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Underground pipelines and railway infrastructure – failure consequences and restrictions

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ABSTRACT

Underground pipelines are an essential part of the transportation infrastructure. The structural deterioration of pipelines crossing railways and their subsequent failures can entail critical consequences for society and industry, resulting in direct and indirect costs for all the stakeholders involved. Therefore, continuous and accurate condition assessment is critical for the effective management and maintenance of pipeline networks within the transportation infrastructure. The aim of this study has been to identify failure modes and consequences related to pipelines crossing railway corridors. Expert opinions have been collected through interviews and two sets of questionnaires have been distributed to the 291 municipalities in Sweden, with 137 responses in total. The failure analysis has revealed that pipe deformation has the highest impact, followed by pipe rupture at locations where pipelines cross railway infrastructure. For underground pipelines under railway infrastructure, ageing and the external load were awarded a higher ranking than other potential causes of pipeline failure.

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Pipes; pipelines; renovation; maintenance; inspection; maintenance debt; life cycle costs; failure modes; axial loads; pipelinerailway crossings

1. Introduction

Pipelines crossing traffic infrastructure represent an ongoing concern of all the stakeholders involved. Examples of interactions between railways and pipelines are rail tracks built above existing pipelines and new pipelines installed under or along existing rail tracks. Such interactions should be a major concern in the design, construction and maintenance of both rail track infrastructure and pipeline networks (Ben-Daya, Kumar, & Murthy, 2016; Garmabaki, Ahmadi, Mahmood, & Barabadi, 2016; Thomson, Morrison, Sangster, & Hayward, 2010).

Furthermore, the condition of the land transport infrastructure (railways, roads, and pipelines) has a strong social and economic relevance, since a poor condition results in service disruptions. The next 20-30 years will see an unprecedented demand for growth in rail transport in terms of the axial load and the number of trains in service. European railways will have to deliver increased productivity to fulfil the growth demands that will be made on all modes of transport; productivity will have to increase by 80% for freight services and by 50% for passenger services by 2050 (Transport, 2015). Besides, the ageing of infrastructure will necessitate more maintenance interventions, which will affect normal traffic operations. Therefore, one way to increase the capacity of the transportation infrastructure is to optimise the performance of the existing infrastructure to fulfil the increasing transportation demand (INFRALERT-H2020, 2015).

From an urbanization perspective, railways going through towns and cities often enter urban centres with developed urban areas on both sides of the railway. Therefore, pipelines for water, sewage and stormwater, for example, must at some points go under the railway infrastructure to connect these areas with drinking water and wastewater treatment plants, as well as to fulfil their task of conveying surface water for draining towns and cities. With an increasing urbanisation and densification of cities, underground pipelines crossing railways have become an increasingly important concern for railway infrastructure owners and municipalities.

The current changes in the climate will result in a change in the rain patterns and in more intense rainfall (Andersson et al., 2015). Depending on the topography, the railway embankments in urban areas can function as dam constructions. With an increase in the rain intensity, the risk of urban flooding will increase (Wicklén, 2016). Therefore, it is likely that the existing drainage pipes running through or under railway embankments will need to be replaced with pipes of larger dimensions, and new pipeline-embankment crossings will be needed to avoid urban flooding in the future. Gould, Boulaire, Marlow, and Kodikara (2009) found that seasonality impacts could be observed in pipe failure data 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 (2011) identified the relationship between climate

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Table	1.	Problem	definition	and	description

Problem	Description
1. Railways act as dams	Railway structures act as water dams in urban zones. Once the railway structure can pond up water, it is difficult to install drainage pipes and other piping across the railway without disrupting the train traffic. Costly solutions exist (e.g. press-in tunnels), but are rarely used for smaller-scale projects and pipes.
2. Increased dynamic load affects existing pipelines	The Swedish mining company LKAB and the Swedish Transport Administration (Trafikverket (TRV)) are attempting to increase the axial load from 30 to 32.5 tonnes on the Swedish Iron Ore Line, which may affect old piping designed for a lower axial load. They plan to increase the axial load even more in the future, to over 40 tonnes.
3. New pipes and old railway infrastructure	The installation of new piping in pipeline-railway crossings or modification of the existing piping in such crossings.
4. Transport infrastructure crossing pipelines	Pipeline failure at pipeline-infrastructure crossings and/or the performance of maintenance actions at such crossings can obstruct transport infrastructure and pipeline networks.
5. Failures occurring prior to planned maintenance	Due to the cross-correlation between pipeline failures and railway infrastructure failures, both types of assets can fail prior to the scheduled maintenance.

change and expansive soil volume variation, which results in most of the pipe damage occurring in shrink-swell soil.

Despite the critical role of various pipeline networks, these assets are often regarded as small structures which are secondary to large infrastructure, and the underground maintenance of these assets is often neglected, leading to pipeline failures interrupting both traffic systems and transport infrastructure. For instance, uncased pipes that cross under major motorways, highways, rivers and railways, and uncased pipes suspended from bridges belong to the category of infrastructure components which suffer the largest number of consequences of failure events, including disruptions to major roads, railroads or society (Hess, 2015; Kim, Won, Cho, & Park, 2013; Lines, 1998; Liu & Kleiner, 2013).

An additional problem is that most of the pipelines installed under railways have an age above 50 years and there is a lack of nowcasting and forecasting models to assess the health of the asset. To evaluate the health of pipelines, predict failures, decide on maintenance actions, and facilitate maintenance, condition assessment methods are required (Misiūnas, 2005; Røstum, 2000). Pipeline health monitoring techniques and fault detection techniques for pipelines under transport infrastructure can be categorised as direct (e.g. visual) techniques or indirect techniques. Direct observations include, for instance, observations of settlements within the railway corridor, the accumulation of surface water, or odorisation. Direct observations of failures can be made by maintenance crew during periodic inspections and can be reported by customers. Examples of indirect detection techniques are closed circuit television (CCTV), inspection pig-based monitoring, pressure point analyses, flow balancing and direct burial detection systems for pipeline leak detection (Misiūnas, 2005; Yazdekhasti, Piratla, Atamturktur, & Khan, 2017).

The present study has investigated the dominant modes and causes of failures in pipelines crossing under railway infrastructure and has evaluated issues and challenges in this field, for the purpose of achieving robust pipeline-infrastructure crossings. The study included comprehensive questionnaire and interview surveys which involved the participation of a large number of water and wastewater (W&W) experts representing municipalities, municipal utilities and private companies in Sweden, and which were conducted to achieve the above aims. To the best of our knowledge, no previous systematic empirical study has been conducted which places an emphasis on the maintenance engineering of pipelines crossing under railway infrastructure and which considers the different factors dealt with in the present study. This paper is structured as follows. Section 2 deals with the problem definition and the research methodology applied in the present study. Section 3 presents the condition assessment and maintenance of pipelines crossing under infrastructure. The results of two questionnaire surveys and an interview survey are presented in Section 4. Section 5 deals with the risk assessment of pipeline-railway crossings. Finally, Section 6 provides the conclusions and a discussion.

2. Problem definition and methodology

2.1. Problem definition

Due to the increasing rate of pipeline installation under and near railways, there is a need to study the modes and consequences of failures in pipelines crossing under railway corridors and pipelines installed close to railway corridors, for the purpose of reducing the number of potential failures in the future transport system (Environmental-Protection-Department, 2011; Wicklén, 2016). Some of the problems related to the interaction of these infrastructures are listed in Table 1.

2.2. Society's debt to pipeline maintenance

The infrastructure owners and managers in Sweden have failed to keep up with the increasing rate of increase of maintenance required for pipeline networks (InfraSweden2030, 2016). In economic terms, the gap between the maintenance performed and the maintenance required is known as the "development debt" within the maintenance discipline. It is possible that future efforts to pay off this debt will be made more difficult by the addition of an accumulated "interest" to the debt (Bokrantz, 2017; InfraSweden2030, 2016). The above-mentioned issues were raised in InfraSweden2030 (2016). An explanatory model of the discrepancy between the required maintenance and the actual status of pipeline maintenance, in terms of resources, tools and techniques, is visualised in Figure 1. The discrepancy between the required maintenance and the actual status of pipeline maintenance up to today represents the development debt until today. If the current maintenance policies are allowed to continue in the same manner, the debt will continue to increase, leading to a loss of resources and sustainability in the future.

Figure 1 illustrates the gap between the current status of maintenance of the pipeline networks and the maintenance required for pipeline networks based on a simulation using a typical linear regression model. Pearson's r nominally used



Figure 1. The gap between the current status of pipeline maintenance and the maintenance required for pipeline networks, adapted from (Bokrantz, 2017).

to measure the correlation between two variables, namely the urban development of pipeline networks and the maintenance required for pipeline networks. The relationship between these two variables (the black dashed line in Figure 1) is assumed to be a total positive linear correlation ($\tilde{r} = 1$). Through urban development, the transport infrastructure networks and the pipeline networks will be expanded and the importance of pipeline maintenance is expected to increase at the same rate. In addition, the correlation between the progression of urban development and the actual status of pipeline maintenance (the green dashed line) is also positive and has a lower rate (0 < r < 1). The discrepancy between the required maintenance and the actual status of pipeline maintenance has created the development debt until today (the red dashed area in Figure 1), which has increased with accumulated interest. Efforts are needed to close the gap of the maintenance debt (the green dashed area in Figure 1) and reach a state where the maintenance required for pipeline networks is reconnected with the actual status of pipeline maintenance, i.e. where $\tilde{r} = r = 1$.

2.3. Methodology

Different performance indicators, such as reliability, availability, maintainability and safety (RAMS) indicators, can be used to evaluate the condition of each asset, considering their interconnectivity within the transport infrastructure (Ben-Daya et al., 2016; Garambaki, Thaduri, Seneviratne, & Kumar, 2016). Since the pipeline degradation rate varies according to the environmental impact, it is important to consider this effect on the pipeline degradation process. As can be seen in the "impacts on infrastructure" block in Figure 2, different factors such as traffic, weather, etc. have been considered as input to the condition assessment block. The expert knowledge-based approach and statistically based modelling are two appropriate approaches for describing the failure characteristics of pipelines at pipeline-infrastructure crossings. In this study, the expert knowledge-based approach was selected to identify the potential failure modes and their related consequences. To obtain a more accurate estimation of the remaining useful life of pipelines in pipeline-infrastructure crossings and the failure risk involved for such crossings, one needs to assess the current health of the asset and consider critical factors such as the type of soil, railway operation factors and the pipeline features, etc.

Different categories of fault detection techniques have been used in the literature. For instance, Dai and Gao (2013) classified these techniques into three categories: (i) physical model-based methods; (ii) signal-based methods;



Figure 2. The interaction of pipelines with transport infrastructure and the decision process.

and (iii) knowledge-based, historical data-driven methods. Alzghoul, Backe, Löfstrand, Byström, and Liljedahl (2014) categorised fault detection techniques into model-based methods and data-driven approaches. Figure 3 illustrates the different categories of data-driven diagnostic methods.

2.4. Data collection: questionnaires, interviews, and the failure database of the Swedish railway system, Ofelia

The initial step of the present study was to collect historical failure data from maintenance records for both the railway system and the pipeline networks in Sweden concerning those locations where the railway and a pipeline cross each other. Most of the pipes are buried underground and a relatively small amount of data is available about their failure modes, which contributes to an incomplete knowledge in this field (Røstum, 2000) (see Sections 4 and 6 for further details). In fact, the physical mechanisms leading to pipeline failures are often very complex and are not completely understood. Hence, two questionnaire surveys and one interview survey were conducted, and the Swedish railway failure database, Ofelia, was used to collect the required information and knowledge concerning the problems occurring at pipeline-railway crossings. Details of the data collection procedure are provided in the following subsections.

2.4.1. Details of the first questionnaire survey

The aim of the first questionnaire survey was to identify those areas which had experienced failures in pipelines crossing under the railway and in pipelines installed close to railway infrastructure. The first questionnaire was sent to the 291 municipalities in Sweden and received 100 responses. In this questionnaire, experts were asked about their experience of pipeline failures at pipeline-railway crossings and pipeline-road crossings. The questionnaire was distributed to all the municipalities in Sweden without excluding those which did not have any railway infrastructure in their municipal area, due to the possible mobility of experts between municipalities in the previous 10 years. The questions asked were as follows.

- During the past ten years, have you been working on the installation or renovation of pipelines at pipeline-rail-way crossings?
- Have you been working on the installation or renovation of pipelines at pipeline-road crossings during the past 10 years?

2.4.2. Details of the second questionnaire survey

Based on information received from the first questionnaire survey, a second and more detailed questionnaire was distributed to those W&W experts who had experience of failures of pipelines crossing under a railway area or installed close to a railway area. The selection of municipalities for the second questionnaire survey was based on input received from the first questionnaire survey. The second questionnaire was sent to 63 W&W experts and received responses from 25 experts, which represent around 40% of the total number of experts in the sample. In this questionnaire, the experts were asked a total of eight questions designed for different purposes. The questions included both single-choice and multiple-choice questions. The experts were asked to specify the type of fault detection technique that had been used to discover pipeline failures at pipeline-railway crossings. In addition, four of the questions were designed to identify the potential failure modes of the pipelines and the severity of the effects of these modes. Here a method using a scale of four was applied to measure the severity of the failures and their related consequences. The experts were asked to specify the underlying reasons for the installation of new pipelines and the renovation of pipelines under railway embankments and the techniques used for such installation and renovation. To reduce the uncertainty in the expert judgements, the experts were requested to give their answers using a multiple-choice checklist, as well as providing written supplementary explanations.

2.4.3. Interview survey

An interview survey was carried out in which experts representing 12 infrastructure managers were interviewed to obtain qualitative data for the analysis and classification of the failure modes and their related consequences for risk assessments related to the rail-pipe-soil interaction. Based on the data from TRV's failure report database and the supplementary information from the questionnaire surveys, 12 municipal infrastructure managers were selected. In total, experts from 10 municipal infrastructure managers and two private companies were interviewed by telephone. A summary of the findings of the interview survey is presented in Section 4.3. The presentation is arranged according to the seven questions asked.



Figure 3. Data-driven diagnostic methods, adapted from (Alzghoul et al., 2014).



Figure 4. The Swedish railway network.

2.4.4. Ofelia – the Swedish railway failure database

Trafikverket (TRV), the Swedish railway infrastructure manager, owns several databases for monitoring and assessing the condition of railway assets (Thaduri, Galar, & Kumar, 2015). The Ofelia database (TRV's failure database) was searched in the present study to find failure-related incidents that had occurred on railway lines, from Kiruna to Malmö (see Figure 4), during the period 2001-2017. The records from the Ofelia database were used as support for the questionnaire and interview surveys. The Ofelia database was designed to manage railway component failure, and since pipelines at pipeline-railway crossings are not owned by TRV, pipeline failures at such crossings are not registered in the Ofelia database. Furthermore, pipeline-related failure modes are not defined in this database and tracking such failure modes is a complex and time-consuming task. In the case of a failure at a pipeline-railway crossing, the maintenance experts provide a case description in a text format without any failure mode categorisation, which makes the failure mode categories difficult to track. Hence, a software has been developed by using a text-mining technique to filter the database records and extract related records.

2.5. Processes for data collection

In the questionnaire and interview surveys, a number of experts were asked to share their ideas and experiences

concerning the failure modes, failure causes and failure consequences, etc. which they had encountered. The procedures for expert selection and expert-opinion elicitation are discussed in Step I and Step II below, respectively.

Step I: Expert selection

The expert-judgment process was selected to identify the effects of different failure modes and to perform a qualitative analysis of the consequences of failures of pipelines crossing under the railway or installed in the railway corridor. This process was selected due to a lack of data or an insufficient amount of data in the municipalities and the TRV databases. This process can be considered as a subjective process due to its dependence on the knowledge and experience of experts and the subjective selection of experts. The selection of experts is the first and major step in the process and concerns the selection of an appropriate number of reliable experts. In the literature, various definitions of the term "expert" have been offered; for example, see Naseri & Barabady (Naseri & Barabady, 2015, 2016a; Otway & Winterfeldt, 1992). According to Meyer & Booker (Meyer & Booker, 1991), an expert can be defined as: "a person who has a background in the subject matter at the desired level of detail and who is recognised by his/her peers or those conducting the study as being qualified to solve the questions".

Following qualitative criteria for expert selection makes the expert-judgement process more subjective. For instance, having "a desired level of detailed background in" W&W can be considered as a qualitative criterion for the selection of experts and is subjective. From another perspective, it is advantageous to select a group of experts with a wide background, but on the other hand, the person selecting the experts may be under pressure to exclude experts who are perceived as being less experienced (Bedford & Cooke, 2001). In the present study, the respondents to the questionnaires were experts at different levels of the W&W hierarchy, as shown in Table 2 below.

Step II: Expert-opinion elicitation

"Expert-opinion elicitation" was the second step in the expert-judgment process and can be defined as the process

Table 2. Types of experts participating in the questionnaire and interview surveys.

Participant type	First questionnaire	Second questionnaire	Interview
Head of W&W and roads	41	9	-
W&W project engineer	24	6	4
Grid manager/Municipal W&W manager	25	7	4
Operator/Operation and Maintenance + Other role	10	3	2
Sum	100	25	10

of obtaining the subjective opinions of experts through specifically designed methods of communication, such as surveys, interviews, group meetings and questionnaires (Meyer & Booker, 1991). Expert-opinion elicitation may be performed using a qualitative or a quantitative structure. Using a quantitative structure, the experts are asked to express their subjective opinions about a parameter in the form of, for instance, a single-point or distribution estimation, an absolute rating, an interval scaling, or a ratio scaling (Cooke & Shrader-Frechette, 1991; Meyer & Booker, 1991; Naseri & Barabady, 2016b). In the present study, the first questionnaire consisting of two general questions was distributed to all the municipalities without considering the internal consistency of the questions. However, the second questionnaire was validated and Cronbach's alpha value is 0.866 which is located in the acceptable range.

2.6. Failure modes and effects analysis

This study utilised failure modes and effects analysis (FMEA) for identification of the dominant failure modes of pipelines at pipeline-railway crossings. FMEA is a tool used in operation and maintenance engineering to analyse the potential failure effects and identify the dominant failure modes and classify them according to their severity and the likelihood of their occurrence (Ben-Daya et al., 2016; Naseri & Barabady, 2015; Stamatis, 2003). Furthermore, an additional objective of FMEA is to provide feedback for the design phase for improvement of the quality, reliability and availability of the system being investigated. When applying FMEA, one determines the failure modes to identify the potential and actual failures in a product design or operation, with an emphasis on failures affecting the customer or end-user. A failure effect is the consequence of a failure mode for the operation of the product or system. The study of consequences of identified failures is called "effects analysis". FMEA prioritises failures according to their severity, the probability of their occurrence and their detectability. The severity of failures means the seriousness of their consequences. The probability of the occurrence of failures indicates how often they can occur. The detectability of failures indicates the degree of difficulty of their detection. The FMEA process is illustrated in Figure 5.

The risk priority number (RPN) (see Figure 5) is an important factor for FMEA and can be defined as the mathematical product of the severity (S), occurrence probability (O) and detectability (D). The RPN serves the purpose of

determining the risk priority for a process or item and is a useful tool for maintenance decision making.

3. Condition assessment and maintenance of pipelines crossing infrastructure

When assessing the condition of a pipelines, one can assess its structural condition and its operational condition. The structural condition of a pipeline network describes the physical condition of its pipes, while the operational condition describes the capability of the pipeline to meet its service requirements. Continuous condition assessment is needed to assure fulfilment of the service requirements.

Numerous documented studies have determined the main failure modes in pipeline networks to be the following: pipe rupture, deformation, erosion & corrosion, and cracks. In addition, the effects resulting from each failure mode and the related consequences, as presented in the literature (Misiūnas, 2005; Muhlbauer, 2004; Røstum, 2000) and determined through interviews with W&W experts, are as follows: limited sanitation capacity, poorer wastewater treatment, flooding, sinkholes and rail settlement The four above-mentioned failure modes and the effects resulting from each failure mode are listed in Table 3. These failure modes and effects were selected as a basis for the questions posed to the W&W experts in the questionnaire and interview surveys.

3.1. Factors affecting pipeline deterioration at locations where pipelines cross transport infrastructure

To assess the condition of pipelines crossing transport infrastructure, which are more prone to damage, one needs to characterise and standardise the failure modes of these pipelines. This can be achieved by studying and analysing geotechnical models used in tunnelling, pipeline engineering and maintenance engineering. Based on the literature (Morris, 1967; Røstum, 2000), the factors influencing the structural deterioration of the pipeline network can be categorised into four groups: structural variables, environmental variables, internal variables, and maintenance variables. The parameters under each variable type are presented in Figure 6.

Today the condition assessment of water pipelines mainly depends on the information provided in operational disruption reports. The only time a pipeline can be inspected is when it is laid bare through excavation, which is too expensive a method to use for status assessment. Internal condition assessment of pipes is not practical since they often have coatings along their walls that hide cracks and corrosion; therefore, this is not a reliable, time- or cost-efficient method for pipeline condition assessment.

Furthermore, the relation between the age and the leakage rate of pipes is not straightforward and there may be several covariates that might affect the leakage rate for instance, previous leaks, pipe loads, construction work, construction periods, the pipe length and material, and the geographical location (Malm et al., 2011; Røstum, 2000;



Figure 5. The failure mode and effect analysis process.

	Table 3.	Possible	failure	modes	and	effects.
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Failure mode	Effects resulting from each failure mode
Pipe rupture	Limited sanitation capacity
Deformation	Poorer wastewater treatment
Erosion & corrosion	Flooding
Cracks	Sinkholes and rail settlement

Standard-BVS-585.20, 2005-09-19). For instance, it has been shown that grey-iron pipes installed during the 1950s and 1960s have an increased leakage rate. This is most likely due to the transition from digging by hand to digging using excavators, as the pipes were dropped into larger pipes with poor support from the surrounding soil. Similarly, road salting increases the risk of external corrosion. Due to the need to develop urban areas during the 1960s, a construction rush took place in which the installed pipes were of poorer quality. Pipelines are installed in various geographical locations, and certain soils in these locations can increase the external corrosion of the pipeline. The soils that are especially corrosive are clay soils with a high sulphur content. In a British study, it was found that pipes in clay soils exhibited almost twice as much leakage as pipes in sandy soils (Malm et al., 2011). Moreover, loose soil can cause sedimentation, as well as changing the pressure conditions, resulting in pressure drops which can lead to leaks in nearby pipes.

According to Sundahl (1996), leaks tend to come in groups and to be close to each other physically and temporally.

The traffic load on pipelines and the degree of pressure are important covariates, mainly at locations where pipelines and transport infrastructure have an intersection area. Pressure due to axial loads causes a type of circular fracture known as a beam fracture. Transverse voltages are caused by land and traffic pressure. When the ground becomes cold, it expands and the pressure may create longitudinal cracks in pipes. The quality of the construction work also varies from period to period and, therefore, different failure rates may occur in different areas of the pipeline network.

Temperature has also been considered as an important factor for the leakage frequency in several studies (Andersson, Sjörs, & Jonelind, 2006; Habibian, 1994). The connection between increased leakage in the winter and the temperature of the outgoing water from waterworks has been studied by Swedish Water (Andersson et al., 2006). When the temperature of the outgoing water falls below zero and the ambient temperature in the ground is warmer, this may lead to leakage. This combination of phenomena creates stresses in the outer surface of the pipes and ring pressure in the inner surface (Andersson et al., 2006). A temperature drops in the outgoing water to below zero can increase the number of circular cracks in grey-iron pipes,



Figure 6. Factors affecting the structural deterioration of water distribution pipes (Røstum, 2000).

and this type of crack can occur in pipes with a diameter of 76–203 mm. In addition, grey-iron pipes are sensitive to rapid falls in the temperature, and by levelling the water temperature, the number of leaks can be reduced (Habibian, 1994).

In addition to the above-mentioned factors causing pipeline deterioration, internal corrosion can occur and also cause pipe leakage. The internal corrosion rate may be affected by the water quality and flow rate. Corrosion results in a reduction of the pipeline wall thickness and a deterioration of the pipeline's hydraulic function. An alkaline pH in drinking water reduces the corrosion rate (Andersson et al., 2006).

Furthermore, Lee et al. (2017), Misiūnas (2005) reviewed the existing condition assessment technologies for pipelines in urban areas, but most of these technologies are not applicable for the condition assessment of pipes crossing under railway infrastructure owing to the special nature of pipeline-railway crossings. Hence, most of the assessments of pipelines at pipeline-railway crossings are performed on the basis of interruption reports, and these are the main source of information about the pipe condition status.

3.2. Rehabilitation of pipelines crossing railway infrastructure

Pipeline renovation and replacement techniques can be divided into two main categories, namely open-cut renovation and replacement techniques and trenchless renovation and replacement techniques. Open-cut or excavation-based techniques are a common tool for renovating pipelines and consume a large part of the renovation and replacement budget. In addition to the substantial cost incurred by these techniques, excavation-based techniques consume a large amount of time and reduce the availability of the pipeline and the surrounding infrastructure.

Recently, different trenchless methods have been developed to avoid excavation and reduce the high cost of pipeline renovation and replacement. For instance, the installation of a new pipe within an old pipe is an economically and technologically proven method. A textile-based pipe impregnated with a resin made of a plastic material can be installed in the old pipe to reline it. The installation can be performed through a manhole in one run (up to about 1 km) by using air pressure and hardening the textilebased pipe with UV light, see Figure 7. With this method, the infrastructure owner can cut the installation time (compared to that required for installing a new pipe) by about 80% and reduce the installation and material costs and other costs by (40–60)%; see Hay (2014) for a comprehensive comparison of trenchless technologies with traditional open trenching for the replacement of ageing pipelines.

Pushing a new pipe into an old pipe can also be used for renovating the pipeline without excavation. This technique is used mainly when the renovation can create different types of disturbances for society. For instance, the renovation of pipelines at locations where pipelines cross transport infrastructure can be performed using this method without causing disturbance to the other infrastructure in the vicinity, see Figure 8.

The installation of a new pipe within an old pipe using pipe bursting is an alternative approach. By installing a new pipe with a smaller diameter inside an old pipe, the capacity of the pipeline will decrease. If there is a demand for a larger capacity, the diameter of the new pipe should be larger. In such a case, the old pipe can be broken with a special torpedo and a new pipe with a larger diameter can be pulled and/or pushed by the torpedo (Figure 9). All sorts of pipes, including concrete, cast iron and steel pipes, can be broken using this method. The new pipe can have a dimension which is up to 50% larger than that of the old pipe, thus increasing its area by 125% and its capacity by 200% (Levlin, 2004).

The type of method to be selected is highly dependent on the type of crack involved, the size of the crack, whether there is a need for a higher capacity, and the impacts on society, etc. For instance, it may not be possible to carry out excavation on a main line in an urban area because of the



Figure 7. Textile-based pipe impregnated with a resin made of a plastic material inside an old pipe.



Figure 8. Pushing a new pipe into an old pipe.

different types of social costs that would be involved, Examples of such costs are the cost of traffic disruption, costs for the stakeholders concerned, and the cost of losing public trust, etc.

4. Pipelines crossing the railway – questionnaire and interview surveys

The present study adopted an expert-based knowledge-based approach for analysing pipeline failure modes and the consequences of pipeline failure at locations where pipelines cross railway infrastructure. The data for the study were collected through two questionnaire surveys, an interview survey and the retrieval of information from the Ofelia database (TRV's failure report database). Details of the adopted research methodology and the outcomes of the surveys are summarised in the following subsections.

4.1. Outcome of the first questionnaire survey

For the first questionnaire, 100 responses were received from the W&W experts and the participation rate was around 35%. A plot of the distribution of the responses is presented in Figure 10.

In the first questionnaire, the first question asked whether the respondent had experience of working on the



Figure 9. Pipe bursting for renovation.



Figure 10. Geographical distribution of the responses according to municipality (the colours are in alignment with those in Figure 10).

installation or renovation of pipelines at pipeline-railway crossings during the previous 10 years. The proportion of respondents who answered "Yes" to that question was 63%, while 37% of the respondents answered "No". It can be noted that the latter percentage includes those W&W experts who worked in municipalities which did not have railway infrastructure in their municipal area. The answers were analysed and categorised into six groups, and the percentage of respondents belonging to each group is presented in the pie diagram provided in Figure 11, where a different colour has been selected for each group.

Some W&W experts experienced several issues and these issues are indicated by their respective colours in the columns on the map provided in Figure 10. For example, a W&W expert in Gävle reported experience of performing emergency activities, as well as renovating a pipeline and installing a new pipeline under railway embankments. These three categories are represented by the orange-green-red bar in the Gävle municipal area in the map in Figure 10.



Figure 11. Questionnaire response statistics for pipeline-railway crossings.



- = Reported "yes" but without case description
- Have installed new pipes under the railway
- Renovation of existing pipes under railway
- Activities within the railway area
- » Operation/maintenance activities
- Acute activities
- Reported "yes" but without case description
 Have installed new pipes under the road
 Renovation of existing pipes under road
 Activities within the road area
 Operation/maintenance activities
 Acute activities

Figure 12. Questionnaire response statistics for pipelines crossing road infrastructure.

Although the focus of the present study was on pipelinerailway crossings, a second question was posed which asked whether the respondent had experience of installing or renovating pipelines at pipeline-road crossings. Detailed response statistics for this second question are presented in Figure 12.

4.2. Outcome of the second questionnaire survey

We received 25 responses for the second questionnaire and the response rate was around 40%. The questions in this questionnaire survey were designed based on the FMEA framework.

The aim of the first question in this questionnaire was to identify the types of methods and techniques used for inspecting pipeline-railway crossings and pipelines installed close to the railway. Question 1 was as follows: "What method did you use to detect problems with W&W pipelines crossing under the railway and W&W pipelines installed close to the railway?"

The results are presented in Figure 13 and reveal that the identification of most of the faults and failures was based on visual inspections. This confirms that there is a substantial need to utilise new condition monitoring technologies for pipeline networks, especially at pipeline-railway crossings due to the load and the traffic frequency.

The second question posed to the experts was as follows: "What types of pipe defects were detected in pipes at pipeline-railway crossings or in pipelines installed close to the railway?" The aim of this question was to verify the failure modes described in Section 3 and reported in the literature in this field, namely pipe rupture, deformation, cracks, and erosion & corrosion. In addition, supplementary information has been requested from the experts. A diagram presenting of the percentages for the observed failure modes is provided in Figure 14. It can be noted that some of the experts reported more than one failure mode.

In the next step, the respondents assessed the severity of the effect of each failure mode according to a scale of four as follows: (1) there is no effect, (2) there is little impact, (3) there is a moderate impact, and (4) there is a severe impact. Numerical scale 1, 2, 3 and 4 respectively were used to convert the four linguistic variables into numbers. Based on an additive weighting analysis, a colour-scaled matrix was created and it is shown in Table 4 (where each section has its own colour-scale). The first four columns of this table contain the severity index for the four consequences in relation to each failure mode, evaluated using a weighted average approach. In addition, the experts were requested to rank the importance of the effects of the different failure modes. The normalised weights are presented in column 5 till 8 (indicating the importance of the effects). The final severity was calculated by multiplying the severity index by the normalised weights. Finally, the weighted averages were calculated through a summation of the final severity indexes of the four effects for each failure mode.



II Visual observation

Indirect detection

Figure 13. Type of failure detection method used for pipeline-railway crossings.



Figure 14. Percentages for the experienced failure modes for the railway case.

To visualize the failure modes in correlation with the consequences of the failure modes, a radar chart was created and it is provided in Figure 15. This figure reveals that a limited sanitation capacity and flooding are the two most dominant effects resulting from the failure modes. Based on the analyses, it was found that pipe deformation has the highest impact, followed by pipe rupture at locations where pipelines cross railway infrastructure.

Misiūnas (2005); Røstum (2000) reported that there were several covariates which could be considered as the causes of failures in the pipeline network, for instance maintenance actions, the installation period, ageing, corrosion, nearby excavations, seasonal variation, the pipe properties (e.g. the pipe's diameter, length and material), the soil condition, previous failures, the pressure in the pipeline, and the external load stress (due to the traffic frequency, axial load, etc.). The experts selected these covariates as the most important failure causes for pipeline crossing railway infrastructure. In the present study, the W&W experts were asked to identify the causal factors that had the greatest impact on pipeline failure at pipeline-railway crossings. Figure 16 illustrates the experts' assessment of the impact of each defined cause. Ageing, the external load, erosion & corrosion, and piperelated weaknesses were ranked as having a higher impact than the other causes of pipeline failures.

The next step involved a more detailed identification of the possible consequences of failure and their impact by asking the experts the following question: "What were the consequences of pipeline failure at pipeline-railway crossings?" Different alternatives had been extracted from the literature and interviews with W&W experts. In addition, the experts were given the opportunity to describe their cases in detail. The results reveal that "delivery disruptions or pressure changes" were ranked as having the highest impact, followed by "deterioration of roads in the vicinity of pipe damage", as shown in Figure 17.

The W&W experts were then asked the following question: "What was the main reason/motivation for installing new pipelines under railway embankments?". In this connection, five alternatives were suggested, and the results are presented in Figure 18. The results confirm some of the hypotheses and show that the replacement of old pipelines and the need to increase the capacity of pipelines are the main reasons for installing new pipelines under the railway. Furthermore, this study was interested in finding out which techniques had been utilised for the installation of new pipelines and the experts were given the opportunity to describe their cases in more detail. The following question was asked: "Which technique was used for the installation of new pipes near or under the railway corridor?" The results for this question are illustrated in Figure 19 and show that "no-dig" trenchless technology using steered drilling and "no-dig" trenchless technology with pipe pushing were used for more installations than the other techniques. 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 perform curved drilling, for instance under roads, railways and rivers. Steered drilling exhibits best performance if the ground is stone-free and the technique can be used for pipes with a diameter of less than 1,200 mm and with lengths of up to 1,500 m.

It is important to note that 26% of the municipalities participating in this survey used open excavation for the installation of new pipes. This issue needs to be studied in more detail to identify why 26% of the municipalities used such an expensive solution. Some of the relevant answers through the interview survey were presented in the next section.

Furthermore, this study was focused on investigating the extent to which the different new techniques were used for renovating pipes and installing new pipes. Several popular

	Expe the	ert Ass Severi Conse	sessme ty of F quence	ent of Each e	Nor	malize	ed Wei	ghts	I	Final S	severit	у	
	Limited SanitationCapacity	Poorer Wastewater Treatment	↓ Flooding	Pinholes	Dim Limited Sanitation Capacity	Poorer Wastewater Treatment	✓ Flooding	Pinholes	Limited Sanitation Capacity	Poorer Wastewater Treatment	<i>Mei Kei</i>	binholes binholes	Weighted Average
Fracture/Pipe Rupture	3	1.89	2.11	2	0.31	0.22	0.26	0.21	0.94	0.42	0.54	0.42	2.32
Deformed Pipe	2.83	1.83	2,33	3	0.3	0.22	0.25	0.23	0.85	0.41	0.58	0.69	2.53
Pipe Cracks	2.83	1.5	2.33	1.67	0.3	0.21	0.27	0.22	0.86	0,31	0.63	0.36	2.17
Erosion & Corrosion	3.13	1.57	2.29	1.57	0.34	0.2	0.26	0.21	1.05	0,31	0.6	0.32	2.28

 Table 4. Evaluation of the effects of the possible failure modes of pipelines crossing under the railway.



Figure 15. Distribution of the failure modes in correlation with the consequences of the failure modes at pipeline-railway crossings.

methods were selected based on the literature and interviews with the W&W experts. The results are presented in Figure 20 and show that trenchless technology with flexible pipes was ranked highest, followed by open excavation and "nodig" lining with a rigid pipe. For this question, some blank responses or information was received on other techniques used; for instance, one expert reported the use of drilling to install a new pipe next to old pipes.

4.3. Outcome of the interview survey

In order to understand the driving forces behind damage to pipelines crossing under the railway and to reduce the number of failures in the future, more specific questions were asked via interviews with experts. The questions asked in the interviews were based on the findings of the two questionnaire surveys which were presented in Section 4.1 and



Figure 16. Pipeline failure causes at pipeline-railway crossings.



Figure 17. Possible consequences of failure at pipeline-railway crossings.



Figure 18. The reasons for the installation of new pipelines under railway infrastructure.

4.2 above and which highlighted the need to acquire a deeper knowledge of operational disturbances caused by the failure of municipal water pipes buried in railroad beds. A rough estimation based on a selection of all the reported instances of railbed damage (based on Ofelia database records) or disturbances between 2001 and 2017 is that only a minor number of disruptions can be connected to water or wastewater pipes crossing under railway embankments. The total number for 2001–2017 was estimated to be a couple of dozen (<50), while the total number of instances of railroad damage exceeded 60,000 annually, of which 20% affected train movements (based on statistics extracted from the Ofelia database). A first rough estimate of the total



Figure 19. Techniques used for the installation of new pipes under railway infrastructure.



Figure 20. Techniques used for renovating pipelines and installing new pipelines under railway infrastructure.

number of (municipal) W&W pipeline-railway crossings in Sweden is that there are 3,000-5,000 such crossings (based on the estimated number of W&W pipeline-railway crossings per larger urban area). The total length of piping in pipeline-railway crossings in Sweden is 45,000-75,000 m (based on an estimated pipe length of 15 m per crossing). The estimated frequency of W&W pipe damage occurrence near railways (i.e. within 15 m from the perimeter of rail bed areas) or inside railway or rail bed areas is below the overall mean W&W pipe damage frequency of 0.2 damage instances/km of pipe and year. This estimation is based on the estimated length of W&W pipes crossing the railway in Sweden and the reported number of instances of W&Wrelated damage in the areas of interest in Sweden, compared with the total figures for the municipal W&W piping length and frequency of W&W pipe damage. A summary of the discussions held with the experts in the interviews is presented in the following. The presentation is arranged according to the questions asked.

Questions and answers

 What kind of legally binding agreements are there between TRV and the municipal W&W service providers concerning water pipes crossing railroad beds? Results: In a rare number of cases (3) there exists a written legally binding document known as an agreement. The overwhelming number of respondents stated that an "avtalservitut" (easement agreement), a "ledningsrätt" (pipe entitlement) and a "grävtillstånd" (excavation permit) represent the general administrative ways to handle this kind of issue. The *grävtillstånd* is connected to the time when the pipe is to be taken through the railbed or is to be repaired etc. All the respondents stated that they did not possess complete knowledge of "all" the legal documents; the general belief was that the documents of interest, if needed, were to be found (and could be found) one by one in the municipal archives by searching for the occurrences of pipe crossings and rail beds on W&W service maps.

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

Results: Nearly all the pipeline-rail bed crossings are protected in the vast majority of the municipalities (all of them but two) by using pipe-in-pipe technology to 100%. In multi-rail track areas, one can find reinforced walkable conduits large enough to handle the output from a number of municipal service providers, i.e. providers of district heating, water & wastewater, electricity and digital information lines.

Experts from two municipalities reported that gravity flow (wastewater) pipes are not in all cases protected. Concerning those municipalities which were reported not to use protective devices to 100%, it is unclear whether they did so in many cases and whether they still continue this practice.

3. When problems arise connected to pipes crossing rail beds or pipes installed near rail beds, is there a prepared strategy ready to be implemented and, if not, have there been any discussions about the need for one? Or are such problems handled from one time to another when they emerge?

Results: Since these cases are so rare and in most areas happen only a few times during a decade, most of the interviewees representing municipalities could not give a clear answer, probably because they were usually responsible for operation and/or maintenance and not for planning and/or design. In many cases, planning and design were performed by consultants who had no further responsibility for this after the completion of projects.

7.

4. Has a strategy been decided for the planning and construction of new pipe structures near rail beds and in rail bed areas, or for the planning and construction of new rail systems in areas with gravity or pressure pipe systems?

Results: The strategy reported is as follows: (1) try to avoid crossings during the pipe system design stage; (2) if necessary, use natural openings in rail beds (traffic crossing viaducts) or other technical structures; (3) if a pipeline-rail bed crossing is necessary, use conduit technology in combination with inspection manholes on both sides of the rail bed; (4) regarding multiple rail bed areas (e.g. railway station areas), use walkable reinforced concrete conduits.

5. What is your attitude to the risks connected to pipes placed near rail beds in general, and, in particular, in

the case where these structures together create "shut-in" drainage areas?

Results: The risks connected to pipes located near rail beds or even crossing rail beds must be addressed by proper design and operation. In most cases, the design of pipeline-railway crossings focused on pipe-in-pipe technology, with the use of the pipe material at hand at the time of implementation. In some cases, pipe-in-pipe technology was not used, usually in the case of gravity flow sewers. The interviewees representing municipalities were unaware of the present municipal security policy, and surmised that if there was a person responsible for such a policy, they were probably connected to a consulting firm and followed the firm's risk assessments and general standards.

One interviewee, representing who represented a contractor responsible for nationwide pipe repair and replacement, reported that many pipe materials could be expected to have a very limited remaining operational time, e.g. the material of reinforced concrete gravity flow sewers.

Concerning the issue of shut-in areas and potential drainage problems associated with them, the interviewees gave very vague answers and regarded this issue as a problem to be handled internally by the land owner concerned (usually Järnhusen and not a municipality).

During recent work on pipes crossing rail beds or located near rail beds, what kind of technology was used?

Results: Very few instances of such work were reported and in all of them, a "no-dig" technology was applied. During the digging and installation phase, continuous and accurate measurement of the rail levels had to be performed and on-line warning technology had to be used.

Concerning pipes installed in the ground parallel to rail beds and pipes installed near rail beds, the approach adopted was not known.

In general terms, is there something which we have not discussed yet and which, if discussed, would or could facilitate projects involving pipeline-railway crossings? Results: An experience described by interviewees representing municipalities is that TRV, the state owners of the rail bed areas, and Järnhusen AB, the owner of many railroad structures, tend to see their ownership and connection to the Swedish state system as entitling them to certain prerogatives, and they tend to regard their interests and regulations as being of primary importance to society. In consideration of this and in order to enhance the possibility of increasing the speed of structural change in society, there is a need to create a better balance between the interests of the local municipal infrastructure owner, the state railway infrastructure owner and the operators (which include private businesses). This can be achieved by creating a better and more stable legal structure.

5. Risk assessment of pipelines at pipeline-railway crossings

As explained in Section 2.6, the severity, probability of occurrence, and detectability of failures are the key parameters in RPN evaluation. The severity and occurrence probability of failures were discussed in Section 4 and estimation of the detectability parameter is discussed in this section.

5.1. Scaling the detectability parameter

In the literature, one can find that a detectability scale ranging from 1 to 5 has been commonly used to convert the linguistic variables into numerical values, as shown in Table 5. It can be noted that if the detectability scale is arranged in the reverse order, a high ranking will be awarded when failures are not likely to be detected and a low ranking when they are very likely to be detected.

In general terms, W&W pipe failures can be detected by the following means: (i) water flooding up to the urban soil surface, (ii) sudden cracks or depressions in the surface layers of streets etc, (iii) pipe capacity changes as observed by rising levels in manholes, (iv) loss of access to a water service in dwellings in urban areas, (v) basement flooding caused by both wastewater and drinking water, (vi) sudden or unexpected changes in the water level in water reservoirs, (vii) unforeseen capacity problems in waterworks, (viii) dramatic changes in the incoming flow to wastewater treatment plants, (ix) unexpected disturbances in the operating hours of pumping stations, (x) manual observations of sewage or stormwater overflow entering recipients (even under an ice or snow cover).

Most of the municipalities do not have a SCADA system dedicated to detecting the occurrence of the above-mentioned changes in the pipeline network and alerting the operation staff as to their occurrence. In some of the municipalities, it is the case that the general SCADA system has been installed and has been running for more than a decade, while the system software for detecting the above-mentioned changes in the network has not been added. To obtain a more accurate estimation of the detectability parameter, W&W experts were interviewed and the results can be summarised as follows.

- *Pipe rupture detectability*: This was judged by the experts to have a level of 2.
- Deformed pipe detectability: The estimated level for this is 2. "Deformed pipes" mostly means "pipes that are near collapse". The detection of deformation can either be immediate (e.g. soft PP pipes not laid in the soil properly) or take place when the pipes start to break down into large pieces due to soil pressure, for example, at some point in time during a 30–50 year period (e.g. concrete pipes lacking steel reinforcement).
- *Pipe crack detectability*: This was given an estimated level of 4. If water is transported by gravity, the crack might be harder to detect, especially in the case of small gravity systems.

Table 5. Detectability scale.	
Ranking	Likelihood of detection during diagnosis
1	Almost certain
2	High
3	Moderate
4	Low
5	The fault is unlikely to be detected by operators or maintenance personnel

• Detectability of eroded or corroded pipes: The estimated level for this is 4. The problem with this kind of failure mechanism is that it is expected to be fairly widespread and is a major factor for drinking water leakage, especially in the case of customer service pipes made of galvanised steel (which represent 40–50% of all service pipes). Most damage connected to corrosion is difficult to detect in time and it can result in a deteriorated water quality.

A summary of the statistics of the detectability index and the RPNs are presented in Table 6.

5.2. Risk priority number (RPN) and uncertainty estimation

Due to the subjective nature of the data collection and the expert opinions, there was a need to analyse the associated uncertainties of the analysis. Nonsequential Monte Carlo simulation (MCS) is utilised to investigate how such uncertainties propagate through the risk priority number (RPN) model (Zio, 2013).

In the first step of the uncertainty analysis, the probability mass function and, further, the cumulative distribution function (CDF) of the expert data on the detectability of the different failure mechanisms were obtained, as shown in Figure 21.

As mentioned earlier, the severity of each failure mechanism was discussed from the perspective of the effects of the failure mechanism, which include a limited sanitation capacity, poorer wastewater treatment, surface flooding and pinholes. Different experts expressed their opinion on the degree of these effects (i.e. the severity of each failure mechanism) by choosing a ranking from "one" to "four", with "one" representing "no effect" and "four" representing "the maximum effect". Later, the experts were also asked to rank the importance of the failure causes. In order to obtain the distribution of the effects of each failure mechanism, a weighted arithmetic averaging method was used, as given by the following equation:

$$F_{i}(s) = \sum_{j=1}^{4} w_{i}^{j} F_{i}^{j}(s)$$
(1)

where i = 1, ..., 4 refers to the *i* th failure mechanism (i.e. pipe rupture, deformation, cracks or corrosion), j = 1, ..., 4 refers to the *j* th failure effect (i.e. limited sanitation capacity, poorer wastewater treatment, surface flooding or pinholes), $F_i^i(s)$ is the CDF of the severity of failure mechanism *i* from the viewpoint of failure effect *j*, and $F_i(s)$ is the CDF of the severity of failure mechanism *i*. In Eq. (1), the

 Table 6.
 Summary of the statistics for the severity and detectability indexes and the RPN for each failure mechanism.

		Pipe rupture	Pipe deformation	Pipe cracks	Pipe corrosion
Severity index	Mean	2.32	2.53	2.17	2.28
	5 th Percentile	1.52	1.69	1.30	1.59
	Median	2.31	2.55	2.12	2.27
	95 th Percentile	3.15	3.32	2.98	3.06
Detectability	Mean	1.892	1.927	3.862	4.145
	5 th Percentile	1	1	2	3
	Median	2	2	4	4
	95 th Percentile	3	4	5	5
Occurrence probability		0.31	0.18	0.22	0.28
RPN	Mean	1.359	0.876	1.841	2.651
	5 th Percentile	0.583	0.355	0.880	1.507
	Median	1.341	0.819	1.835	2.601
	95 th Percentile	2.429	1.867	2.993	3.818



Figure 21. CDFs of the severity index of each failure mechanism.

parameter w_i^j is the normalised weighting factor denoting the importance of effect *j* of failure mechanism *i*, where:

$$\sum_{j=1}^{4} w_i^j = 1$$
 (2)

Using similar approaches, the CDF for the detectability can be obtained. The mean, median, 5th percentile and 95th percentile are presented in Table 6. Finally, having obtained the values of the occurrence probability of the failure mechanisms, the risk priority number is calculated as:

$$RPN_i = O_i \times S_i \times D_i \tag{3}$$

where O_i is the occurrence probability of failure mechanism i = 1, ...4, and S_i and D_i are the severity and detectability, respectively, of failure mechanism i = 1, ...4, obtained from the corresponding CDFs.

The corresponding CDFs of the risk priority numbers of the respective failure mechanisms are depicted in Figure 22, which also represents the uncertainties associated with the pool of expert opinions and their propagation through the risk priority number model.

As this figure shows, the RPN for erosion & corrosion has the highest value, which means that if the resources are limited, this hazard should be treated first. It may note that there is overlap of confidence intervals (for instance, 5th percentile95th percentile) of failure mechanisms which may due to dealing with a limited amount of data for RPN analyses.

5.3. Qualitative risk assessment

In Section 4, it was identified that the failure modes of pipelines crossing railway infrastructure can lead to undesirable situations. Different approaches to risk analysis have been proposed in the literature (Abspoel et al., 2018; Barabadi, Garmabaki, & Zaki, 2016; Hu, Yang, Macey, Moncrieff, & Agha, 2016; Muhlbauer, 2004; Taylor, 2003). In the present study, failure modes and effects analysis (FMEA) was applied for risk analysis. Moreover, having obtained the occurrence rate for the different types of consequences, as well as the frequency of failure, the level of risk for each failure mode can be plotted on a risk matrix. The decisionmakers, including W&W project engineers, grid managers, municipal W&W managers, operators, and operation and maintenance experts, can use the risk matrix to determine 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 results provided in Tables 4 and 6, the risk matrix shown in Figure 23 was created for pipe rupture, erosion & corrosion, cracks and deformation. On the basis of the risk matrix, the failure mode/modes with the highest risk level should be chosen for a risk reduction programme.

6. Conclusions

The aim of this study was to identify pipeline failure modes and their consequences at locations where pipelines cross railway corridors. The analysis revealed that pipe deformation has the highest impact, followed by pipe rupture at pipeline-railway crossings. Ageing and the external load gained higher rankings than other potential causes of pipeline failure. Furthermore, with regard to failure consequences, analyses show that, at pipeline-railway crossings, delivery disruptions were ranked as having the highest impact, followed by deterioration of roads close to pipeline failures.

To identify the most important reasons for the installation of new pipelines under railway embankments, the W&W experts participating in the study were provided with five alternatives to choose between, and the results show that the replacement of an old pipeline and a need to increase the capacity of the pipeline are the two main reasons for installing new pipelines under railway infrastructure. Furthermore "no-dig" trenchless technology using steered drilling and "no-dig" trenchless technology with pipe pushing are the most commonly used techniques for the installation of new pipelines. The analysis shows that, according to the W&W experts, trenchless technology with flexible pipes has been used most, followed by open excavation for pipeline renovation under rail infrastructure.

During the course of the study, it was found that the data availability, the data quality and the data management system are the main bottlenecks for RAMS analysis. In general, small datasets and incomplete failure data are the main two obstacles for the reliability analysis of pipeline networks. Small datasets may originate from the use of an inappropriate data collection system. Each municipality has their own reporting system and each individual system acts independently, which restricts comprehensive data analysis. Furthermore, many municipalities have recorded their inspection and failure data in handwritten documents, and



Figure 22. CDFs for the RPNs of the respective failure mechanisms.

integrating such records may not be a cost- and time-effective solution. A lack of protection of data integrity is also an important issue leading to small databases. The above-mentioned factors can explain the low level of use of advanced condition assessment tools for the health assessment of pipeline networks.

Based on the investigation and the literature review performed for this study, it was concluded that few water utilities in Europe are trying to implement preventive maintenance in their pipeline rehabilitation policies. The majority of utilities are following a corrective maintenance strategy and only a few of them are concentrating on a rehabilitation strategy that maintains pipelines before they wear out. This is contrary to the strategy adopted for trans-European oil and gas pipelines, although W&W infrastructure can be of equal importance to the local stakeholders. In Sweden, most of the municipalities are aware of the advantages of prediction-based maintenance. In addition, it was found that unavailability of data is an issue that is not restricted to pipelines at pipeline-railway crossings. Maintenance managers are also having to face the challenge of poor availability and quality of data for pipelines buried in urban areas due to the structure of old pipeline networks and the utilities connected to them. Hence, there is a need to use new condition monitoring tools based on state-ofthe-art hardware (using highly advanced sensor-based technologies), software and data management tools. The success of implementing a proactive approach obviously depends on the criteria used for rehabilitation planning. The rehabilitation strategy should be based on the prediction of future pipe failures, continuous assessment of the reliability of the water network serving the customers, and estimations of the cost of improvements. If this information is available, it will be possible to optimise the rehabilitation programmes.

The present study revealed that there has been insufficient interest and investment in monitoring the operation and maintenance of pipelines using advanced condition assessment tools and related technology, which has led to the creation of a large gap between the required level of maintenance and the actual level of maintenance; this gap is referred to as the "maintenance debt". Extra efforts are

		Consequence						
		Insignificant	Minor	Moderate	High			
		0-0.5	0.5-2	2-3	3-4			
	4							
Frequency	(85-100)%							
of Failure	3							
	(60-85)%							
	2			Pipe Rupture				
	(20-60)%			Erosion &				
				Corrosion				
				Cracks				
	1			Deformation				
	(0-20)%							

Figure 23. Risk level for identified pipeline failure modes at pipeline-railway crossings.

required to close this gap and reach the state where the maintenance required for pipeline networks coincides with the actual status of pipeline maintenance. In addition, the utilisation of digitalisation and artificial intelligence (AI) techniques can convert the current maintenance engineering for pipelines and railway infrastructure into smart infrastructure maintenance. The present authors believe that the maintenance debt can be reduced through smart infrastructure maintenance via the installation of sensors for the collection and analysis of new datasets for the condition health monitoring of buried pipelines. Smart infrastructure maintenance will enable pipeline maintenance to be more efficient and to be kept in alignment with current and future maintenance technology.

The present fresh water networks, sewage networks and culvert installations are ageing, and estimations of their remaining useful life can be performed based on their age and material properties. Estimation of the remaining life of older pipelines requires the availability of different data, for instance installation dates, the maintenance history, the costs of inspection and condition assessment, inspection records, etc. At present, work is in progress to collect such data from different stakeholders to estimate the remaining life of pipelines at pipeline-railway crossings.

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References

Abspoel, L., Courage, W., Dabekaussen, W., de Bruijn, R., Kruse, H., Wiersma, A. P., Hijma, M. P., van den Heuvel, F., & van den Broeck, W. (2018). Risk-based asset management: Automated structural reliability assessment of geographically distributed pipeline networks for gas and water in the Netherlands. *Structure and* Infrastructure Engineering, 14(7), 928-940. doi:10.1080/15732479. 2018.1437641

- Alzghoul, A., Backe, B., Löfstrand, M., Byström, A., & Liljedahl, B. (2014). Comparing a knowledge-based and a data-driven method in querying data streams for system fault detection: A hydraulic drive system application. *Computers in Industry*, 65(8), 1126–1135. doi:10. 1016/j.compind.2014.06.003
- Andersson, L., Bohman, A., L., Van Well, A., Jonsson, Persson och, G., & Farelius, J. (2015). Underlag till kontrollstation 2015 för anpassning till ett förändrat klimat. Norrköping, Sverige: SMHI.
- Andersson, L., Sjörs, Å. B., & Jonelind, C. (2006). Vattenledningar och vattenläckor Variationen på dricksvattnets temperatur och dess betydelse för antalet vattenläckor (2010-11). Retrieved from http://www. svensktvatten.se/: http://vav.griffel.net/filer/VA-Forsk_2006-06.pdf
- Barabadi, A., Garmabaki, A., & Zaki, R. (2016). Designing for performability: An icing risk index for Arctic offshore. Cold Regions Science and Technology, 124, 77–86. doi:10.1016/j.coldregions.2015.12.013
- Bedford, T., & Cooke, R. (2001). Probabilistic risk analysis: Foundations and methods (2nd ed.). Cambridge, UK: Cambridge University.
- Ben-Daya, M., Kumar, U., & Murthy, D. P. (2016). Introduction to maintenance engineering: modelling, optimization and management. Singapore: John Wiley & Sons.
- Bokrantz, J. (2017). On the Transformation of Maintenance Organisations in Digitalised Manufacturing. (Licentiate of Engineering thesis), Chalmers University of Technology, Gothenburg.
- Cooke, R. M., & Shrader-Frechette, K. (1991). *Experts in uncertainty: Opinion and subjective probability in science*. New York: Oxford University Press.
- Dai, X., & Gao, Z. (2013). From model, signal to knowledge: A datadriven perspective of fault detection and diagnosis. *IEEE Transactions on Industrial Informatics*, 9(4), 2226–2238. doi:10.1109/ TII.2013.2243743
- Environmental-Protection-Department (2011). *Hazard Assessment -Environmental Protection Department*. Retrieved from Governoment of Hong Kong: http://www.epd.gov.hk/eia/register/report/eiareport/ eia ... /11.pdf
- Garambaki, A. H. S., Thaduri, A., Seneviratne, A., & Kumar, U. (2016). Opportunistic inspection planning for railway emaintenance. *IFAC-PapersOnLine*, 49(28), 197–202. doi:10.1016/j.ifacol.2016.11. 034
- Garmabaki, A. H. S., Ahmadi, A., Mahmood, Y. A., & Barabadi, A. (2016). Reliability modelling of multiple repairable units. *Quality* and Reliability Engineering International, 32(7), 2329–2343. doi:10. 1002/qre.1938
- Gould, S., Boulaire, F., Marlow, D., & Kodikara, J. (2009). Understanding how the Australian climate can affect pipe failure.
- Habibian, A. (1994). Effect of temperature changes on water-main breaks. *Journal of transportation Engineering*, 120(2), 312–321. doi: 10.1061/(ASCE)0733-947X(1994)120:2(312)
- Hay, S. (2014). A comparative study of trenchless technologies versus traditional open trenching for the replacement of ageing potable water pipelines.
- Hess, J. (2015). Assessing the condition and consequence of failure of pipes crossing major transportation corridors (pp. 1750–1761).
 Pipelines Conference 2015, August 23–26, 2015 | Baltimore, Maryland, USA.
- Hu, Y., Yang, W., Macey, C., Moncrieff, M., & Agha, A. (2016). Managing the risk of critical water trunk mains: A municipal perspective (pp. 460–470). Pipelines 2016.
- INFRALERT-H2020 (2015). Linear infrastructure efficiency improvement by automated learning and optimised predictive maintenance techniques. Retrieved from https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-transport/infrastructure/infralert
- InfraSweden2030. (2016). The strategic innovation programme InfraSweden2030. Retrieved from https://www.vinnova.se/en/e/strategiska-innovationsprogrammet-infrasweden2030/
- Kim, M. K., Won, J. H., Cho, S. H., & Park, M. (2013). Integrated assessment for route selection of river-crossing pipeline using structural and hydraulic approach. *Structure and Infrastructure Engineering*, 9(9), 860–876.

- Lee, A., Kleiner, Y., Rajani, B., Wang, L., & Condit, W. (2017). Condition assessment technologies for water transmission and sewage conveyance systems. Retrieved from Metro Vancouver's water: https://sustain.ubc.ca/sites/sustain.ubc.ca/files/Sustainability%20Scholars/ 2017_Sustainability_Scholars/Final_Reports/Condition%20Assessment% 20Technologies%20for%20Water%20Transmission%20and%20Sewage% 20Conveyance%20Systems_Lee_%202017%20SS.pdf
- Levlin, E. (2004). Water and Waste Pipes. Water Resources Engineering-Royal Institute of Technology.
- Lines, I. (1998). The Implications of Major Hazard Sites in Close Proximity to Major Transport Routes (1368-6828).
- Liu, Z., & Kleiner, Y. (2013). State of the art review of inspection technologies for condition assessment of water pipes. *Measurement*, 46(1), 1–15. doi:10.1016/j.measurement.2012.05.032
- Malm, A., Horstmark, A., Larsson, G., Uusijärvi, J., Meyer, A., & Jansson, E. (2011). Rörmaterial i Svenska VA-Ledningar-Egenskaper och Livslängd.
- Meyer, M., & Booker, J. (1991). Eliciting and analyzing expert judgement: A practical tour. London: Academic Press.
- Misiūnas, D. (2005). Failure monitoring and asset condition assessment in water supply systems. (Doctoral Thesis), Vilniaus Gedimino technikos universitetas, Lund University. (91-88934-40-3)
- Morris, R. (1967). Principal causes and remedies of water main breaks. Journal – American Water Works Association, 59(7), 782–798. doi: 10.1002/j.1551-8833.1967.tb03414.x
- Muhlbauer, W. K. (2004). Pipeline risk management manual: Ideas, techniques, and resources. USA: Elsevier.
- Naseri, M., & Barabady, J. (2015). System-reliability analysis by use of gaussian fuzzy fault tree: Application in arctic oil and gas facilities. *Oil and Gas Facilities*, 4(03), 085–096. doi:10.2118/170826-PA
- Naseri, M., & Barabady, J. (2016). An expert-based approach to production performance analysis of oil and gas facilities considering time-independent Arctic operating conditions. *International Journal* of System Assurance Engineering and Management, 7(1), 99–113. doi:10.1007/s13198-015-0380-4
- Naseri, M., & Barabady, J. (2016). An expert-based model for reliability analysis of Arctic oil and gas processing facilities. *Journal of*

Offshore Mechanics and Arctic Engineering, 138(5), 051602. doi:10. 1115/1.4033932

- Otway, H., & Winterfeldt, D. (1992). Expert judgment in risk analysis and management: process, context, and pitfalls. *Risk Analysis : An Official Publication of the Society for Risk Analysis*, 12(1), 83–93. doi:10.1111/j.1539-6924.1992.tb01310.x
- Rajeev, P., & Kodikara, J. (2011). Numerical analysis of an experimental pipe buried in swelling soil. *Computers and Geotechnics*, 38(7), 897–904. doi:10.1016/j.compgeo.2011.06.005
- Røstum, J. (2000). Statistical modelling of pipe failures in water networks. PhD Thesis. University of Science and Technology, Norway.
- Stamatis, D. H. (2003). Failure mode and effect analysis: FMEA from theory to execution. ASQ Quality press.
- Standard-BVS-585.20 (2005, 09-19) Krav pa Infodring med Flexibelt Foder i Trumma (pp. 11): BANVERKET.
- Sundahl, A. C. (1996). Diagnos av Vattenledningars Kondition. Lund: Institutionen för Teknisk Vattenresurslära. Lunds Tekniska Högskola. Lunds Universitet.
- Taylor, J. R. (2003). Risk analysis for process plant, pipelines and transport. London, UK: E & FN SPON, an imprint of Chapman & Hall.
- Thaduri, A., Galar, D., & Kumar, U. (2015). Railway assets: A potential domain for big data analytics. *Proceedia Computer Science*, 53, 457–467. doi:10.1016/j.procs.2015.07.323
- Thomson, J., Morrison, R. S., Sangster, T., & Hayward, P. (2010). Inspection Guidelines for Wastewater Force Mains. Water Environment Research Foundation.
- Transport, E. S. G. F. R. (2015). Multi-annual action plan: European Union. Belgium: Brussels.
- Wicklén, J. (2016). 200 meter långt slukhål svalde bilar. SVT Nyheter.
- Yazdekhasti, S., Piratla, K. R., Atamturktur, S., & Khan, A. A. (2017). Novel vibration-based technique for detecting water pipeline leakage. *Structure and Infrastructure Engineering*, 13(6), 731–742. doi:10. 1080/15732479.2016.1188318
- Zio, E. (2013). The Monte Carlo simulation method for system reliability and risk analysis (pp. 7–17). London: Springer.