Reykjavik's Sæbraut Road Tunnel: Balancing Development and Safety

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ABSTRACT

The Sæbraut Road Tunnel project in Reykjavik enhances connectivity in the Vogar neighbourhood, tackling a unique opportunity for urban development and the transport of dangerous goods. This project adds to existing knowledge due to the project's complex infrastructure, diverse risk profile, and multiple competing objectives from various stakeholders. It aims to achieve sustainable urban development while addressing the challenges of transporting dangerous goods, with few or no alternatives available for reaching key destinations not accessible by sea. Additionally, the lack of detailed regulations both nationally and internationally for such an infrastructure necessitates innovative solutions, as the traditional Icelandic approach of adopting infrastructure design regulations from other Nordic countries is no longer viable. This paper presents and discusses the comprehensive risk analysis conducted to address some of these challenges and ensure a safe and sustainable built environment in the area, focusing on the evaluated challenges, opportunities, and solutions. The paper will present how these issues were tackled in an Icelandic context, with key measures like QRA, sprinklers, buffer zones, and transport restrictions reducing risks, aligning with the ALARP principle. The project illustrates effective risk management for resilient urban development.

KEYWORDS: tunnel, decking, capping, overbuilding, fire, safety, risk analysis, life safety, dangerous goods, sprinkler.

INTRODUCTION

Background

The initiative to construct city tunnels in Reykjavík presents several challenges that need careful consideration. While Iceland has existing tunnels, the city has not previously implemented this type of infrastructure. One major challenge is Reykjavík's low population and population density, which can complicate the need for such extensive projects. The city's harsh weather conditions also demand designs that prioritize safety and durability to withstand extreme elements. Geotechnical challenges also play a crucial role, as the local geology may impact construction techniques and overall feasibility. Moreover, the current infrastructure has limited capacity for emergency response, making it essential that new tunnels are designed to enhance access for emergency services.

There is a growing determination within Reykjavík to shift away from a long-standing tradition of prioritizing car usage towards developing more environmentally sustainable transportation options. This project is part of a broader vision to establish a bus metro system to reduce reliance on cars and promote public transport. Lastly, by integrating city tunnels into the urban landscape, Reykjavík aims to increase population density while simultaneously creating more green spaces, thereby enhancing the quality of life for residents and improving the overall urban environment. These challenges and opportunities must be navigated strategically to ensure the success of the city tunnel project.

Transitioning from open roads in developed neighbourhoods to tunnels, along with the potential for sustainable urban development above, can significantly enhance traffic flow, create more green spaces, increase population density, and support greater sustainability in public transportation operations. This project established a foundation for city-tunnel design, essential for guiding future development and decision-making. Supporting future development on the road to better urban development.

Sæbraut Road Tunnel

The Sæbraut Road Tunnel project in Reykjavik is a significant urban development initiative by the Icelandic Road and Coastal Administration (Vegagerðin) and the Reykjavík city (Reykjavíkurborg). It aims to enhance connectivity between the older and newer sections of the Vogar neighbourhood (see Figure 1). This undertaking is characterized by its complex infrastructure and diverse risk profile, addressing multiple competing objectives from various stakeholders. A significant aim is to achieve sustainable urban development while managing the unique challenges posed by the transportation of dangerous goods, given the limited alternatives for accessing key destinations. ÖRUGG Consulting Engineers was responsible for fire safety design, which included a risk analysis for the superstructure carried out with Brandskyddslaget AB. The main design contractor is Verkís Engineering.

Figure 1 Tunnel entrance, seen from south with proposed overbuild example/Verkís.

Regulations and risk

There are no city tunnels nor covering and decking in Iceland, making this project unique in nature. This also poses a challenge for both designers, clients, authorities and other stakeholders. At the same time, it can create an opportunity for improved traffic flow, lowering accidents regarding pedestrians, increasing green spaces, and reducing pollution related to sound and vehicle exhaust, ultimately enhancing the overall quality of life for residents and dwellers.

Typically, Iceland has relied on infrastructure design regulations from other Nordic countries, but the lack of detailed national and international regulations for this type of infrastructure has necessitated innovative approaches. The project involves integrating housing, offices, retail, and public transport around and above the tunnel, fostering a vibrant urban community and improving accessibility within Reykjavik. This development is a collaboration between Vegagerðin (the Icelandic Road Administration) and the City of Reykjavik.

Transport systems are essential in industrial societies and urban, economic, and social development. Utilizing underground space for transport has been a continuing trend across the globe during past decades [1]. Underground transport systems, such as city tunnels, have been chosen by cities as potential solutions for solving urbanization problems, such as noise and air pollution and traffic congestion, allowing cities with land shortages to expand [1], [2]. This suggests that underground infrastructure, such as city tunnels contributes to sustainable urban development [3]. However, city tunnels are not without risks. Palm et al. [4] mention that underground structures represent a complex environment with other risks than everyday enclosure fires. As J. Gehandler mentions in his thesis, tunnel fire safety is largely a low probability-high consequence risk issue [5].

Projects involving the covering, decking, or overbuilding of transportation routes are becoming increasingly common, often involving underpasses beneath populated areas where the transportation of hazardous materials takes place. Recent studies show that there is a lack of research in this area, hence significant uncertainty remains regarding how to manage the risks associated with such projects effectively [6].

Guidelines exist internationally for assessing and evaluating risk in spatial planning around tunnels or overbuild (see, e.g. Swedish Road Administration, Trafikverket). However, there are no established regulations or guidelines specifically for land use directly on top of or close to an overbuild. The key distinction lies in population density and potential catastrophic consequences. The impact outside a road or rail tunnel is generally limited due to lower population density, whereas overbuilds are typically located in areas with higher population density. Consequently, the potential damage outside and below the overbuild significantly contributes to the overall risk.

The risk acceptance guidelines for decking, developed by the City of Stockholm [7], require an advanced analysis of potential barriers. This involves identifying and evaluating measures that can reduce either the likelihood or the consequences of catastrophic events. A common approach involves extending the criteria from Det Norske Veritas (DNV) and applying the same valuation principles for scenarios involving fewer than 1,000 fatalities. However, this approach does not align with the original intent behind the criteria [8]. The absence of established guidelines and practices for conducting risk assessments within the ALARP framework, as well as for addressing catastrophic scenarios, complicates the challenges associated with overbuild projects. The capacity of the emergency servises in the Reykjavik capital area is very limited which affects the „catastrophic“ level. Due to this lack of specific guidance or accepted standards, project-specific adaptations are currently required.

Safety for road tunnel users

A considerable amount of literature has been published about city tunnels. Previous studies show that the accident rate in road tunnels (excluding portals) is lower than on open roads, but the consequences tend to be more severe [9], [10]. By allowing traffic to flow through tunnels instead of an open road, the negative effect on drivers of sudden weather changes is lowered, distances between pedestrians and vehicles are lengthened, and surveillance cameras can be more efficient due to more constant sight without the effect of rain, sun, snow, and etcetera. A study from Israel shows that redirecting traffic from open roads to tunnels saves travel time, reduces air pollution, and decreases traffic noise in the environment and its surroundings [11], commonly appreciated by city dwellers.

Purpose and objective

The purpose of the project was to assess the risk of overbuild and compare it to the international context. The objective is to propose risk measures that meet these requirements and identify potential barriers that need to be included in further design. The lack of acceptable Icelandic risk measures requires an extensive summarization of the proposed project.

Delimitations

In this paper, the project-specific tunnels are "dug and covered twin tube tunnels" and, therefore, possibly not representable for tunnels buried deeper in the ground or with two-way traffic in the same tube regarding consequences from larger explosions. The transport of dangerous goods ratio related to daily traffic is not known, but it is likely to be higher than the average ratio due to the close proximity to the harbour and the largest fossil fuel storage/depot in Iceland.

METHOD

The risk analysis utilized a Quantitative Risk Analysis (QRA) approach to evaluate various scenarios and their potential impacts. The QRA involved calculating the societal and individual risk levels, considering factors such as traffic volumes, types of dangerous goods transported, and the tunnel's structural integrity, along with other safety measures which can impact the risk for people on top of, and alongside the tunnel. The analysis only covers sudden and unexpected accidents with acute consequences for the life and health of people staying within the studied area. In the analysis, the long-term effects of substances hazardous to health, noise, or environmentally hazardous emissions have not been taken into account. Nor are risks for operational disruptions studied. Natural disasters (for example, flooding), suicide or antagonistic threats have not been considered. The analysis does not cover the safety of road users within the tunnel, which is covered by the analysis "Sæbraut Road Tunnel – Risk Analysis" [12]. The analysis only includes consequences in the form of the number of fatalities. The analysis is focused solely on studying fatalities, as there are no evaluation criteria available for assessing injuries. The risk analysis is limited to the operational stage of the tunnel and urban development, i.e. the risk impact when the facility is completed.

RISK ASSESSMENT

General Overview

The risk analysis serves as a foundation for the municipality's development plan, evaluating urban development's suitability concerning human health and safety. It provides recommendations for managing identified risks in line with current legislation based on the proposed land use in the master plan. Building placement and design is guided by initial concepts from Vegagerðin and Veitur [13].

Risk Identification

Risk identification begins with an inventory of potential hazards within the studied area, focusing specifically on sources that could lead to sudden and significant accidents with extensive consequences.

Dangerous goods are categorized under the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) into nine classes, each representing different chemical properties and associated risks. Key challenges include managing high population density and the risks posed by transporting hazardous materials such as ADR Class 1 (explosives, which may cause mass explosions, fragmentation, or intense fires) and ADR Class 5 (oxidizing substances and organic peroxides, which can intensify or sustain fires). These materials increase the potential for severe accidents involving explosions, toxic gas releases, or uncontrolled fires within the tunnel.

Infrastructure limitations and unique tunnel geometry further complicate traditional safety concepts, requiring tailored evacuation and emergency response adaptations. Addressing these challenges involves comprehensive risk management strategies to ensure a resilient and safe built environment.

Initial Qualitative Risk Analysis

Following the risk inventory, a qualitative assessment determines the consequences and likelihood of identified risks affecting individuals in the area. Risks associated with fatal injuries are prioritized for further analysis, while those with low consequences and probabilities are typically excluded from deeper assessment.

Quantitative Risk Analysis (QRA)

For risks deemed impactful, a quantitative risk analysis (QRA) is conducted. This involves calculating societal and individual risk levels, incorporating factors such as traffic volumes, tunnel design, and proximity to hazardous goods transports. Societal risk measures the risk a source poses to the surrounding environment, reflecting the expected number of fatalities per year based on frequency and consequences. The assessment considers planned building structures and their implications on regional safety.

Individual risk evaluates the likelihood of fatal injury for a specific person in proximity to a risk source, presented as location-specific profiles. This analysis accounts for the height of structures above the tunnel, differing from traditional distance-dependent risk calculations.

Risk criteria ALARP (As Low As Reasonably Practicable)
To evaluate the acceptability of risk levels, they must be compared against established acceptance criteria, which are not clearly defined by legislation. It is recommended to use the ALARP criterion, which establishes lower and upper limits for acceptable risks. Risks falling below the lower limit are deemed acceptable, while those above the upper limit are classified as unacceptable and require mitigation measures. Risks between these limits require cost-efficiency assessments of additional safety measures to be considered tolerable.

No specific criteria for acceptable risks related to the transport of dangerous goods exist in Iceland, although various countries have proposed such measures, resulting in considerable disparities. Specific acceptance criteria examples shown in Figure 2 are from DNV report (Sweden) [14], the Netherlands [15], and the United Kingdom [16] and highlight this variability.

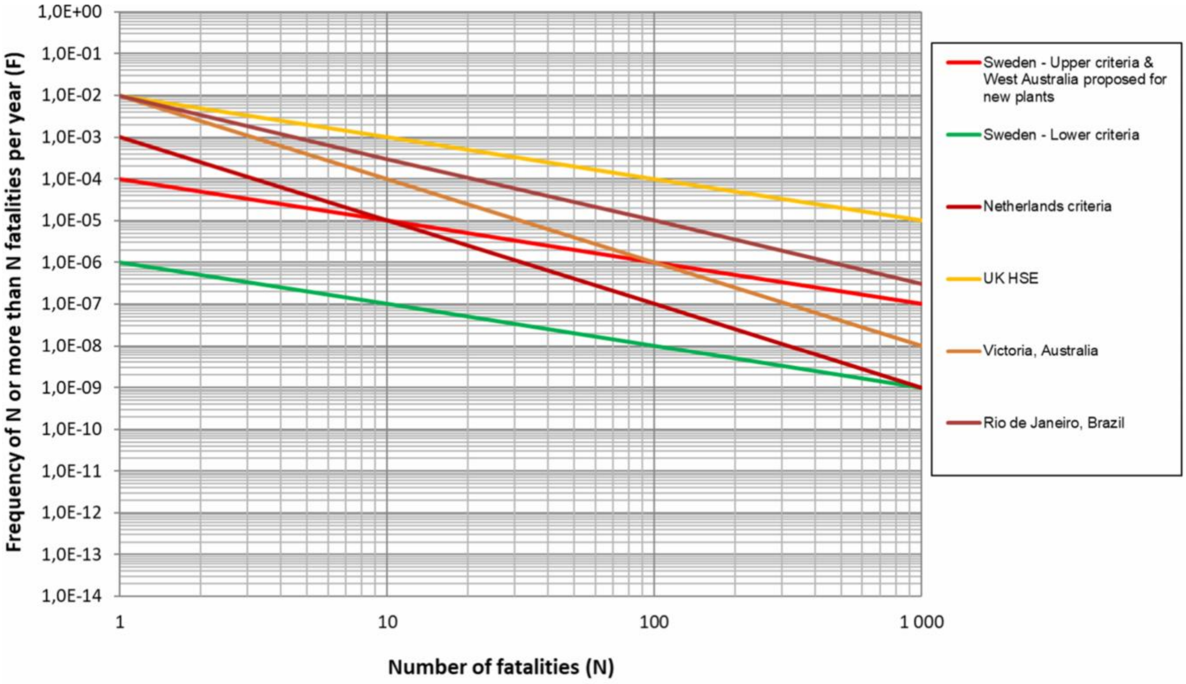

Figure 2 Acceptance criteria in different countries for societal risk regarding third party (the criteria is based on a 1 km road/railway section.

In this project, societal risk assessments will adopt the recommended acceptance criteria from Sweden for conservative evaluations of limited consequences (lesssp than 10 deaths). In contrast, larger consequences necessitate using the ALARP framework for enhanced risk evaluation without exceeding higher risk levels observed in other countries. Furthermore, there are currently no universally accepted criteria for disaster scenarios exceeding 1,000 fatalities. While society typically views such catastrophic risks as unacceptable, the methodologies for assessing these risks remain underdeveloped. Given the potential for large fatality numbers, especially in densely populated areas like around the Sæbraut Road Tunnel, special consideration is needed for scenarios involving dangerous goods.

Existing societal risk criteria often apply an upper limit of 1,000 casualties, beyond which it remains unclear if risk acceptance can be appropriately extrapolated [8]. Therefore, decision-making should prioritize risk-informed strategies over rigid risk-based approaches. Lacking national guidelines and international consensus, there is a critical need to establish project-specific acceptance criteria. Initial suggestions for assessing catastrophic risk scenarios may be proposed, yet any evidence of potential large-scale incidents necessitates specialized analysis to ascertain risk tolerance.

Sensitivity analysis
In risk assessments, various input data such as design specifications, traffic flows, accident statistics, anticipated population levels, and the behavior of different constructions are essential. Given the infrequent occurrence of the studied accident types, many assumptions are necessary, often leading to limited knowledge of the event sequences and environmental impacts. Conservative estimates are employed to address uncertainties related to these assumptions, providing a safety margin in frequency and consequence calculations.

The calculated risk levels presented should not be interpreted as absolute but serve as guideline values that indicate the approximate risk in the area. To emphasize these uncertainties, a sensitivity analysis was conducted on the most critical input parameters affecting the societal risk level. The analysis aims to demonstrate the robustness of the methods used, revealing how variations in uncertain parameters influence risk levels. The sensitivity analysis encompasses multiple parameters. By adjusting these parameters, both upward and downward, the analysis assesses their impact on the societal risk level, which can inform risk assessments and decisions regarding mitigation measures.

RISK EXPOSURE TO SURROUNDINGS

Societal risk level
Figure 3 plots the societal risk level for third parties and for the planned development on top of, alongside, the tunnel and for surroundings. The societal risk level is plotted in total, both planned development and its surroundings and serves as a baseline for evaluating risk-reducing measures. The Figure shows the societal risk for the planned development in the year 2045 and acceptance with upper and lower criteria according to Sweden.

Figures 4 and 5 plot the societal risk for third parties as well as for planned development on top of and alongside the tunnel and for surroundings. Figure 4 evaluates the impact of a sprinkler system, reduced footprint of the built population, and 20m minimum distance to development. This combination reduces the risk significantly. Figure 5 adds restrictions for the transport of dangerous goods during rush hours, which in particular greatly affects the risk with catastrophic consequences.

The Figures illustrate how different types of buildings, land use and consequence-reducing barriers affect the total societal risk, which can be used in the continued discussion around potential safety-enhancing measures.

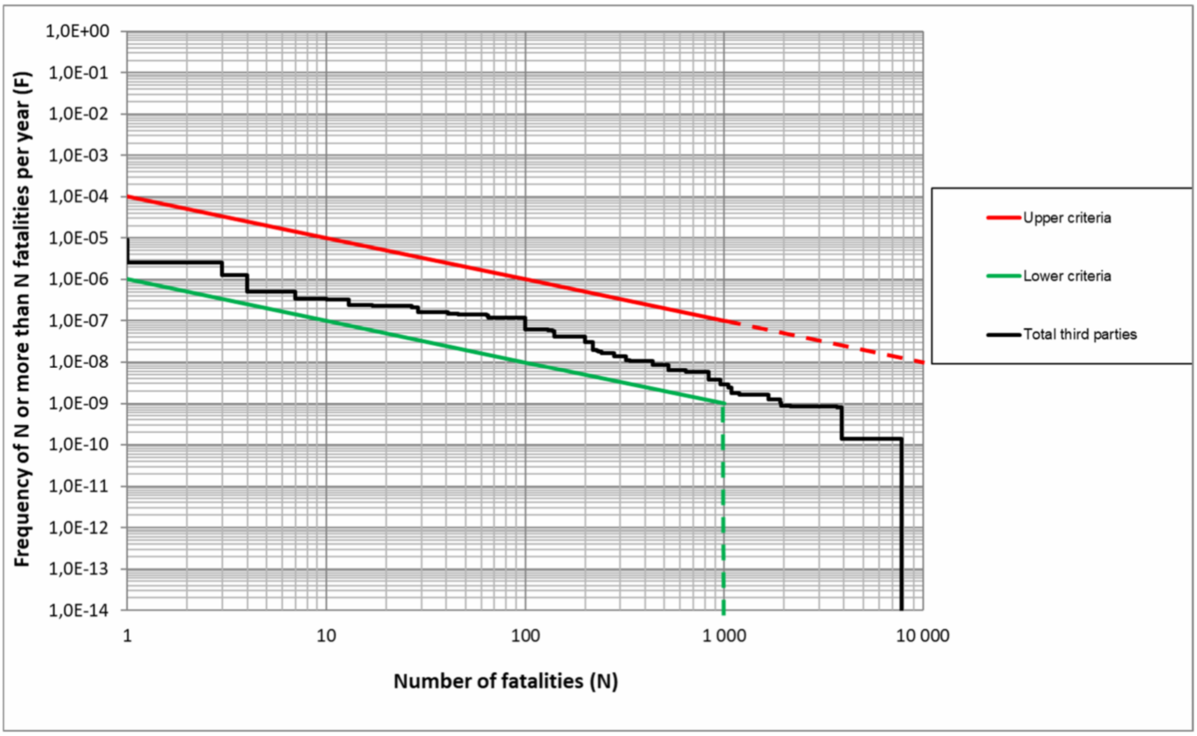

Figure 3 F/N curve that reports the societal risk level for third parties: total for third parties and for planned development on top of, alongside, the tunnel and for surroundings.

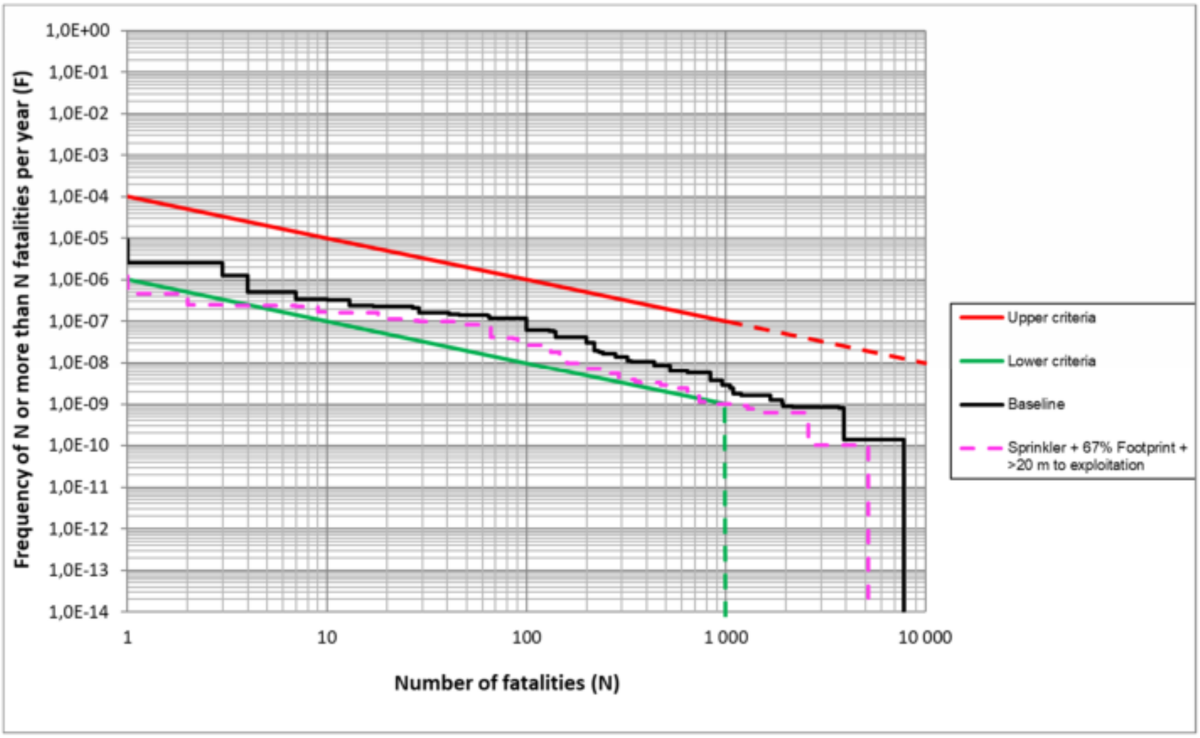

Figure 4 F/N curve that reports the societal risk level for third parties (planned development and surroundings) + Sprinklers, limited planned development 2/3 of the footprint and 20m safety distance within southern tunnel portal.

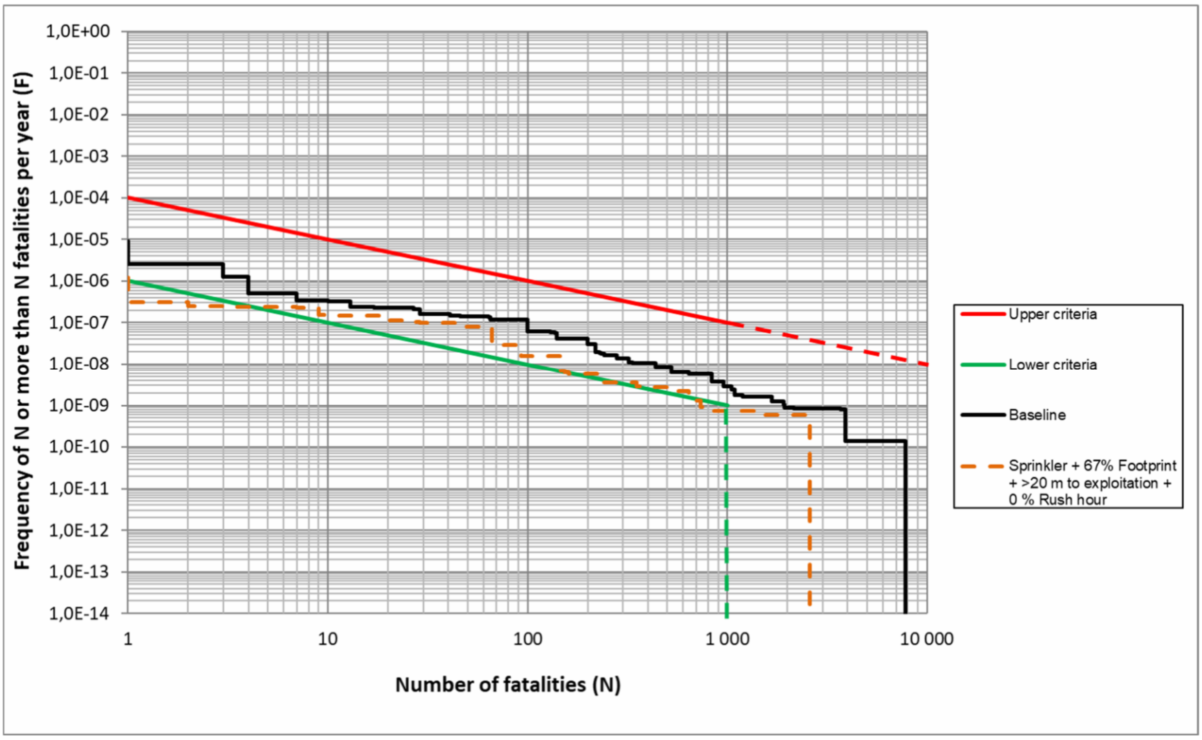

Figure 5 F/N curve that reports the societal risk level for third parties (planned development and surroundings) + Sprinklers, limit the planned development 2/3 of the footprint, 20m distance within southern tunnel portal and restriction regulation on dangerous goods during rush hour.

Individual risk

Figure 6 shows the individual risk level as a function of the distance from the roadside. The diagram shows the individual risk for traffic data in the year 2045. The diagram also plots acceptance criteria.

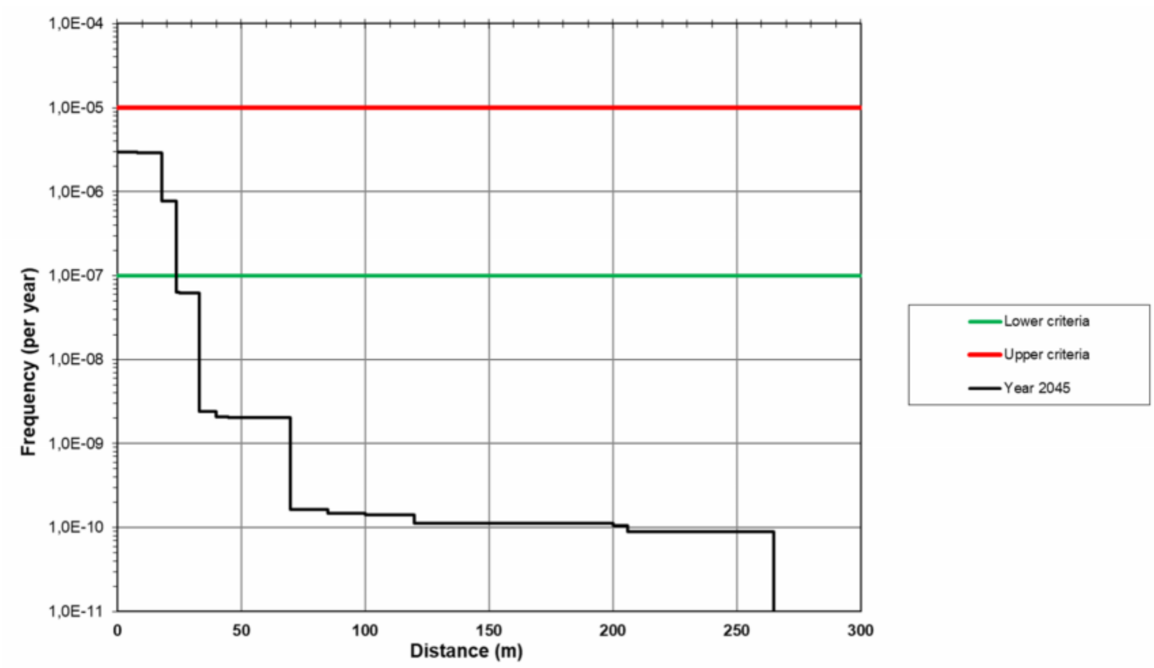

Figure 6 Individual risk profile as a function of distance to the roadside. Open road accident.

For areas on top of and alongside the Sæbraut Road Tunnel, the calculation of the individual risk will differ slightly. This is because the tunnel means that the individual risk level is dependent on the level in relation to the risk source rather than distance-dependent, as described above. For people on top of the tunnel, the individual risk is calculated by summing up the frequency of all scenarios that are expected to lead to fatalities on top of the tunnel.

By summing up the frequency of all the scenarios within the tunnel which are expected to have an impact on the societal risk on top of the tunnel, the total frequency can be calculated as 3.50 x 10-7 per year. This frequency is roughly assumed to contribute to the individual risk level within the planned development. You can call it a baseline of the individual risk on top of the tunnel. In addition, there are scenarios that also contribute to the individual risk on top of the tunnel when they occur in the open, mainly in connection with the tunnel portals. The contribution to the individual risk level on top of the tunnel from surface road scenarios is assumed based on the individual risk profile in Figure 6.

Figure 7 shows the individual risk level on top of the tunnel as a function of the distance from each tunnel portal. The diagram shows the individual risk for traffic data in the year 2045.

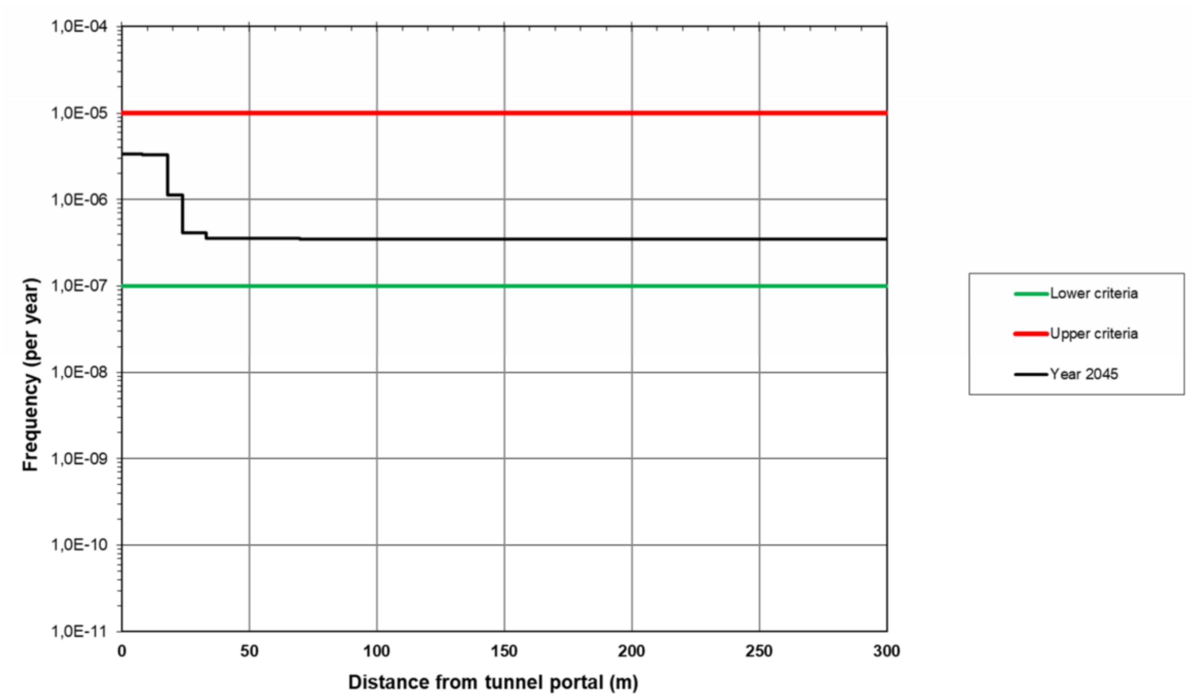

Figure 7 Individual risk profile as a function of distance to tunnel portal. Underground accident + open road accident.

Risk evaluation

The societal risk for planned development and its surroundings has been calculated. Based on the examples of acceptance criteria presented in Figure 2, accidents with dangerous goods are assessed to have a critical effect on the societal risk level within the area. Compared to acceptance criteria in Sweden the societal risk level is within ALARP, which means that cost-efficient safety measures need to be introduced. Within the consequence interval >1.000 deaths, the societal risk is at a level which means, according to the initial suggestion of the chosen acceptance criteria from Sweden, given in Figure 2, that a special analysis of scenarios and measures must be carried out to determine whether the level of risk can be tolerated or not.

The individual risk level for areas on top of the tunnel exceeds 10-7 per year but is less than 10-6 per year, except within approx. 25 meters from the tunnel portals where the individual risk level can exceed 10-6 per year. However, the individual risk level never exceeds 10-5. Along surface road sections, the individual risk level for areas alongside the tunnel is less than 10-7 per year beyond approx. 30 meters from the roadside. Beyond approx. 25 meters from the roadside, the individual risk level is less than 10-6 per year. The individual risk level never exceeds 10-5.

Based on the individual risk, the risk level is generally within ALARP of the chosen criteria, which means that cost-efficient safety measures or restrictions need to be introduced on top of the tunnel. The same applies to areas closer to 30 meters alongside the surface road, such as the ramps to/from nearby intersection.

Results of Sensitivity Analysis

The sensitivity analysis indicates that only a few parameters significantly affect the risk levels. Major contributors to the societal risk include scenarios involving explosions categorized as ADR Class 1 and ADR Class 5, while ADR Class 2 (For example. LPG, acetylene, chlorine, ammonia, nitrogen etc.) and ADR Class 3 (For example. Gasoline, diesel and fuel oils, solvents and industrial chemicals) scenarios have minimal impact. Notably, the calculations related to ADR Class 1 and ADR Class 5 entail the most assumptions and uncertainties due to the limited statistical data available for these incidents. Additionally, a critical factor not included in the quantitative sensitivity analyses is the planned development above and alongside the tunnel, which may include high-density housing, commercial facilities and transport systems. This development substantially influences societal risk. The consequence calculations rely on conservative assumptions regarding the footprint of this planned development. Therefore, incorporating more detailed information about the planned development will yield a more accurate assessment of the risk level, and this parameter should be considered in the analysis of safety measures.

MITIGATING RISK BARRIERS

The tunnel design is supposed to fulfil Icelandic requirements for new tunnel constructions and the Norwegian requirements for tunnels, N500:2022 [17]. In those requirements, only a few guidelines are provided about rescue services and how to ensure that they can fulfil their task in case of an emergency. The European Union regulations for tunnel structures, state, that safety measures should ensure that emergency services can act effectively [18], but without further guidelines.

Given the complex combinations of scenarios possible in road tunnel accidents, mitigating procedures can be very important. Explosions can have a devasting effect on the tunnel structure causing collapse or serious damage to the tunnel lining and technical equipment. Release of chemical substances might not only cause health hazards and fatilities within the tunnel, but also have a far reach effect on nearby businesses and residences. Large scale consequences can also cause a lack of faith in authorities and limit further development. One crucial aspect of minimizing the consequences of incidents in tunnels is enhancing the efficiency of emergency rescue operations. Early implementation of key measures during the design and planning phases of new tunnels can significantly influence this efficiency. For the fire brigade the key considerations include:

- Training for firefighters and tunnel control center operators to support fluent communications and detailed scene rapport, short responce time, accurate location of emergency and etc.
- The availability and strategic location of access and emergency egress points are critical for minimizing response time and improving firefighters safety. Proper placement can reduce required fire hose length and egress travel distances, while also decreasing the risk of access points being obstructed by a single hazard.
- Design of the smoke ventilation system to increase visability during firefighters egress as well as minimizing the affect of heat ratiation, conduction and convection from smoke layer.
- Availability of fixed firefighting systems/fire sprinklers witch to control and or suppress (reduce) fires.
- Design of the drainage system and holding tanks for combustible liquid to prevent downstream contamination, ignition in drainage, minimizing possible spillage and therefor possible poolfire.

By incorporating these measures, response times can improve, and the effectiveness of emergency services in managing tunnel incidents can be increased, ultimately reducing their impact [19]. Therefore, findings from a risk analysis can serve as valuable input for determining which measures will have the most significant impact on both the probability and consequences of incidents within tunnels. This analysis not only aids in assessing the likelihood of requiring emergency services but may also enhance the chances of executing a safer and more effective rescue operation.

The holistic approach in the mitigating phase involves the interwoven responses of tunnel operators and responders, including the information to and response of the tunnel users, proximate dwellers and buisnesses. At the design stage, it is paramount to include these factors as they may include both the technical design of tunnels and more general road and traffic management. However, from the risk assessment perspective, these barriers involve complex behavioural and technical factors that are difficult to assess quantitatively but involve an uncertainty that must be taken into consideration.

VULNERABILITY IN A SOCIETAL CONTEXT

When faced with a decision on whether or not to implement a protection measure to limit the risk of catastrophic failures, it is important to assess the vulnerability of the road system network in a larger context. By adding vulnerability, the traditional risk assessment framework is broadened in two key ways. First, it expands the focus to include areas with high consequences and low or uncertain (but non-zero) probabilities of occurrence. This shift acknowledges that accurately measuring the likelihood and impact (both human and economic) of many incidents is challenging. Furthermore, society often deems inevitable potential consequences unacceptable and worth mitigating, even when their probabilities are uncertain. Second, vulnerability analysis offers a structured approach to prioritizing and refining risk assessments.

The unavailability of key roads is poised to lead to unacceptable congestion for the road network [20]. The lack of measures and acceptable levels of service for the road system could lead to significant disruptions to traffic flow, increased travel times, and economic losses, highlighting the urgent need for strategic planning and investment in infrastructure resilience and alternative routes. Any accident affecting large and complex infrastructure, such as a tunnel, will have a long-term effect on the entire network since it might take several months or years until the network is put back in working conditions. Hence, it is of large importance to reduce the risks at these links or to increase the redundancy since the consequences of a failure of these links might be regarded as unacceptable.

CONCLUSION AND KEY FINDINGS

This risk analysis initially includes an inventory of possible risks. The inventory shows that only accidents with the transport of dangerous goods impact the risk level for planned development on top of and alongside the tunnel.

Key conclusions include:

- Buffer zones around tunnel portals are crucial in mitigating the impact of accidents on surrounding buildings and inhabitants.
- Limiting the footprint of the development and regulating land use can effectively manage population density and reduce potential casualties in the event of an accident.
- The installation of sprinklers and other fire suppression systems in the tunnel can significantly reduce the risk of vehicle fires escalating to dangerous goods incidents, enhancing the efficiency and safety of the fire brigade when approaching.
- The fire brigade access and response possibilities are important but are difficult to evaluate in quantitative assessment.
- Prohibiting the transport of dangerous goods can lower the probability of high-impact accidents, especially during rush hours.

The findings highlight the importance of a multi-faceted approach to urban development, incorporating safety measures and risk management strategies to create a resilient and sustainable built environment. The project demonstrates how quantitative risk analysis can guide decision-making and ensure that complex urban development initiatives prioritize public safety and well-being.

The initial risk analysis includes an inventory of potential risks, revealing that only accidents involving the transport of dangerous goods significantly impact the risk levels for the planned development atop and alongside the tunnel. Other substantial risk sources were not identified. The tunnel's construction reduces the risk impact on surrounding areas for most potential accidents compared to current open-air road conditions.

The quantitative risk analysis (QRA) indicates that the overall risk level aligns with the ALARP principle, suggesting that additional safety measures should be implemented if they are practical and economically feasible. However, the societal risk demonstrates a catastrophic potential, and even result in accidents with fatalities exceeding 1,000, while unlikely. The absence of national guidelines for third-party risk assessment and international consensus on acceptance criteria underscores the need for establishing project-specific criteria during the design process. This can start with developing a project-specific risk valuation proposal for stakeholder consultation.

The QRA identifies that extensive explosions involving ADR Class 1 and ADR Class 5 significantly elevate societal risk, primarily due to increased population density and the potential for large-scale impacts. While accidents with ADR Class 2 (gases) and ADR Class 3 (flammable liquids) may have devestating effect within the tunnel, the effect outside of the tunnel will be smaller, due to the distances between planned development and the southern tunnel portal. However, they still pose risks that warrant attention in further design.

Based on the QRA's findings regarding their risk-reducing effects, an initial inventory of possible risk mitigation measures and barriers has been made. It is important to note that these measures are preliminary and ultimately depend on project decision-making. Additionally, some conservative assumptions in the risk analysis can be refined through further customization, potentially resulting in a lower calculated risk.

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