A survey on underground pipelines and railway infrastructure at cross-sections

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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 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 public due to safety, disruption of traffic, inconvenience to society, environmental impacts and shortage of resources. Therefore, continuous and accurate condition assessment is critical for the effective management and maintenance of pipeline networks within transportation infrastructure. The aim of this study is to identify failure modes and consequences related to the crossing of pipelines in railway corridors. Expert opinion have been collected through two set of questionnaires which have been distributed to the 291 municipalities in the whole Sweden. The failure analysis revealed that pipe deformation has higher impact followed by pipe rupture at cross-section with railway infrastructure. For underground pipeline under railway infrastructure, aging and external load gets higher ranks among different potential failure causes to the pipeline.

Keywords: Underground Pipelines, Transportation Infrastructure, Railway, Maintenance, FMEA.

1. Introduction

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. The crossing of pipelines with traffic infrastructure is ongoing concern of transport infrastructure manager to mitigate disruption in railway and water utilities services. To this aim, there is need to consider the interrelation effect of different asset within transport infrastructure and reflect the effects to design, building and maintaining operation of both rail tracks and pipelines network (Ben-Daya, Kumar, & Murthy, 2016; Thomson, Morrison, Sangster, & Hayward, 2010).

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. For most pipelines which are buried underground, little data is available about their failure modes (Rajeev, Kodikara, Robert, Zeman, & Rajani, 2014) 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.

Railways are often entering the city centers and divide urban area into several sections. Therefore, urban infrastructure e.g. water, sewage, stormwater, and cables needs to cross the railways to connect the facilities. With increased urbanization and densification of cities, there is need to increase the capacity of the current utilities under the old railway infrastructure. In addition, such forces leads to increase the demand for installation of new railway infrastructure in urban area.

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 (Shift2Rail Joint-Undertaking, 2015) (INFRALERT-H2020, 2015) for the next 20–30 years. Besides, aging of 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 (INFRALERT-H2020, 2015).

Furthermore, Ciscar et al. (2014); (Nemry & Demirel, 2012) concludes that, more frequent extreme precipitations (and river floods and

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pluvial floods) as projected in different regions in Europe could represent an extra cost for road transport infrastructures (50-192 million €/year for the A1B scenarios, period 2040-2100). Flooding risk will rise with the likelihood of excess precipitation: surface water flooding as a result of direct accumulation, riverine/fluvial flooding as a result of excess runoff and river bank bursts, and groundwater flooding as a result of rises in groundwater levels, depending on diverse geology factors, land use, drainage condition and succession of weather events (Andersson et al., 2015; Eklund et al., 2015; Marteaux, 2016; J. Wicklén, 2016). 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, Marlow, & Kodikara, 2009).

Furthermore, due to urbanization changes there will be a higher demand for railway in terms of frequency and axle load (for freight transportation) for instance, LKAB is increasing the axle load from 30 to 32.5 (tonnes) and will increase further in near future to above 40 tonnes. This paper addresses the failure modes and failure causes and related challenges. This feature can provide comprehensive information for design and maintenance of pipeline and railway infrastructure to have robust pipeline network under railway infrastructure. The paper constitutes a comprehensive survey which have been distributed to all municipalities in the Sweden to address the above aims.

This paper is structured as follows. Section 2 refers to problem definition and methodology. Section 3 presents the analyses of questionnaires and interview study. Finally, Section 4 provides a conclusion.

2. Research Methodology

2.1. *Problem Description*

Society's new demand and climate change are the main motivation to study the health of pipeline and related failure modes and consequences which had been installed under railway corridor. Accordingly, risk analysis have been performed to reduce the potential failures in the future transport system (Environmental-Protection-Department, 2011; Moore, 2015; Johan Wicklén, 2016).

The details of the problem description are as follows:

- Increased dynamic load affects existing pipelines under railway: Swedish transport agency has increased the axial load from 30 to 32.5 tonnes in iron ore line, which may affect old piping designed for a lower axial load.
- Railways act as Dams: due to climate changes it is expected to have more intensive rainning and in several areas railway construction acts as water dams in city zones. In such cases, it is difficult to build drainage and other piping across the railway without traffic disruption.
- New pipes vs old rail infrastructure: Installation of new piping across the railway or modification of the existing piping
- Failures prior maintenance schedules: Due to the cross-correlation effects, both assets can fail prior to the scheduled.

This study aims to identify the bottlenecks link to installation, renovation, and repair of the pipeline under railway corridor.

2.2. *Prop*osed research methodology

Since pipeline degradation rate varies according to environmental impact, it is important to consider these effects on the pipeline degradation process. As can be seen in the "impact on infrastructure" block in Figure 1, different factors such as traffic, weather, etc. are considered as inputs to the condition assessment block. Expert knowledge-based approach or statistical-based modelling 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.

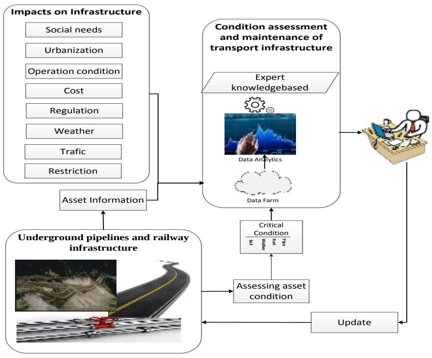

Figure 1: Interaction of pipeline with transport infrastructure and decision process

2.3. *Data Collection: Questionnaires, Interview, and Failure Database*

In this research, *questionnaires, interview, and historical failure database* have been explored for data collection. 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. 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 the incomplete knowledge. 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 questionnaires have been responded by experts at the different hierarchy of VA (Water and wastewater, “Vatten och Avlopp”) section which are given in the Table 1.

Table 1: Participation to the questionnaires

Participation Type	First questionnaire	Second questionnaire	Interview
VA Head	41	9	-
VA Project Engineer	24	6	4
Municipal VA Manager	25	7	4
Operator/ Operation and Maintenance + Other	10	3	2
Sum	100	25	10

First questionnaire has been distributed to 291 municipalities in Sweden and two general questions asked about the possible experience of the failure of the pipeline within railway and road infrastructure. 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 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. 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 (Meyer & Booker, 1991).

Furthermore, interviews study have been carried out with infrastructure managers to obtain qualitative data to analyze and classify failure modes and related consequences for risk assessments related to the rail-pipe-soil interaction.

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 Malmo as depicted in Figure 2 for the years 2001 to 2017. The records from Ofelia database have been used as support for questionnaires and interview studies.

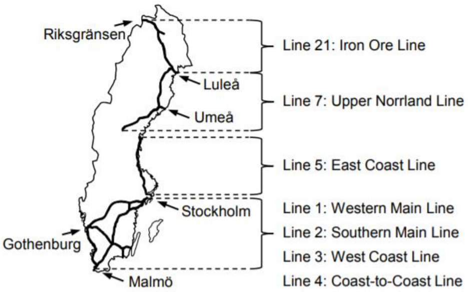

Figure 2: Swedish railway network

3. Analyses of questionnaires and interview study

3.1. First questionnaire outcome: First questionnaire has been distributed to 291 municipalities and we have received 100 responses from VA experts and participation rate is around 35%. Form the responses, 63% report their experiences of pipe failure at cross-section with railway. The details description of the answers has been analyzed and categorized into six groups. The percentage of each group is calculated and presented in the pie form as given in Figure 3.

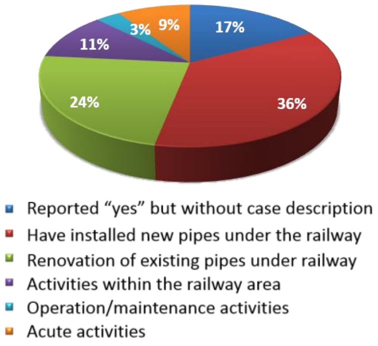

Figure 3: First questionnaire response for railway

3.2. Second questionnaire outcome: In this questionnaire, 8 question have been asked and FMEA analysis have been used. FMEA aims to provide feedback to the design phase for performance improvement of the system in terms of quality, reliability and availability (Ben-Daya et al., 2016; A. Garmabaki, Ahmadi, Block, Pham, & Kumar, 2016; A. H. S. Garmabaki, Seneviratne, Ahmadi, Barabadi, & Kumar, 2017). 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.

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?

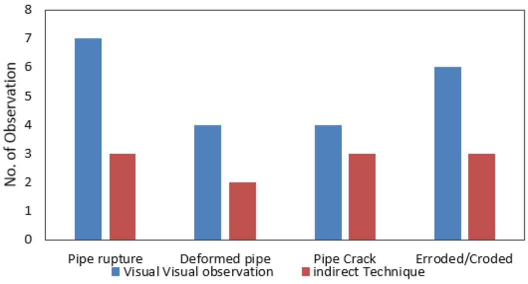

Figure 4: Type of failure detection method

Figure 4 shows that most of the faults are identified 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.

In addition, based on the literature (Misiūnas, 2005; Muhlbauer, 2004; Røstum, 2000) and interview with VA experts the following four different failure modes and resulting effects from each failure mode given in Table 2 have been selected to be asked from VA expert.

In the second question “What types of pipe failure mode have been noted on pipes below / near rail?” we aimed to verify above identified failure modes.

Table 2: Possible failure modes and failure 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

Figure 5 represent the percentage of failure modes. (It may note that some of the experts reported more than one failure mode)

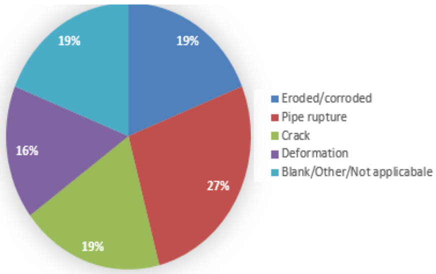

Figure 5: Percentage of failure modes

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 failure effect have been evaluated.

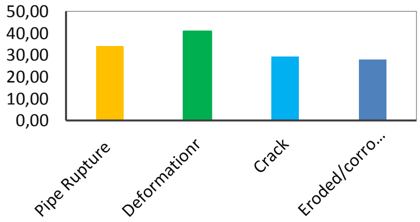

Figure 6: Impact level of identified failure modes

Result as given in Figure 6 reveal that Deformation and pipe rupture are the main failure mode and crack and erosion have almost same contribution for the failure at cross section. Furthermore, Figure 7 shows that limited sanitation capacity and flooding are two dominant effects resulting from failure occurrences.

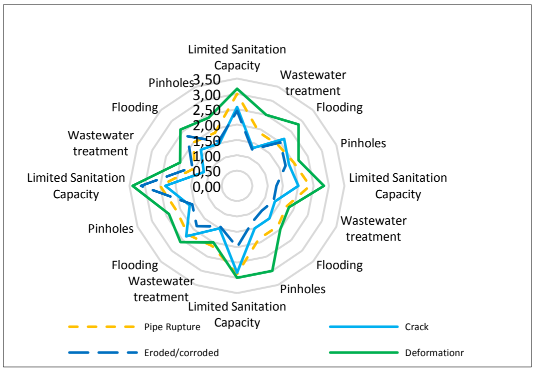

Figure 7: Correlation failure modes and failure effects

Several covariate that may affect the life pipeline, 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) have been studied in the literature. (Misiūnas, 2005; Røstum, 2000). In this question, the experts can select multiple factors as covariant that were the most important failure causes to the pipeline at the cross-section. Study revealed that aging, external load, erosion/corrosion, and reduced pipe function have been received higher impact compared to other causes on pipeline failures as depicted in Figure 8.

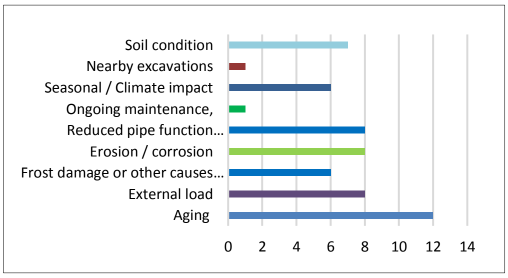

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Figure 8: Covariate effects to pipe failure at rail-cross

Furthermore, the possible consequences of failure occurrence have been asked by a question "what was the consequences of pipeline failure at the cross section with railway?".

The potential impacts that may have greater effect have been extracted from literature and verified with expert (during interview) when we were designing the question. The result as given in Figure 9 reveals that "Delivery disruption or pressure" gains higher impact followed by "Deterioration of road nearby to the pipeline failure".

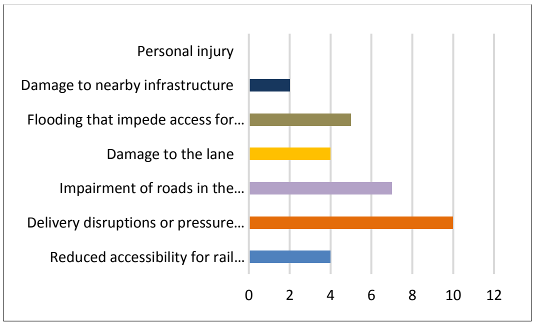

Figure 9: consequences of failure at the cross section

We have explored "greatest needs for installation of the new line under railway embankment" in the next question. In this question, five alternatives have been asked and the results have been presented in Figure 10.

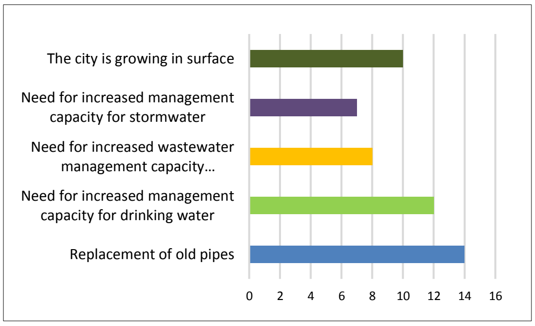

Figure 10: The need for installation of a new line under the railway

The result confirms our hypothesis regarding the replacement of the pipeline as the main demand for installation of a new pipeline under the railway. Also, the result shows that increasing the capacity due to urbanization issue take the second rank aiming for install or renewing pipes under railway.

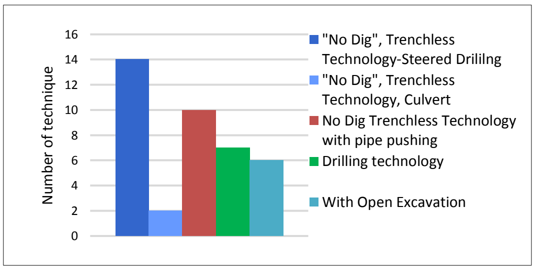

Figure 11: Technique used for installation of new pipe under the railway

Thereafter, we investigate the techniques that have been utilized for the installation of a new pipeline by asking "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 11.

3.3. Interviews studies outcome:

Recent findings based on the two questionaries' '2017/18 at Luleå University of technology 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.

3.4. Risk priority number (RPN) estimation

Severity, occurrence, and detectability are the key parameters in the evaluation of Risk Priority Number (RPN). It serves in fixing the priority for the process/item to focus on maintenance decision making.

For scaling detectability parameter five scaled system has been used and the following is the summary of scaling based on each failure mode.

- 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.

Table 3: 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. 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 the PipeXrail 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.

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.

Furthermore, data availability has been raised in 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 modelling is challenging. Thus acquisition and documenting this information is essential should be initiated from the planning phase.

Small data and incomplete failure data are the main two obstacles for reliability analysis of pipeline network in general terms. Røstum (2000) 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.

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.

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