near rail beds – what kind of technology was used?

   Results: very few works were reported and all used a No Dig-technology. During the digging and installation phase, continuous and accurate measurement of connected rail levels had to be performed, including on-line warning technology [93].

   When it comes to pipes put down in the ground parallel to and near rail beds the approach is not known.

7. Is there in general terms something missing – that if added should or could facilitate project involving pipe-rail structures?

   A general municipal experience is that Trafikverket, the state owner of the rail bed areas, and also the state owner of many railroad structures Järnhusen AB, tend to see their ownership and connection to the Swedish state system as a prerogative that their interests and regulations are primary for society [93-95, 101]. In a conflict situation, it seems that Swedish state authority people (Trafikverket, Järnhusen, etc.) and their top priority issues are always regarded first in priority, regardless of what arguments responsible municipal officers responded. From this perspective and in order to unlock the possibility of increased speed in society structural change [98] there seems to be a need of better balance between local municipal infrastructure owner, the rail state owner and (included private business) operator interests. Among other actions, this can be supported by an improved juridical/legal structure.

4.1.4. Qualitative risk assessment

In section 4, we have identified failures/failure mode in a pipeline under railway infrastructure that may lead to undesirable situations. Different approaches had been proposed in the literature (see Figure 22) which can be used for risk analysis. Here the failure modes and effect analysis (FMEA) have been applied for risk analysis in this project. Moreover, having the rate for different types of consequences, as well as the frequency of the failure, the level of risk for each failure mode can be plotted on the risk matrix. The Decision-makers, including VA project engineer, grid manager/municipal, VA manager, and operator/operation and maintenance experts can use risk matrix to see whether the current level of risk is acceptable or whether some mitigation method should be implemented to reduce the risk of each failure.

Based on the FMEA result given in Table 13 and Table 15 the following risk matrix has been plotted. It should be mentioned that for the following risk matrix, three type of consequences has been considered as given in Table 7. Thereafter, the highest level among them is chosen for risk analysis.

		Consequence			
		Insignificant	Minor	Moderate	High
Frequency of failure	4			Deformation	
	3				Pipe Rupture
	2			Erosion/Corrosion	Crack
	1				

FIGURE 36: RISK LEVEL FOR IDENTIFIED PIPELINE FAILURE MODES CROSSING THE RAILWAY

4.2. Recommendation for maintenance and construction of a pipeline under railway infrastructure

4.2.1. Pipelines perspective: No-Dig (Trenchless) technology for pipe construction and pipe renewal of culverts, pipe bridges and pipelines within or crossing railway boundaries

Dewatering is important for the dependability and function of railway embankment; lack of dewatering can impair the stability of the embankment. Precipitation and groundwater should be certainly managed without affecting the railway infrastructure. The drainage system always covers open bank/ditches, and interactions between trenches, culverts and water pipes which required a proper operation.

The drainage system designed to collect and drain stormwater and ground water from the transport infrastructure and its surroundings. Commissioning single point of action of an urgent nature may be right, but for a larger dewatering area, a holistic approach is needed.

In such contexts, ditches, culverts, pipe bridges, and other pipes within transport infrastructure need to be inspected, and remarks related to the actions and need should specifically be motivated.

For crossing pipes, which is not in the operational responsibility of the Swedish Transport Administration, there is a basic requirement that they always are fitted with protective pipes. This type of pipes can be carried out by a combination of trenchless technologies. A protective pipe is placed with any of the new building technicians, and an installation of a media tube is carried out with a supplementary trenchless technology.

Below are the most commonly used trenchless methods to recreate or expand the drainage function.

Common to all methods is that the scope includes process-enhancing opportunities for all technical infrastructure and that they have clear technical, environmental and economic benefits. The trenchless technology is also advantageously used also for operations needed for other management owners in and around track areas.

4.2.1.1. Construction

The most common methods are: Steered drilling, Hammer drilling, Auger drilling, and Rammning.

Steered drilling (Styrd borrning)

Steered drilling is a suitable method for long and curved bore holes, and is possible for diameters up to 1200 mm. The work is carried out from the ground surface with a small entrance and receiver pits. The drill head position is verified by electronics and controlled by an angled guide shaft. In all steered drilling, a pilot hole is first drilled, which then is extended in one or several steps to a desired final dimension.

Application: mainly in clay and sand,

Geotechnical survey requirements: soil type, shear strength, groundwater level/fluctuation

Drill length, diameter, and material: 0-2000 m, 40-1200 mm, plastic or steel.

Used for: Gas, district heating, electricity, and telecommunication pipes, pressure gaps, pressurized water, sewers, water, even self-evacuation.

Figure 37: Steered drilling

Hammer drilling (Hammarborrning)

Hammer drilling is a method to use when the risk of obstacles in the drill line is high, or when stones, mountains or blocks are to be crossed. Hammer drilling is carried out from an excavation floor without the need for support. The hole is produced and delivered with protective pipes, for all soils except stable mountain ranges. The method gives high accuracy (horizontal/vertical) and self-conduction lines are possible down to 1% inclination.

Field of application: not in clay but in all soils and mountains,

Geotechnical Examination Requirements: Minimum - Clay Control,

Pipe length, diameter, and material: 0-80 m, 100-1200 mm, steel, in mountains without protective pipes,

Used for: gas, district heating, gas, and water pipes, pressure fumes, pressurized water, sewers, water, even self-contained pipelines.

FIGURE 38: HAMMAR DRILLING

Auger drilling (Augerborrning)

Auger drilling is a pressure method for horizontal installation of protective pipes. The method can be used in all soil materials where larger blocks and mountains do not occur and without disturbance of surrounding masses. Auger drilling is used for installation of large protection pipes (up to 1600 mm diameter), e.g. roads and railways. In favorable conditions, the method can be used for protective pipes up to 100 m long. The entrance pit should have a dry, stable floor and support required.

In this method, a protective pipe is pushed forward through the ground material, while soil masses are screwed out of the pipe at the back. High accuracy is achieved and self-conduction is possible with down to 1% inclination.

Application: clay / sand,

Limitations: Larger stones, stone block, mountain,

Geotechnical survey requirements: soil type (block/stone/rock), shear strength, groundwater level/fluctuation,

Pipe length, diameter, and material: 0-70 m, 300-1600 mm, steel,

Used for: gas pipes, district heating, electrical and telephoto, pressure sewers, pressurized water, sewers, water, even self-contained pipelines.

FIGURE: 39:AUGER DRILLING

Stirring (Rammning)

Stirring of pipes is used for rough tubes (300 - 1600 mm diameter) and in absence of large stones. Ramming involves piping with a compressed air hammer. Support is not needed and stirring can be carried out in most soils and under groundwater. The method uses an open front and pipe end, and the material is transported through the pipe that is pushed forward. High accuracy is achieved and self-conduction is possible down to 1%.

Only when the piping is complete the soil is removed. This reduces the risk of landslide and undermining of the underlying soil.

Application: clay / sand

Limitations: Greater stone, stone block, mountain

Geotechnical survey requirements: soil type (rock / stone / block), shear strength, groundwater level / fluctuation

Pipe length, diameter, and material: 0-50 m, 300-1600 mm, steel

Used for: gas pipes, district heating, electrical and telephoto, pressure sewers, pressurized water, sewers, water, even self-contained pipelines.

FIGURE 40: STIRRING METHOD

New building methods contain governing documents, but they are project-specific and usually recorded as AMA codes. See AMA 17 - Advice and Instructions, Cape CBF and PBF.

4.2.1.2. Renewal and Maintenance

Flexible lining

The flexible lining is used for sealing, strengthening and rebuilding of drums, pipe bridges, and wires. The liner is installed and hardened inside the existing drum, pipe or wire after cleaning of existing pipe. The installed liner is against the inner surface and can be designed to take up external loads.

The damage/loss in function may vary and detailed design of the liner is possible.

Application: existing drums, tube bridges, and wires, with both circular and rectangular cross-sections,

Geotechnical survey requirement: none,

Requirements for determination of damage extent and cleaning before installation: yes,

Pipe length, diameter, and material: 0 - 800 m, 100 -> 2000 mm, several lining materials are available,

Used for: day, waste and drinking water, district heating, industrial waste, pressurized wires, and self-contained pipelines.

Figure 41: Flexible lining

BVS.585 is the requirements used for flexible feed performance with a rectangular cross-section (Swedish Transport Administration regulatory documents). For circular cross-sections, the publication P101, published by Svenskt Vatten can be used.

Molded pipes

Molded pipes are a term used for tubes that either are designed with geometrically reduced cross-section or are given a temporary reduction just at the time of installation. During installation, the molded pipe is passed through the existing wire, after which the cross section retrieves a circular shape. At this point, the gap width is minimized between the existing line and the molded pipe. In this way, the function is restored, in terms of capacity, strength, and service life. The existing pipe will then be used as a protective pipe. Typically, molded pipes are made in PE (polyethylene), but they can also be produced in PVC.

The method is well suited both for the maintenance of drinking water pipelines and sewers.

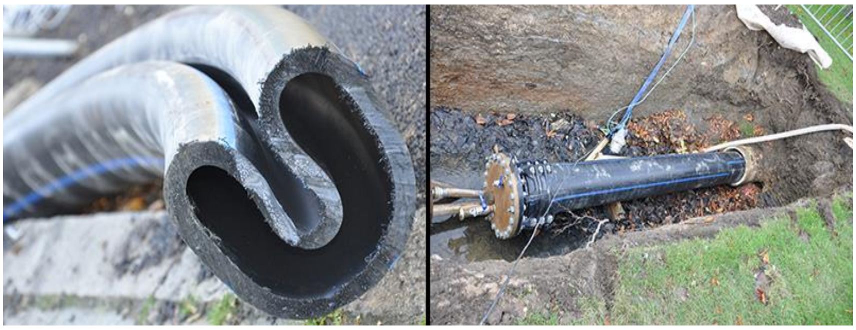


Figure 42: Molded pipe just before and after installation

Complete PE pipe

Complete PE pipe installed into the protective tube and the pipes are fixed to each other.

FIGURE 43: INSTALLATION OF WHOLE PE-PIPE WITHIN A PIPE FOR RENOVATION

Other trenchless based renovation technology

Over the years, some alternative technologies have been used by operation and maintenance companies for pipe renovation. Concrete repair of large drums and pipe bridges, either in spots or in full length, still exists but the popularity has reduced and it has been replaced by other technologies.

Bolted pipe halves in sheet metal are used to cover single defects in open joints and mainly in large circular cross-section.

Complete rigid pipes with concrete casting exist but the use of the technology has decreased. Rigid pipes have been used both for circular and rectangular cross-sections. However, the area reduction is large and the choice of technology requires thorough capacity calculation.

4.2.2. Soil perspective: preventive measures

As from section 2.4, we have seen how different soil conditions and factors are responsible for the failure of pipelines crossing under railway beds. In this section, various techniques and recommendations to provide better soil conditions around pipeline are discussed. The various measures which can be taken to avoid pipeline failures at railways crossing have been grouped below:

4.2.2.1. Soil Investigation

Soil samples should be collected where the pipeline will be installed at different depths. Soil type, moisture content, organic content, soil pH, Atterberg's limit, shear parameters, resistivity etc. should be determined and the proper geotechnical report should be prepared. This should be the first measure taken in any project and is unfortunately often neglected [102].

4.2.2.2. Soil-Pipe interaction

A proper finite element analysis of Soil-pipe interaction subjected to dynamic loading should be done by using any available FEM software packages such as Plaxis, Abacus, Flac etc. Robert [103] suggested the use of Modified Mohr-Coulomb Model to simulate the behavior of Pipelines in unsaturated soils. Also, time-dependent modelling and thermodynamic analysis should be carried out to take the effect of freezing and thawing into account [104].

4.2.2.3. Use of geotextile

Geotextile can be used across the pipe which prevents the infiltration of soil particles into pipes and allows the water drainage [105, 106] (Monroy et. al, 2012 and Hedge et. al, 2014). Also, Geotextile helps in increasing strength or capacity of the pipe. It reduces the stress around pipe materials hence, there is less deformation of the pipe.

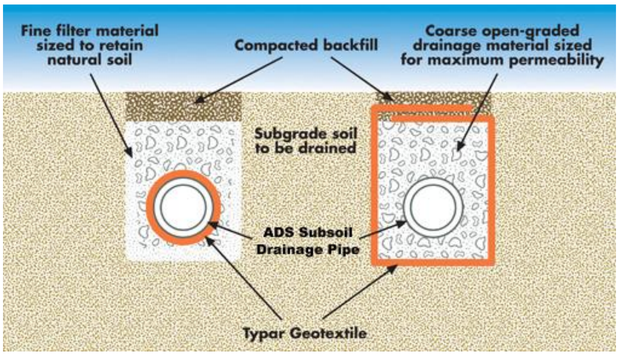


FIGURE 44: GEOTEXTILE AROUND BURIED PIPELINE[107]

4.2.2.4. Pipeline stabilization using rock berms

The placement of rock berms around a pipeline increases the resistance to pipeline material. As the pipeline is not in direct contact with the surrounding original soil no soil particles should be able to infiltrate. Also, uplift of pipelines due to frost heave can be prevented but local high contact stresses might be reached[108].

4.2.2.5. Monitoring tool: vibrating wire strain gauges (VWSG)

Soil movement is very slow, sometimes takes up to 50 years before the onset of pipeline failure. In these cases, strain gauges are used to assess the axial and bending loads transmitted to the pipe. When the effect of soil movement on pipe strains is no longer acceptable, remedy is required. These involve first separating the pipeline from the surrounding soil, and then, once soil-induced stresses in the pipe are relieved, to repair the surrounding soil so as to ensure that soil movement is stopped or greatly delayed.

4.2.2.6. Densification of soil

The density of soil has a great impact on the soil stiffness. In densified soil, there is considerable more interlocking of grain particles which restricts the movement within soil mass. Therefore, loose soil permits more deflection of pipe for a given load than a dense soil. Densification of soil can be achieved by cement stabilization sand, grouting etc. Compaction can be used to achieve a higher degree of density.

4.2.2.7. Geothermal modelling for frost heave and thaw settlement

This analysis helps in determining the strain on the pipe due to the freezing and thawing process, accordingly, the thickness of pipe can be determined. To prevent frost heave and thaw settlement, avoid the most susceptible frost material i.e. silt. Silt can be replaced by clay or granular material. There should be no free water access to soil material which is the primary condition for freezing and thawing process [109].

4.2.2.8. Pipeline depth under railroads crossings

The pipeline should be located below the active zone. Moisture change, freezing, thawing, the surface dynamic load due to the railroad, etc. occurs in this active zone. By locating pipeline under the active zone, stresses will be less as the effect of this load progresses downward into the soil, the area over which it is effective grows larger and since the total load is fixed, the pressure or load intensity is diminished. Thus pipes will be subjected to the low intensity of surface load [110].

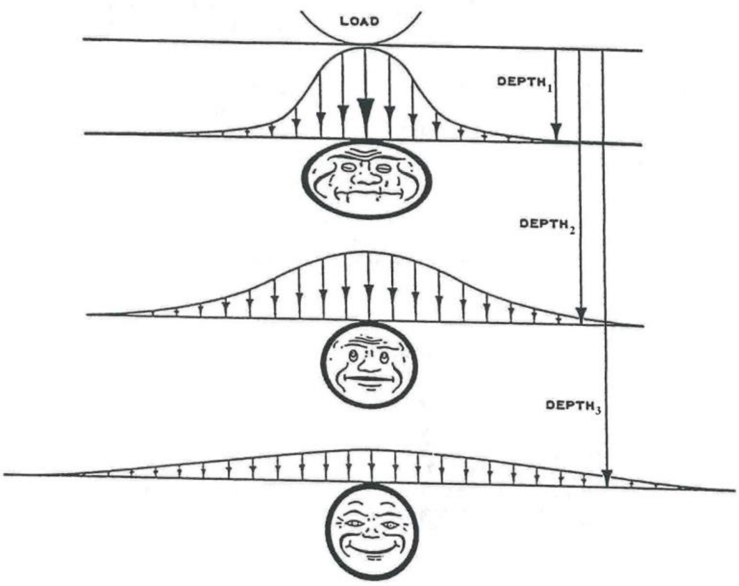


FIGURE 45: PIPE ACTION UNDER LIVE LOAD

4.2.2.9. Controlled low strength material as pipe backfill

Controlled Low Strength Material (CLSM) is a fill material which consists a mixture of cement, water and, when appropriate, fly ash, aggregate, or chemical admixtures such that the final product displays a low compressive strength after curing and a large spread capability prior to setting. CLSM is used as a replacement for soil backfill in sites where adequate compaction of the backfill is difficult to achieve or may be too time-consuming.

4.2.2.10. Sleeves/encased pipes under railroads

Sleeves are encasement pipes, tunnels, or galleries for carrier pipes under highways/railroads. Steel, reinforced concrete, plastic or cast iron encasement pipes may be used with either trenched or trenchless construction. Encased pipes have been extensively used for protection of pipeline crossing. Tunnels or galleries protect carrier pipes from loads and in case of leakage convey materials from underneath the highway traveled way. Even though tunnels and galleries are often relatively more expensive than other protection methods, they do offer some advantages. For example, several utilities can be placed in a tunnel or gallery. If there are no conflicts with placing different utilities in close proximity to one another, the need for multiple easements, construction, and maintenance activities can be combined in a single crossing. Also, tunnels or galleries can be constructed to allow an increase in utility sizes, the addition of utilities in a crossing, or as a means of inspecting the utilities in the crossing.

4.2.2.11. Grouting

Grouting along with jacketing is the only concrete encasement methods suitable for trenchless construction. When boring or jacking is used with a pipe, there is often a space between the carrier pipe and adjacent soil. This space can be filled with grout by pumping grout material into the space or void. When the grout hardens, it provides additional protection from corrosion and loads around the carrier pipe and helps prevent settling of the carrier pipe and the railway track subgrade. The grout does not protect pipe coatings from damage during installation when it is placed after the pipe is bored or jacked. Because placing grout is not a precise operation, the grout may not cover all such damaged areas.

4.2.2.12.Jacketing

Jacketing is the placing of concrete around the pipe prior to boring or jacking. Many configurations are possible for jacketing. An example of a design developed and used in numerous highway crossings is shown in Figure 3. In this example, a thicker wall pipe is coated with a double coat of asphalt or coal tar. Primer, enamel, and fiberglass wrapping may also be used as insulation. A 1-in, thick concrete jacket reinforced with wire mesh is applied outside the asphalt or coal tar coating. The pipe is then placed by boring, keeping the annular space between the pipe and hole to a minimum. The space is then filled with urethane foam to prevent water channelization along the pipeline and to mitigate the potential for settlement around the pipe [111].

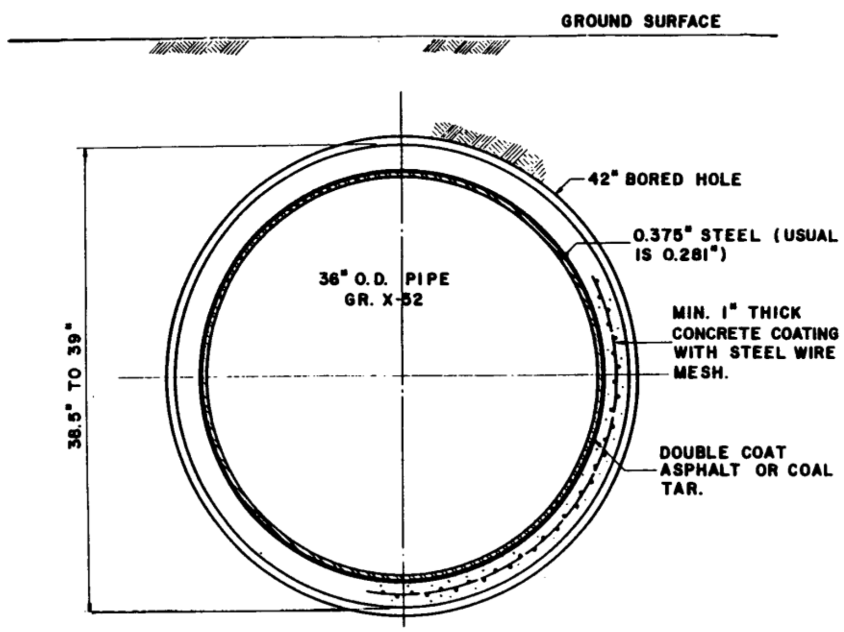


FIGURE 46: JACKED PIPELINE CROSSING EXAMPLE[111]

4.2.2.13. Concrete protective slabs

Capping is the placing of a slab in contact with the top of the pipe. This method provides good protection from loadings and dig-ups. A protective slab is similar to a concrete cap. However, the slab is not in contact with the carrier pipe and "floats" above the pipe. The slab can be precast or cast in place. Such slabs do not provide protection from corrosion or settlement, but they provide excellent protection from loads or dig-ups by construction or maintenance equipment. Trenched construction is required. These methods may be used for protection of the pipeline in the area between the traveled way and the right-of-way limit, even if trenched construction is not allowed in the traveled way. The slab or cap would thus provide protection from dig-ups in the area most likely to be damaged by construction or maintenance work. Damage to the roadway pavement can be eliminated and traffic disruption limited during construction [112].

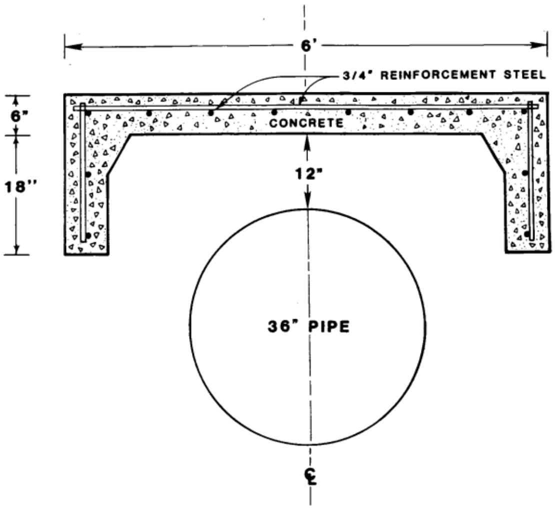


FIGURE 47: CONCRETE PROTECTIVE SLAB EXAMPLE[112]

4.2.2.14. Surface loading mitigation measures

In past years, several analytical solutions were suggested to calculate the Surface dynamic load (Spangler's work from 1940s to 1960s, IOWA Formula, etc.) [113-116]. There are ways to mitigate this surface load via Limiting Surface Vehicle Footprint Pressure. Several of the mitigation methods have been listed in Table 16 (i.e., steel plates, timber mats, concrete slab) can be classified as "Surface Protection" methods. These methods deploy a flat surface structure on the ground surface as a means of dispersing the surface vehicle load over a wider area. The idea behind these methods is that they distribute the surface loads over a larger "footprint" area than that provided by the surface vehicle alone. The effective footprint area of the vehicle load would be distributed uniformly over the entire footprint of the surface structure for a rigid flat surface structure centered under a vehicle load [117].

TABLE 16: SURFACE LOAD MITIGATION MEASURE[117]

Method	Advantages	Disadvantages
Reduce the operating pressure of the pipeline.	• Provides a direct reduction of the hoop stress due to internal pressure. This reduction allows for additional circumferential stress due to equipment loads.	• Reduces the beneficial effect of internal pressure on the pipe circumferential bending stresses due to filling and traffic loads. • Could reduce the overall capacity of the pipeline and therefore should not be considered as a long-term fix.
Limit surface pressures under vehicles (e.g., using floatation tires or caterpillar tracks)	• Spreads the surface load over a larger area and reduces the overall load to the pipe.	• Depends on equipment. May not be possible or too costly to implement

Consider the beneficial effect of lateral soil restraint on circumferential stress	• Has effect similar to pressure stiffening	• Requires estimates of soil stiffness parameter, E’
Provide additional soil fill over the pipeline in the vicinity of the crossing	• Reduces circumferential stresses due to traffic loads.	• Increases circumferential stresses due to fill loads.
Deploy steel plates over the crossing	• Easy to install.	• Flexibility of steel plates can result in bending of the plate with a corresponding reduction in loaded footprint. Need to consider required thickness.
Deploy timber mats over the crossing area	• Provides large loading footprint. • Relatively easy to deploy.	• Flexibility of timber mats can result in bending of the mats with a corresponding reduction in loaded footprint.
Construct a concrete slab with steel reinforcement over the crossing area	• Provides large loading footprint. • Slab can provide high bending stiffness.	• Relatively expensive. • Usually reserved for permanent crossings. • Slab limits access to pipeline for inspections and repairs.
Construct a short bridge crossing over the pipeline	• Completely uncouples the traffic loading from the buried pipeline.	• Requires construction of foundation structures. • Expensive to construct. • Usually reserved for permanent crossings. • Bridge structure may limit access to pipeline for inspections and repairs.
Relocate the pipeline	• Removes pipeline from loaded area.	• Expensive to construct. • Usually considered only as a last resort.
Lower pipeline	• Reduces circumferential stresses due to traffic loads.	• Expensive to perform. • Usually considered only as a last resort.

4.2.2.15. Trenchless installation methods

The installation of a pipe to the proper alignment and elevation requires disturbance to the surrounding area, the extent of which is a consequence of the specified technique. The Designer must weigh factors understanding that the most straightforward method of installation (open excavation) often results in a sizeable level of disturbance while an alternate, resourceful method of installation (trenchless technology) can reduce the level of disturbance but will be more costly and require more up-front investigation. The various widely used trenchless methods are described in Appendix III.

4.2.3. Railways perspective

The recommendations to improve the operations at the railway/pipeline crossings from the railways perspective are:

1. Better communication with respective municipalities
    i. Better understanding about pipeline infrastructure and its effects on the railway infrastructure,
    ii. Inventory and regular update of the pipeline network and sharing the data with Trafikverket,
    iii.
    iv. Better failure reporting mechanisms for both infrastructure,
    v. Co-ordination of maintenance actions between railway and pipeline infrastructure
    vi. Implementation of maintenance planning for the renovation of old pipelines under railway infrastructure.
2. Development of an integrated system consisting of legalized agreements between Trafikverket and municipalities to represent access to cross-sectional sites with its location, type of agreement, asset features and condition, future maintenance planning. Benefits being; for new construction of lines, TrV needs to communicate with municipalities with locations of cross-sectional sites; rewriting the agreements with new municipalities, maintenance planning.
3. Interaction of the databases from railway and pipeline infrastructure at cross-sectional assets (include in the database). Registration of non-ownership assets (like pipelines) in the Trafikverket database structure (cross-sectional failures)
4. Application of new technologies/methods for digitalization of pipeline network for the purpose of asset management, condition monitoring, health assessment and future prediction and remaining useful life estimation of the pipeline at the cross-section.

5. Conclusion and Remarks

With the growth of the urban area, there will be more crossing of VA services with transport infrastructure. Demands for increasing the transport infrastructure results in more cross section with the installed pipeline network and demand for increasing VA services results in new crossing or installation of bigger pipes under the railway. Furthermore, demand for increasing axle load can create new challenges on the reliability of the old transport infrastructures that have not been designed to fulfill the new society’s demand. Hence asset condition evaluation becomes increasingly important at cross-sections.

In this research project, failure mode, failure consequences and the root cause of failures have been investigated by failure mode and effect analysis approach. The risk assessment for pipe systems was studied. Based on these studies, a risk framework has been developed and two approached have been suggested for risk assessment at pipeline-railway cross-sections.

The pipeXrail research methodology is based on qualitative research study via distribution of questionnaires and interviews with VA experts. Based on discussions with experts and the barriers which we faced during the course of PipeXrail, we are summarizing some remarks. Most of the municipality’s experts raise a less development of maintenance methodology and tools in VA domain. Section 5.1 has been formulated to address the current status and the needs to fulfill new maintenance demands.

Furthermore, data availability has been raised in section 5.2 and 5.3 as an important issue. Without enough knowledge of the actual site conditions including soil properties and geometrical backgrounds as well as structural properties including stiffness and strength of pipelines and their specific usage, pipeline condition assessment and maintenance modeling is challenging. Thus acquisition and documenting this information is essential should be initiated from the planning phase.

5.1. Society debt to the pipeline maintenance

The urban development/administration has failed to keep up with the growing rate of required maintenance of the pipeline network. In economic terms, it is known as "development debt" within the maintenance discipline, possibly resulting in an accumulated "interest" for the future efforts to pay off this debt. The above hypothesis had been raised in the InfraSweden 2030- call 2016 [118] and we have validated through our interview and discussion with a number of experts. Based on the deviation between required maintenance and actual status of pipeline maintenance in terms of resource, tools, and techniques an explanatory model of the gap of the discrepancy is visualized in Figure 48. The deviation between required maintenance and actual status of pipeline maintenance has been induced as a development debt up until today. Continued development in the same manner in terms of the policy will increase the debt and lead to a loss of resource and sustainability in the future. Therefore, the maintenance debt could be paid by smart infrastructure maintenance so that the required maintenance on the pipeline network and actual status of pipeline maintenance are merged.

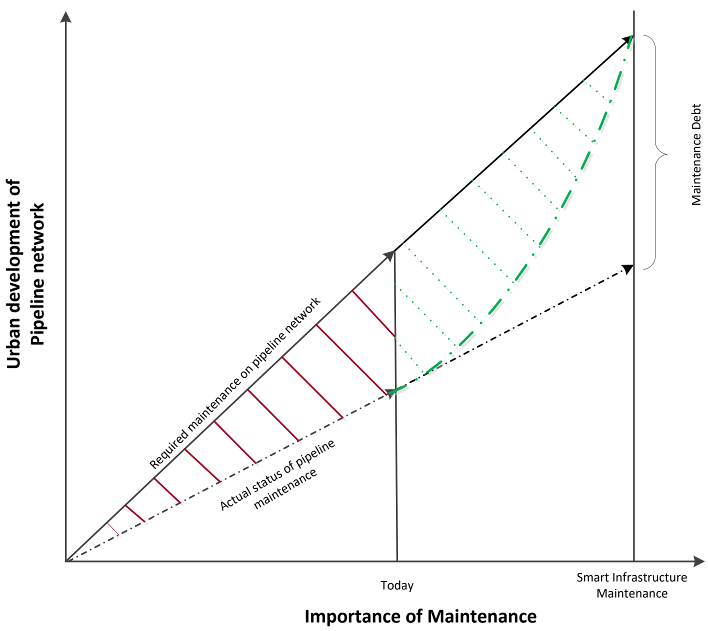


FIGURE 48: THE CURRENT STATUS AND REQUIRED MAINTENANCE OF THE PIPELINE NETWORK, ADAPTED [119].

Figure 48 representation is stimulated by a typical linear regression model, however, statistical terms are used symbolically to make the relation between parameters. Furthermore, Pearson's *r* has been used as a measure of the linear correlation between two variables. The relationship between the urban development of the pipeline network and required maintenance on the pipeline network (dash line) are assumed as a total positive linear correlation ($\tilde{r} = 1$). By urban development, the transport infrastructure and pipeline network will be expanded and the importance of pipeline maintenance is expected to be increased with the same rate. In addition, the correlation between the progression of urban development and the actual status of pipeline maintenance (green line) is also positive with a lower rate ($0 < r < 1$). This discrepancy between the required maintenance and actual status of pipeline maintenance has been created the development debt with accumulated interest (red dashed area). An efforts are needed to close the gap of maintenance debt (green dashed area) and reach a state where required maintenance of pthe ipeline network is reconnected with the actual status of pipeline maintenance $\tilde{r} = r = 1$. The implementation and utilization of digitalization and artificial intelligence (AI) techniques can convert the current pipeline/infrastructure maintenance engineering to smart infrastructure maintenance, with a plenty of opportunities that might reduce the maintenance debt through the installation of sensors and collection and analysis of a new set of data for condition health monitoring of buried pipeline. Smart infrastructure maintenance will enable pipeline maintenance to be more efficient, aligned with current and future maintenance technology.

5.2. Small data and incomplete failure data of pipeline at the cross section

Small data and incomplete failure data are the main two obstacles for reliability analysis of pipeline network in general terms. Røstum [18] pointed out that unavailability of required historical failure data as the critical issue for analyzing time to failure and subsequent reliability analysis of water networks. In such cases, those models that are able to handle small or incomplete failure data should be selected. To have effective reliability analysis, the analyst needs to have a comprehensive knowledge and a good understanding of (i) the methodology, data and required information for model building, (ii) the properties of different models and (iii) the tools and techniques to determine whether a particular model is appropriate for a given dataset [43]. However, in many cases, such misunderstanding leads to using statistical models with wrong assumptions. In other words, neglecting these issues may lead to wrong or low accurate parameter estimation of the model.

Small data sets are a common major problem associated with reliability data, limited statistical methodologies can be carried out on small datasets. Facing small data sets may be originated from an inappropriate data collection system. For several years, municipalities have been recorded the inspection and failure records/datasets in handwriting booklets and integrating of such records may not cost/time effective solution. Lack of data integrity is also an important issue leads to small databases. Each municipality has their own reported system and acting in an individual form which restricts comprehensive data analysis of pipeline networks. Moreover, facing small failure data may due to the type of asset, i.e. the expected number of failures will be reduced, when the asset has a high level of reliability index. In another word, the pipeline can be considered an asset with a long expected life due to the type of material, stress, operational condition and collecting enough number of failure and inspection time is time-consuming. Means we have lost valuable information from the past due to lack of suitable data collection infrastructure and lack of knowledge on the importance of such information.

In recent decades, most of the industrial managers have been aware of beneficiaries provided by maintenance engineering and the role of maintenance engineering is going to increase with higher rate aiming for prolonging the life of the assets. Several industries, e.g. aviation, nuclear sites, railways identified the role of maintenance in advance and they have and enrich data collection infrastructure, however, the less attention has been paid for data collection of pipelines networks in urban areas of Sweden. This ignorance may due to other factors such as ownership of the assets, rule and regulation and type of contracts. The Ownership can be categorized in four parts when dealing to cross section of Swedish rail network.

1) TRV is the owner of the railway corridor
2) Järnhus is the owner of the area where the asset is located close to the station,
3) Municipalities: most of the time municipalities have an asset that goes under track embankments and there is a need to have close collaboration with TRV and Järnhus to solve the problems. This is the missing part of the puzzle which needs to be considered.
4) Private owner.

In addition, maintenance contractors also need to be specified in the contractual agreement about maintenance of culverts and pipes at the cross-section.

Data availability is an important factor for reliability and maintenance analysis of pipeline at crosses sections with rail and road infrastructure. Neglecting of proper data collection process will increase the maintenance debt (See section 1.2) of pipeline networks.

5.3. Challenges found for risk assessment of pipeline under the railway

- The lack of historical RAMS data which will increase the uncertainty associated with any RAMS analysis.
- The complexity of the environment, for instance, types of soil, location, weather which make a prediction of the consequences a challenging task. In the northern part of Sweden railway infrastructure frozen for a long period of the year.
- The lack of data regarding the effect of operational conditions for instance soil, cyclic stress, location, cross angle, etc on the pipeline.
- Lack of infrastructure which makes any logistic activities a complex and challenging

- *Lack of enough knowledge:* When little information and knowledge of original design, contraction, or maintenance practices, the inspectors can collect different evidence of pipeline history. However due to facing an asset that may be affected by railways, understanding the interrelation factors may lead to preventing or mitigation of the failure. Based on the interview with the experts in VA sections in a different location of Sweden, the lack of enough knowledge of maintenance expert and inspector of the pipeline at the cross section can be classified as one of the hazardous factors in the risk assessment.

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Appendix I: First Questionnaire:

Enkät om VA-ledningar nära väg- och järnvägar

Denna enkät vänder sig till den som är ansvarig för VA-ledningnätet i er kommun. Vänligen vidarebefordra enkäten till berörd person, t ex VA-chef eller VA-ansvarig.

Om- och nyanläggning av VA-ledningar som ligger nära eller korsar huvudvägar eller järnvägar kräver ofta skyddsåtgärder. Denna enkät syftar till att till att börja med undersöka hur omfattande problematiken är och vad det ger för konskvenser i det dagliga arbetet.

VI är tacksamma om ni svarar på detta. Enkäten omfattar två frågor förutom bakgrundsinformation!

Enkäten ingår som del i ett Vinnovafinansierat projekt:
http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2015-06114/Underjordiska- rorledningar-och-jarnvagsinfrastruktur--Konsekvenser-och-begransningar-av- ledningsbrott/

Ansvariga för denna enkät är Annelie Hedström, Stefan Marklund och Amir Garmabaki vid Luleå tekniska universtet

Your answer

E-post

Your answer

Telefon eller mobilnummer

Your answer

Befattning

Your answer

Avdelning

Your answer

Kommun

Your answer

❖ Har ni under den senaste 10-årsperioden arbetat med om- eller nyanläggningar av ledningar i Trafikverkets (eller motsvarande) servitutsområden för järnväg?

Frågan avser både planerade aktiviteter eller akuta åtgärder.

○ Ja

○ Nej

Om svaret är ja, ge oss gärna lite information

Your answer

❖ Har ni under den senaste 10-årsperioden arbetat med om- eller nyanläggningar av ledningar i Trafikverkets (eller motsvarande) servitutsområden för vägar?

Frågan avser i första hand högtrafikerade vägar och gäller både planerade aktiviteter eller akuta åtgärder.

○ Ja

○ Nej

Om svaret är ja, ge oss gärna lite information

Your answer

Kan ni tänka er att vara med på ett seminarium om detta under sen vår 2017?

○ Ja

○ Nej

○ Kanske

Appendix II: Second Questionnaire:

Fördjupad enkät om VA-ledningar nära järnvägar

Hej,

För någon tid sedan skickade vi er en kort enkät med två frågor kopplade till risker med förläggning av VA-ledningar i närhet eller under järnväg/banvallar och stora vägar. Vi fick överlag god respons och mycket

Det finns därför anledning att fördjupa frågeställningarna en smula. Ni som har fått denna enkät har svarat att ni under de senaste 10 åren haft projekt som rört ledningsarbeten i anslutning till järnväg. Vi vore därför mycket tacksamma om ni kan ägna oss en stund för att svara på följande enkät med nio delfrågor som rör VA-ledningar i närhet eller under järnväg/banvallar. Det tar mindre än 10 minuter.

Med tack på förhand,

* Required

Namn (valfritt)

Your answer

E-post (valfritt) *

Your answer

Telefon eller mobilnummer (valfritt)

Befattning

Your answer

Avdelning

Your answer

1- Hur har det framkommit att det varit problem med VA-ledningar under/nära järnväg? (Flera alteranativ är möjliga) *

- [ ] Visuell observation (t ex observerade sättningar, uppkomna sättningar, vatten på yta)
- [ ] Upptäckt på indirekt sätt genom t ex flödesändringar
- [ ] Other: ____________________

2- Vilka typer av rördefekter har noterats på rör under/nära järnväg?(flera alternativ möjliga) *

- [ ] Rörbrott
- [ ] Deformerade rör (på grund av sättningar eller last)
- [ ] sprickor
- [ ] Eroderade rör
- [ ] Korroderade rör
- [ ] Other: ____________________

2.1- Följdverkan av rörbrott *

	Har inte skett	Liten påverkan	Moderat påverkan	Allvarlig påverkan
Begränsad VA-kapacitet	○	○	○	○
Bräddning av avloppsvatten	○	○	○	○
Översvämmade ytor	○	○	○	○
Sjunkhål	○	○	○	○

2.2- Följdverkan av deformerade rör *

	Har inte skett	Liten påverkan	Moderat påverkan	Allvarlig påverkan
Begränsad VA-kapacitet	○	○	○	○
Bräddning av avloppsvatten	○	○	○	○
Översvämmade ytor	○	○	○	○
Sjunkhål	○	○	○	○

2.3 - Följdverkan av rörsprickor *

	Har inte skett	Liten påverkan	Moderat påverkan	Allvarlig påverkan
Begränsad VA-kapacitet	○	○	○	○
Bräddning av avloppsvatten	○	○	○	○
Översvämmade ytor	○	○	○	○
Sjunkhål	○	○	○	○

2.4 - Följdverkan av eroderade/korroderade rör *

	Har inte skett	Liten påverkan	Moderat påverkan	Allvarlig påverkan
Begränsad VA-kapacitet	○	○	○	○
Bräddning av avloppsvatten	○	○	○	○
Översvämmade ytor	○	○	○	○
Sjunkhål	○	○	○	○

3 - Potentiell felorsak till rörskador nära/under järnväg.(flera alternativ möjliga) *

- [ ] Pågående underhåll
- [ ] Säsongs-/Klimatpåverkan
- [ ] Åldrande ledningar
- [ ] Erosion/korrosion
- [ ] Närliggande urgrävningar
- [ ] Tjälskador eller andra årstidsrelaterade orsaker
- [ ] Rörrelaterade svagheter (material, rörkopplingar, fogtyp)
- [ ] Jordartsförhållanden
- [ ] Tryckrelaterade skador (t ex tryckslag, tryckförändringar)
- [ ] Jordlast
- [ ] Yttre last (Trafikintensitet och axellaster)
- [ ] Återkommande fel på samma plats
- [ ] Other: ____________________

4- När rörskador har inträffat, vad blev konsekvenserna?(flera alternativ möjliga) *

- [ ] Försämrad framkomlighet för tågtransporter
- [ ] Försämrad framkomplighet på vägar i närheten av rörskadorna
- [ ] Skador på banvall
- [ ] Skador på närliggande infrastruktur (broar, vägar mm)
- [ ] Översvämning som försvårar framkomlighet för fordon och/eller gående
- [ ] Leveransavbrott eller trycksänkningar av dricksvatten i bostadsområden
- [ ] Personskador

- [ ] Other: ____________________

5- Om/när nya ledningar har lagts nära eller under järnväg - Varför var detta nödvändigt? (flera alternativ möjliga) *

- [ ] Staden tillväxer i yta
- [ ] Behov av ökad ledningskapacitet för dricksvatten
- [ ] Behov av ökad ledningskapacitet för spillvatten (avlopp)
- [ ] Behov av ökad ledningskapacitet för dagvatten
- [ ] Utbyte av gamla rör
- [ ] Other: ____________________

6- Med vilken teknik har nya ledningar lagts nära/under järnväg (flera alternativ möjliga) *

- [ ] Schaktfritt ledningsläggande - Styrd borrning
- [ ] Schaktfritt ledningsläggande - kulvert
- [ ] Schaktfritt ledningsläggande - rörtryckning
- [ ] Augerborrning/Hammarborrning
- [ ] Med öppet schakt
- [ ] Other: ____________________

7- Med vilken teknik har ledningar renoverats nära/under järnväg (flera alternativ möjliga) *

- [ ] Schaktfritt infodring med styvt rör
- [ ] Schaktfritt betongsprutning
- [ ] Schaktfritt flexibelt foder
- [ ] Med öppet schakt
- [ ] Other: ____________________

8- Skulle ni vara intresserad av att delta i en fördjupad studie med något av de fall ni tagit upp här?

- Ja
- Nej
- Kanske

SUBMIT

Appendix III: Trenchless installation methods

In this appendix, short description of sex type of trenchless technology that may utilize for installation or renovation of pipeline under railway corridor have been provided.

- **Auger Boring (AB)**

The auger boring method forms a bore hole from a drive shaft to a reception shaft by means of a rotating cutting head. Spoil is transported back to the drive shaft by helical-wound auger flights rotating inside a steel casing that is being jacked in place simultaneously. AB may provide limited tracking and steering capability. It does not provide continuous support to the excavation face. AB is typically a 2-stage process (i.e., casing installation and product pipe installation).

- **Slurry Boring (SB)**

The slurry boring method forms a bore hole from a drive shaft to a reception shaft by means of a drill bit and drill tubing (stem). A drilling fluid (i.e., bentonite slurry, water, or air pressure) is used to facilitate the drilling process by keeping the drill bit clean and aiding with spoil removal. It is a 2-stage process. Typically, an unsupported horizontal hole is produced in the first stage. The pipe is installed in the second stage. A pilot hole is drilled and checked for accuracy. Once confirmed, the pilot hole is reamed to the desired bore-hole diameter and a casing is inserted. Any type of casing can be installed. The casing may be installed by tension forces, compressive forces or both.

- **Pipe Jacking (PJ)**

The pipe jacking method installs a prefabricated pipe through the ground from a drive shaft to a reception shaft by propelling it by jacks located in the drive shaft. The jacking force is transmitted through the pipe to the face of the PJ excavation. The excavation is accomplished, and the spoil is transported out of the jacking pipe and shaft manually or mechanically. Both the excavation and spoil removal processes require workers to be inside the pipe during the jacking operation. Therefore, the minimum inside diameter of the pipe is usually set at 42 in. A jacking or tunneling shield is typically used at the excavation fact to provide protection for the workers performing the work. Since the jacking force is transmitted through the pipe to the face of the PJ excavation, the type of casing must be capable of transmitting the required jacking forces from the thrust plate to the jacking shield.

- **Microtunneling (MT)**

The microtunneling method is a remotely controlled, guided pipe-jacking process that provides continuous support to the excavation face. The guidance system usually consists of a laser mounted in the drive shaft communicating a reference line to a target mounted inside the MT machine’s articulated steering head. The MT process provides ability to control excavation face stability by applying mechanical or fluid pressure to counterbalance the earth and hydrostatic pressures. Since the microtunneling process is a cyclic pipe jacking process, the discussion on the pipe jacking method applies, except for the minimum pipe diameter requirement.

- **Horizontal Directional Drilling (HDD)**

The horizontal directional drilling method is a 2-stage process which consists of drilling a small diameter pilot hole along a predetermined path and then developing the pilot hole into the required final bore hole by performing repeated passes with a reaming cutter, and then pulling the utility into place. The HDD process provides the ability to track the location of the pilot hole drill bit and steer it during the drilling process. The vertical profile of the bore hole is typically in the shape of an arc entrapping drilling fluid and excavation spoil to form a slurry filled pathway rather than an open hole. This entrapped slurry provides continuous support to the bore hole, even after the utility line is placed. To allow the slurry to be displaced from the bore hole while installing the utility line, the final borehole diameter is typically 50% larger than the outside diameter of the utility line.

- **Utility Tunneling (UT)**

The utility tunneling method is a 2-stage process which consists of initially supporting the bore with tunnel liner plates to permit the installation of a utility. The tunnel liner is installed as the tunnel excavation is progressed. Workers are required inside the tunnel to perform the excavation and/or spoil removal. The excavation can be accomplished manually or mechanically. The minimum inside diameter of the tunnel is usually set at 42 in. When a tunnel shield is used to provide protection for the workers at the excavation face, the tunnel liner plates shall be designed to withstand the thrust from jacking the tunnel shield against the full front edge of the last installed tunnel lining section. Tunnel liner plates may be manufactured from steel or designed as precast concrete. Following table shows the summary where above methods can be used with its limitations.

Summary of Trenchless Techniques

Installation Method	Typical Installation Diameters	Typical Installation Lengths	Casing Material	Compatible Soil Types	Limitations
Auger Boring (AB)	0.1 m to 1.50 m	Typical project lengths range from 30 m to 90 m.	Steel	Variety of soil conditions.	Cannot be used in wet, running sands or soils with large boulders.
Slurry Boring (SB)	0.050 m to 1.20 m	Typically, SB is a non-directionally controlled process; therefore, the risk of obtaining an unacceptable pilot hole increases greatly with distance. Although the common bore hole spans are approx. 15 m, bore holes longer than 100 m have been installed by SB.	Any Material	Firm, stable cohesive material. Wet, non-cohesive material can be accommodated provided that special precautions are exercised.	A major concern with using any type of drilling fluid under a roadway is the potential for over-excavation.
Pipe Jacking (PJ)	Person-entry and hand mining requires a min. 1.1 m Dia. tunnel	The length of the PJ drive is determined by the amount of available jacking thrust and the compressive strength of the pipe. The most common range for drive lengths is from 150 m to 300 m.	Steel, Reinforced Concrete (RCP), Glass-fibre reinforced plastic pipes (GFRP)	Stable granular and cohesive soils are best. Unstable sand is least favourable. Large boulders cause frequent work stoppage. Method can be executed with any ground condition with adequate precautions.	Large boulders cause frequent work stoppage.
Microtunneling (MT)	0.25 m to 3.50 m	The most common range for drive lengths is from 150 m to 300 m for slurry MT and 60 m to 120 m for auger MT.	Steel, Reinforced Concrete (RCP), Glass-fibre reinforced plastic pipes (GFRP)	Variety of soil conditions, including full face rock and high groundwater head.	Obstructions are an issue. A special concern that is critical to the success of an MT project is the ability to predict and control jacking forces. A very expansive method.
Horizontal Directional Drilling (HDD)	0.075 m to 1.20 m	Bore lengths can range from 120 m to 1800 m depending on the site conditions.	Steel or High Density Polyethylene (HDPE)	Clay is ideal. Cohesion less sand and silt require bentonite. Gravel and cobbles are unsuitable.	Not suitable for high degree of accuracy such as gravity sewer application
Utility Tunnelling (UT)	Person-entry and hand mining requires a min. 1.1 m Dia. tunnel	No theoretical limit.	Liner plates can be made of Steel or designed as Precast concrete	Variety of soil conditions.	Carrier pipe is required to be installed to carry the utility and the annular space between the tunnel liner plates and carrier pipe need to be grouted.