Common Life Safety Targets in Traffic Tunnels

Bo Wahlström¹, Johan Lundin², Oskar Jansson³ & Erik Hällstorp²
¹Brandskyddslaget AB, ²WSP Sverige AB
³RiskTec Projektledning AB

ABSTRACT
This paper focuses on quantifying a common safety target level that can be used to verify safety levels in road tunnels, railway tunnels, and subway systems with regards to life safety. This safety target should provide a risk acceptance level, according to which tunnel projects can be compared to one another while factoring in the benefit of the tunnel in terms of the value of transporting people and goods. In order to ascertain a reasonable safety target, risk acceptance levels of regulations and recent tunnel projects were studied. The estimated risk levels of recent road and railway tunnel projects were also identified, and converted into the same entity of risk. These risk levels were also compared to estimated risk levels of several fictional road and railway tunnels that comply with current standards, with and without the transportation of dangerous goods.

There are large differences in how risk is expressed in road and railway tunnel projects, and none of the projects or regulations studied fully factor in the societal benefit of traffic when formulating safety target as a societal risk profile. Risk-benefit assessment, however, is quite common in the projects studied. The railway tunnel risk acceptance levels used by the Swedish Transport Administration (Trafikverket) are close to incorporate these benefits, as they state risk on the basis of train-km, whereas other bodies and projects only consider the tunnel as a whole or state it in terms of tunnel-km. The analysis of calculated risk levels shows that they can be stated on the basis of risk per person-km, which provides comparable data for the different transport systems and are directly proportional to transport benefits. Risk acceptance criteria for all three transport systems can preferably be measured in deaths per person-km for societal risk profiles. This unit does not state the total risk of each facility; rather, it allows an ALARP zone to be created, which allows a risk-benefit comparison to be performed. In this paper, it is suggested that risk acceptance levels should be set just above those of tunnel projects that have recently been approved by the Swedish Transport Agency (Transportstyrelsen), and that the establishing of ALARP zones should be a requirement in these processes, as this promotes risk assessment and the design of cost-effective tunnel systems.

INTRODUCTION
Background
The building of road and railway tunnels in Sweden began in earnest in the 1990s, although no rules and regulations specific to this type of project came into existence straight away. For the first few years of this period, requirements were posed within each project; later, Swedish national regulations were introduced, and today there are European-wide regulations stated by the EU enforced in Sweden. The level of safety achieved as a result of these regulations depends on the specifics of individual tunnels, and it is common for risk assessments to be legal requirements for some tunnels in order to ascertain whether further safety measures are required. In Sweden, this has led to a debate regarding which further requirements are reasonable to pose in order to achieve a level of safety that is cost-effective in relation to society. The level of safety required is generally considered to be unclear and discussions regarding it difficult to conduct, during both the planning and approval processes of a tunnel project. Thus, the Swedish Transport Agency (STA) commissioned a research project in order
to facilitate and simplify this process. This article is based on that research project, which was presented in [1]. In the project specification, the STA concluded that:

“If there is no safety target, there is a risk that the measures decided upon during safety work will lack a clear connection to what is desired – protecting people’s lives and health, weighed against the financial cost to society. In order to be able to ascertain whether the desired level of safety has been achieved, methods for verifying whether a safety target has been fulfilled are required. The basic requirements on such methods should be the same, regardless of the transport system.

The transportation-political goals are intended to be guidelines rather than hard and fast rules. Safety cannot be handled separately from other targets in the transportation system, and financial considerations must always be taken into account and considered when formulating a safety target. Existing safety targets have no clear connection to societal benefit. Society should strive to identify and establish a safety level that for operations that are similar to one another which is clearly connected to a suitable verification method.”

At the outset of the project, a workshop was held to which representatives of the STA, the Swedish Transport Administration, the members of the research project, and interested parties relating to roads, railways, and subways were invited. It was concluded that current European regulations for road and railway tunnels form a basis for the project. Based on the discussions held, the following directions were formulated:

- Identify a basic standard for design and functional requirements in order to fulfil the minimum level of safety.
- Suggest risk measures that are suitable for quantifying and assessing the safety of individuals in tunnels.
- Suggest methods for assessing societal benefit when introducing safety measures that are in addition to the basic standard.

The basis on which common safety targets are formulated

Risk acceptance in society is founded on a number of basic principles, formulated in the literature [2] and generally resting on the following concepts:

- Justification of the activity,
- Optimisation of protection,
- Allocation of risk
- Avoidance of disasters,
- Assessment threshold, and
- Continuous improvement (not discussed in the reference above).

One way of creating a safety target that meets these principles is to formulate risk acceptance criteria using quantitative risk measures, which are quantifiable, comparable, communicable, and enable a consistent handling of safety over time. The use of quantitative risk measures results in a risk acceptance level that can be stated or selected, which is one of the main objectives of this work. Risk acceptance levels should be used to identify unacceptable risk levels and facilitate the performing of cost-benefit analyses in cases where it is impossible to tell immediately whether a risk is acceptable or not. Setting an assessment threshold by stating the level below which risks can be considered to be acceptable (without performing a cost-benefit analysis) has the advantage of reducing the number of cases in which analyses must be performed, e.g. with regard to less complex tunnel projects. Risk levels between the acceptance level and assessment threshold are termed ‘ALARP’ (As Low As Reasonably Practicable). This ALARP concept is used in many industry sectors.
In order to be able to accommodate the principles listed above, it is important to standardise the acceptance levels for accident rates in a suitable way. This is important and valuable experience, gained as a result of previous infrastructural projects. It is deemed to be advisable to formulate safety targets and criteria that are nuanced in relation to the benefits that a facility may provide, as not doing so may result in an overly conservative and costly safety standard for some types of facility, and have the opposite effect for others. In the traffic safety work that is carried out for the surface road network in Sweden, this approach is well-established and already applied. It is thus obvious that the predicted number of accidents for a short, lightly trafficked road is not the same as for a long, heavily trafficked one. One way of standardising risk exposure in the context of road traffic is to focus on traffic volume.

Considering only Expected Value/Potential Loss of Life (PPL value) as a figure generally provides insufficient support for handling accident risks involving the likelihood of many casualties. The total contribution to the PPL value of these accidents is often so small that the difference is negligible, and may be significantly lower than the entire uncertainty range of the probability of smaller accidents occurring.

**RESEARCH METHODS**

The research project was commenced by performing a review of the rules and regulations governing the various transport systems, along with accident statistics, previously applied safety targets, and methods for assessing the societal benefit of safety measures.

An analysis was then conducted of the calculated risk profiles of both previous tunnel projects in Sweden and hypothetical tunnels, based on the minimum requirements laid down in law, mandatory provisions and requirements for representative tunnel types.

Based on risk profiles for existing tunnels, hypothetical tunnels, and previously used risk acceptance criteria, it has been possible to suggest a suitable risk acceptance level and assessment threshold.

**THE VARYING SETS OF PARAMETERS FOR EACH OF THE TRANSPORT SYSTEMS**

**Review of accident statistics**

Statistics are available primarily for accidents that involve a small number of people and traffic on surface roads/railways. Larger accidents are very rare. Accident statistics show that, in road traffic accidents, it is primarily the road users themselves that are exposed, whereas the fatalities in railway traffic and subways are primarily non-passengers who are on or near to tracks. The number of fatalities in railway accidents is (per person-km) on par with the number of deaths among road users in road traffic. In total, however, the number of deaths per person-km is significantly higher as the number of suicides is large in comparison to actual traffic volume. These conditions are illustrated in Figure 1 below.
The review of existing safety targets and criteria shows that the targets are stated in different units of measurement, and that in several cases they are connected to societal benefit (PPL values for road tunnels and risk contours for railways). In order to be comparable, they must be stated in a unit that is suitable for all transport systems. There are no international references that can be applied, without modification, to any of the transport systems analysed in this article and still take societal benefit into account.

**Overview of existing safety targets**
According to PIARC’s [3] review, the risk acceptance levels for road tunnels vary strongly both domestically and internationally. Risk acceptance levels are in some instances stated per tunnel and in others per tunnel-/tunnel pipe-km, and the risk sources are in some cases limited to only dangerous goods; regardless of how they are stated, however, the spread is significant (see Figure 2). Risk acceptance criteria can also be related to specific models for risk assessment.

*Figure 1: Fatality statistics for each transport system.*

*Figure 2: Applied safety targets and risk acceptance levels, taken from international references described by PIARC.*
No studies of international risk acceptance criteria for railway tunnels have been conducted. However, the construction requirements of the Swedish Transport Administration (as the commissioner of construction works), as laid out in the document TDOK [4], produces criteria that are to be fulfilled according to figure 3. This risk acceptance level was recently changed from the requirements previously set down in BVH 585.30 [5].

![Risk acceptance in Swedish railway tunnels, produced by the Swedish Transport Administration. A further ALARP zone, not discussed here, is also specified.](image)

No quantitative risk acceptance profiles have been identified for subway systems.

**A study of risk levels in tunnel projects**

The risk profiles of completed tunnel projects were compiled and compared in various ways in order to assess their differences and similarities. The study included the recently opened Northern Link tunnel, consisting of 14 km of tunnel pipes, and the ongoing Stockholm Bypass road tunnel project, consisting of 47 km of tunnel pipes. The railway tunnels that are included in the study are the Hallandsås Tunnel, the West Link in Gothenburg, the Stockholm City Line, the Krokberg Tunnel, and the Strängnäs Tunnel. With the exceptions of the West Link and Stockholm City Line, which are passenger train-only tunnels, all of the tunnels in the study are used by both passenger trains and goods traffic, without restrictions on dangerous goods. In Sweden, the only subway that exists is in Stockholm, but no risk profiles have been calculated for this system. Similar passenger train tunnels have been studied in order to assess the risk level of the currently planned additions to the subway system. The tunnel type that most closely resembles the subway is the Stockholm City Line, which is only trafficked by commuter trains and has a similar safety standard. The existing subway system has a significantly lower safety standard, and is thus not comparable.

The risk profile of road tunnels is normally presented as risk per year and tunnel, whereas railway tunnels are compared to the existing criteria in BVH 585.30 [5], which is stated as risk per train-km. Figure 4 presents the total risk per risk object.
As was expected, the spread is large – in the order of several powers of ten – between the various facilities, as length and traffic flow vary widely. In addition, there are differences in design that may impact safety, e.g. whether a tunnel is single or double pipe. The risk acceptance level (i.e. the probability of an accident occurring, combined with the consequences of said accident) is strongly connected to the size and geographical delimitations of the system, particularly if there exist great differences in terms of the benefit provided by the facility or activity in comparison to its size. For example, a greater number of accidents are accepted on a national level than within a smaller geographical area, e.g. a municipality or single facility. It is thus reasonable to assume that a safety target must be in some way scaled down to suit a system’s size or geographical extent.

An important issue in the project has been investigating the possibility of standardising risk measures so that they reflect the benefit of the facility, as well as formulating a common or equivalent risk acceptance criterion for the various transport systems. A number of approaches to standardisation have been tried for different facilities, but the inevitable conclusion is that, for a standardisation relating to traffic volume that takes both length and road user flow into consideration, a significant reduction in spread between the facilities studied takes place. Traffic volume provides a good metric for the benefit that a facility produces. The conclusion is that risk impact is relatively similar, regardless of facility and transport system. Thus, it appears to be possible to formulate a risk acceptance criterion that spans all transport systems. For the studied facilities, the risk profiles (F/N curves) are similar when risk is standardised against traffic volume, even for differing transport systems. This indicates that the risk level that is the result of current construction approaches and design concept is in fair agreement for the various transport systems, and that risk aversion for large accidents is in the same order of magnitude in relation to the number of people that use the facility.

In Figure 5, the risk for different facilities is standardised per person-km. It can be seen that the range between the highest and lowest risk levels has decreased to roughly two powers of ten. Given an interval of 300-500 fatalities, a risk acceptance level of $10^{-7}/N$ per million person-km would be above but relatively close to existing projects for all transport systems.
Individual fatalities have been found to largely depend on smaller accidents such as collisions, traffic accidents, and, to some extent, fires. These accidents are assumed to have been taken into consideration by the basic standard laid down in the rules and regulations for each type of tunnel, which are generally not designed based on analysis.

**Hypothetical tunnels that follow a basic standard**

An additional analysis has been performed on two hypothetical road tunnels to show how the varying parameters of transport systems affect the risk profiles of different tunnels. One of these is a < 1000 m long, two-way tunnel with a maximum permitted traffic volume, which is the longest possible without requiring a fire detection system and emergency alarm. The other is a heavily trafficked two-way tunnel, the risk level of which was calculated by factoring in all of the safety measures that are required by the rules and regulations. An additional calculation was performed for this tunnel, assuming that 5% of the traffic takes the form of queuing conditions, requiring that the risk be verified through risk assessment. Additional risk profiles were also calculated for these same tunnels, assuming that dangerous goods corresponding to the national average for Sweden are transported through them. Figure 6 shows a selection of these calculated risk profiles.
A selection of risk profiles (presented in Figure 6) lead to the conclusion that the accepted risk in a simple tunnel can be high in the interval of 1-3 fatalities, but that the risk profile rapidly falls to low levels. Figure 6 also shows that tunnels in which dangerous goods are moved can result in a relatively high risk profile, particularly if they are two-way. In comparison to the Northern Link tunnel, which allows the transportation of dangerous goods with some limitations and is calculated to experience queuing conditions relatively rarely each week, it is evident that a corresponding hypothetical tunnel that lacks a fire suppression system and has a slightly larger share of dangerous goods for which no time restrictions has been posed will have a much higher risk profile. It is doubtful whether such a tunnel design could be considered to be acceptable.

A hypothetical railway tunnel that strictly adheres to the requirements of the TSI [6] has been investigated. Complete calculations have not been performed; instead, comparisons have been conducted with the Strängnäs Tunnel, which has a 1.2 m-wide footpath and 800 m between emergency exits, largely corresponding to the requirements of the TSI. The conclusion of the comparison is that a hypothetical tunnel that is constructed in adherence to the requirements of the TSI would attain the ‘tolerable’ rating of the Swedish Transport Administration’s ambition level. The ‘tolerable’ rating means that measures to increase safety shall be assessed in relation to their cost-efficiency. It should be noted that the comparison is general in character; more complex tunnels with a greater number of passengers and red lights may fail to reach this ambition level. Precisely where the line is drawn has not been investigated.

**Delimitations for very small and large accidents**

Frequently occurring accidents involving few fatalities differ markedly between transport systems regarding both frequency and the safety measures used to lessen their impact. Accident types involving few fatalities are not considered to be typical ‘tunnel accidents’. Here, there should be a basis for posing specific requirements and targets for each individual transport system. The best safety
measure is not necessarily related to tunnel construction; rather, more general measures specific to transport systems, e.g. seat belts, should be considered. In order to allow a quantitative target to also encompass smaller accidents, one possibility would be to establish a complementary risk target based on PPL values. Such a method would be equal between transport systems and encompass all types of accidents, but the objective would be specific to the transport system. This has been extensively discussed, but no further investigation has been conducted.

Accidents involving several hundred or thousands of fatalities are very rare, and the cause or combination of causes may be difficult to theoretically define; in the field of nuclear power, for example, incredibly extensive analyses have not yielded thorough explanations of all causes. In addition, the material produced by analyses does not provide a coherent picture of accidents involving several hundred or more fatalities. Our suggestion is thus to not state a safety target as a risk measure on the F/N curve for accidents involving fatalities exceeding the 500. For these accidents, which have a very low probability and extremely severe consequences, it is likely that a different type of handling is required, wherein extremely improbable accidents are weighed together and handled separately. Such analyses are generally not cost-effective for individual projects, as the uncertainties involved are very large. Here, earthquakes, structural material failure, and designing errors, for example, become relevant.

**RECOMMENDATIONS AND CONCLUSIONS**

The research project resulted in the following safety target for all three types of transport systems:

“The risk profile for societal risk during road, railway, and subway tunnel transportation shall be equal, and stated as risk per person-km.”

The risk graphs for various completed tunnel projects regarding the investigated transport systems show a general trend of movement towards this target. A comparison with hypothetical tunnels constructed according to the minimum standards set down in the rules and regulations is, for those parts that are comparable, in line with this. A quantitative, verifiable target has been developed, wherein the probability of fatality per person-km and risk acceptance criteria are evidenced using an F/N curve.

The selection of the risk measure “number of fatalities per person-km” takes transportation benefit into account by considering differences between transport systems and factoring in the high passenger flow that often occurs in new facilities, while at the same time ensuring that the measure is applicable to simpler facilities. The connection to societal benefit also takes place based on the ALARP principle, wherein cost-benefit analyses are to be performed in order to assess whether further safety measures are good investments. The same analyses can also be used to choose the most effective safety measure if the risk level is above that of the maximum acceptable risk.

The methodology and process suggested use the existing rules and regulations as a basic standard which, according to the studies, is deemed to provide a risk level that falls within the ALARP zone. For these tunnels, a qualitative cost-benefit analysis may be sufficient, meaning that less complex tunnels do not need to be further investigated. For those tunnels where the basic standard is insufficient, a risk assessment shall be performed. The methodology for risk assessments exists, is currently actively used in tunnel projects, is deemed to function satisfactorily, and can be used to present risk level measurements. To perform ALARP cost-benefit assessment, less advanced qualitative methods should be used along with more advanced calculation models based on societal cost evaluations that use relevant figures and assessment parameters according to the ASEK report [7].

A delimitation of the proposed measure for safety targets is suggested with regard to frequently occurring accidents involving few fatalities, as well as extremely improbable accidents involving
many fatalities. Frequently occurring accidents involving few fatalities differ markedly between transport systems as regards both frequency and the safety measures used to lessen their impact. Accident types involving few fatalities are not considered to be typical ‘tunnel accidents’. Here, there should be a basis for posing specific requirements and targets for each individual transport system. The best safety measure is not necessarily related to tunnel construction; rather, more general measures specific to transport systems, e.g. seat belts, should be considered. For extremely improbable accidents for which fatalities exceed the 300-500 range, the assessment does not provide a sufficient basis for determining the risk level. In order to allow a quantitative target to also encompass smaller accidents, one possibility would be to establish a complementary risk target based on PPL values. Such a method would be equal between transport systems and encompass all types of accidents, but the target would be specific to the transport system. This has been extensively discussed, but no further investigation has been conducted.

We deem that our suggestion would result in:

- safety being optimised, regardless of transport system, against transportation benefit through the selection of risk measures,
- the introduction of safety measures being optimised against cost benefit (ALARP), and
- the use of existing rules and regulations, methodologies, and processes, helps minimise the cost of its introduction.

Finally, and in summary, we are of the opinion that this suggestion promotes risk assessment as a means of supporting the continued development of the tunnel safety field through an understanding of the ways in which risks arise and how they can be handled. In addition, the suggestion forms a foundation for the assessment and optimisation of the cost efficiency of safety measures. The work on quantitative targets that have a clear connection to societal economy provides a basis for consultation with authorities and decisions based on rational factors.

The project formulates a suggestion based on a review of rules and regulations, general principles and bases for risk assessment, experience from various projects, and analysis of different ways of measuring risk. The suggestion is based on a common safety target that is not specific to any transport system, stated in an F/N diagram for road tunnels, railway tunnels, and subways and with a clear connection to societal benefit. In summary, the suggestion can be formulated as follows:

“The risk during transportation in a road, railway, and subway tunnel shall be equal, and be stated as risk per person-km.”

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REFERENCES


