

Quantification of a Safety Target for an Underground CNG Bus Terminal in Stockholm

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ABSTRACT

There are currently no detailed regulations or guidelines for designing the safety concept for an underground terminal for buses powered by compressed natural gas (CNG). Neither are there any explicit safety targets for this type of facility in legislation or practice. A dilemma arises both in the land-use planning process and building design process when evaluating whether the safety of such a bus terminal is sufficient. However, there are internationally accepted principles in other sectors that may be useful in defining a safety target in this case. In this paper it is proposed that such a safety target can be quantified using risk acceptance criteria expressed in terms of individual and societal risk. The method developed in this study is based on comparisons with risk acceptance criteria applied in other types of facilities and activities, both nationally and internationally, and required an extensive inventory of these. The method also takes into account the fact that people's perceptions of risks affect their acceptance. The proposed safety target is presented in terms of an upper and a lower F-N curve, and includes the ALARP principle. In addition to this a maximum average risk is specified for the facility. A plausibility check was carried out indicating that the risk level defined by the safety target is lower than, or of the same order of magnitude as, many other corresponding risks in society, e.g. in other transport systems.

KEYWORDS: Dangerous goods, risk analysis, compressed natural gas, ALARP

1 INTRODUCTION

Planning for and designing a new underground commuter bus terminal in Katarinaberget in central Stockholm (see Figure 1) required the explicit identification and assessment of the risks and safety aspects affecting human life and health. There were several reasons for this. A project prerequisite was that the terminal would enable traffic with CNG buses. No specific safety targets were available from authorities for such a facility, and common practice in this area was sparse, or had not explicitly addressed the risk of CNG bus fire. In other words, the criteria for determination of environmental impact significance concerning risk exposure to life-safety is lacking. This is not a unique situation in Sweden. Very limited support can be found in international guidelines such as NFPA 502 [1] or AS4825 [2], where the proposed design scenarios at present does not cover the potential severe fire and explosion scenarios from a CNG bus fire in an enclosed space.

In Sweden there are no general safety targets stated in regulations for other sectors or industries, such as the transport sector or the chemical industry, that could be adopted directly. Previous experience has also shown that there can be significant variation between sectors when safety targets are expressed as the level of risk. This indicates that the basis for assessing the risks associated, for example, with a bus terminal involving vehicles fuelled with CNG with the potential for serious accidents, is not well defined when evaluating whether the level of safety is adequate or not. This causes principal problems both in the planning and design processes.

1.1 Purpose and objectives

This paper describes the work carried out to establish a safety target that can be used to assess whether a specific detailed land-use plan has adequately addressed risk to human health and safety, in accordance with the Swedish Planning and Building Act (PBL) [3]. According to the Swedish Environmental Act (MB) [4] it is also stated that human life and health and the environment shall be adequately protected against accidents and other negative consequences. The safety target is necessary in the evaluation of the assessment of the environmental impact in order to evaluate the risk of accidents. The safety target, also used as criteria for impact significance, in the context of this paper, refers to severe risks associated with an underground CNG bus terminal which are not covered or managed by specific detailed regulations governing safety.

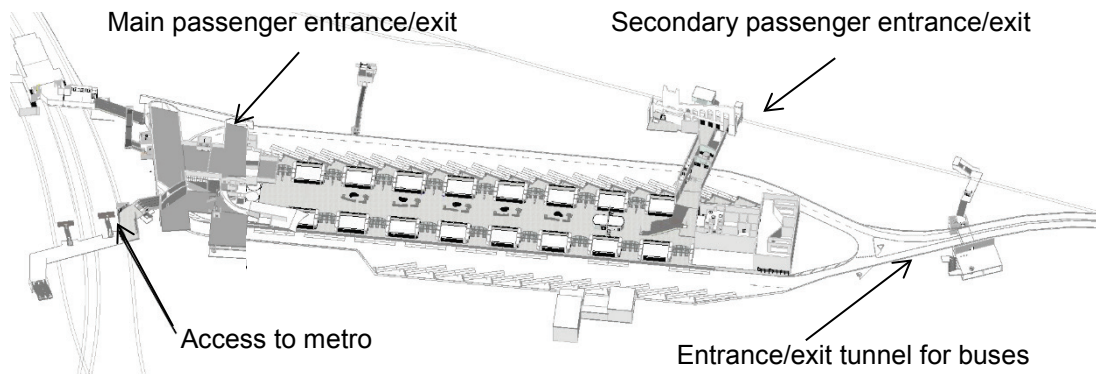


Figure 1. Overview of the commuter underground bus terminal in Katarinaberget in Stockholm.

The objective of this study was twofold. One objective was to develop a method of quantitatively determining the safety target for an underground bus terminal operated with CNG bussed, taking into account the scientific basic principles underlying safety targets. The second objective was to apply the method in a real case for a bus terminal in central Stockholm, in order to derive a risk acceptance criteria (i.e. criteria for impact significance) necessary in both the land-use planning and the building design process.

1.2 Limitations

The safety target considered here is based on the conditions and requirements of a new underground CNG commuter bus terminal in Katarinaberget, Stockholm, during normal operation, and deals only with life safety. The purpose of defining such a target is to enable an evaluation of whether the level of risk in the bus terminal is tolerable with regard to human life and health, and/or whether there is a need for further risk-reduction measures. No such evaluation is made in this study, but is integral to the type of risk assessment used for assessment of environmental impact in each specific project. This paper provides a necessary component to be able to carry out such an assessment, i.e. the safety target. Information about the other component that forms the base for the risk evaluation, i.e. the risk analysis, is presented in [5]. The complete risk assessment performed in the specific project when gaining permission in the planning process is publicly available [6].

The nature of the facility indirectly imposes a number of constraints, for example, the risks associated with the facility do not affect those outside the facility, the natural environment or other important societal functions. The safety target is only relevant for evaluation serious incidents within the bus terminal, that are not sufficiently addressed by other specific regulations, e.g. the building code and the workplace health and safety requirements, and their application, e.g. the fire safety design strategy [7]. The measures for fire protection defined in the concept fire and life safety strategy are intended to fulfil the regulations that apply to the kind of fire scenarios that may occur in the facility and in buses running on liquid fuels such as diesel, ethanol, etc., according to the PBL [3] and the Swedish building and construction regulations [8] [9]. As protection against serious accidents involving CNG buses

is not covered in any detail in the above-mentioned regulations, further risk-reduction measures have been included based on a detailed analysis of these risks [10]. Corresponding means of dealing with serious accidents can be found within other industries internationally, such as the chemical industry or oil and gas industry.

2 BACKGROUND

There are currently no national, regional or local safety targets in Sweden that can be applied to the kind of facility in question in this study.

An overall vision for the safety of the Swedish population has been formulated in the Government Bill, “Goals for the Safety of the Population” [11], where it is stated that society shall “protect the lives and health of the population”. It is also made clear in the “National Safety Strategy” [12] that two of the goals regarding human safety are to protect the lives and health of the population and the functionality of society. A similar general goal has been formulated in the “Safety and Security Programme” [13] of Stockholm City Council, which is both the commissioner and inspector of buildings and facilities.

The Stockholm County Public Transport Authority, which will be operating the terminal, has also formulated a general traffic safety goal [14] in which it is stated that: “No one shall suffer serious injury or death as a result of accidents involving the operations of the Authority”. It is also stated in the “Guidelines for Fire Protection in Buildings, Facilities and Vehicles” [15] that: “The safety of passengers, personnel and third parties shall be high, and shall be continuously improved when deemed reasonable and motivated. The long-term goal is that no individual shall suffer death or serious injury as a result of fire.” These general goals are formulated in different ways in terms of the consideration of safety in Figure 2.

Sweden	Stockholm City Council	Stockholm County Public Transport Authority	Stockholm County Public Transport Authority	New Underground Bus Terminal in Katarinaberget
Goals for the safety of the population National Safety Strategy	Safety and Security Programme	General traffic safety goals	Guidelines for Fire Protection in Buildings, Facilities and Vehicles	
To protect the lives and health of the population. To protect the functionality of society. To protect the country's ability to maintain fundamental values such as democracy, the rule of law, human rights and freedom.	To protect people, property and the environment. To ensure the functionality of society even in the case of undesirable incidents. To strengthen the ability to maintain our fundamental values, democracy, the rule of law, human rights and freedom.	No one shall suffer serious injury or death as a result of accidents involving the Authority's activities.	The safety of passengers, personnel and third parties shall be high, and shall be continuously improved when deemed reasonable and motivated. The long-term goal is that no individual shall suffer death or serious injury as a result of fire.	No specific goal regarding safety.

Figure 2. Some of the general goals regarding safety relevant to the present study.

The way in which safety is related to concepts such as risk, risk assessment, individual and societal risk, is not always clear, which can lead to both the goals and the results from risk analysis being perceived as difficult to understand and apply in planning and design situations. Therefore, a short introduction is given below to the definition of each concept, and the way in which they are used in this paper. This is followed by a brief description of some of the areas that are important in the development of safety targets, such as the principles underlying safety targets, risk acceptance criteria, risk-reduction measures and the perception of risk.

2.1 The concept of risk

The concept of *risk* can have different meanings depending on the context. A common definition, often used in engineering, is that risk is regarded as an accident scenario, the probability of this accident in combination with its negative consequences [16].

Risk management is the name usually given to the process of identifying, analysing, evaluating and managing undesirable incidents (risks) that can prevent specific goals from being achieved. In this case, the goal is to achieve a sufficient level of *safety* from the perspective of society.

A *risk assessment* is part of the risk management process and deals with the identification, analysis and evaluation of risks to determine whether there is a need for measures to reduce the consequences or probabilities of that risk. In order to reduce the risk and complete the risk management process it is necessary for the assessment to be connected to decision making that leads to the implementation of any necessary measures, and monitoring and review of the effects of the measures.

2.2 The principles underlying safety targets

Determining whether a facility or activity is “sufficiently safe” involves determining whether a specific safety target has been achieved. In other words, it involves adopting a position and making decisions regarding the effects of risks and the need for mitigation measures, i.e., following the steps of the risk management process.

Safety targets have been developed by several countries in many sectors [17], including public transport, nuclear power, the process industry, aviation, road transport, shipping and health care, in order to fulfil, in various ways, the basic principles presented in Figure 3.

Justification of the activity An activity should not lead to risks that are unreasonably high in relation to the benefit to society as a whole.	Optimization of protection Risks should always be minimized through reasonable protective measures, bearing in mind their benefit (in terms of reducing the risks), cost and practicability.	Distribution of risks Risks should be reasonably distributed within society, in relation to the benefit of the activity. This means that individuals or groups of people should not be exposed to disproportionately high risks in relation to the benefit received.
Avoiding catastrophes If risks are realized, they should be of the nature that they can be dealt with using existing resources, rather than causing catastrophes.	Proportionality The level of detail in risk assessments should be proportional to the level of risk, and it should be possible to exclude negligible risks from detailed risk assessments.	Continuous improvement Levels of societal risk should in general, be reduced over time.

Figure 3. The basic principles underlying the development of safety targets.

The above principles were deemed to be appropriate as a starting point for the development of the safety target in the present case. In other words, it is reasonable to expect the safety target to address all these principles, and it is suggested that these be applied to the case of the proposed underground bus terminal in Stockholm.

One way of developing a safety target that takes into account the above principles is to formulate risk acceptance criteria using quantitative measures of risk. The advantage of quantitative measures is that they are measurable, allow for comparison and consistent management of safety over time. Quantitative measures of risk allow an explicit risk acceptance level to be stated. In principle, this means that a level of risk above this level is unacceptably high (i.e., the level of safety is too low), while a risk

level under the risk acceptance level can be regarded as acceptably low (i.e. the safety is sufficiently high). This principle, or method of application, has been elaborated in many areas to define a range between acceptable and unacceptable, in which it is not possible to state directly whether the risk is acceptable or not [18]. This is sometimes called the As Low As Reasonably Practicable, or ALARP region, and means that the risks can be accepted if all *reasonable practicable* measures are taken (see Figure 4). What can be regarded as reasonable practicable, can be evaluated using cost-benefit analysis, for example.

The above-mentioned basic principles (Figure 3) can be accommodated in a satisfactory way by studying the two risk measures *individual risk* and *societal risk* using a model that includes the ALARP region.

The *individual risk* is the probability (often expressed as the frequency per year) of the fatality of a hypothetical single person, who is exposed to a specific risk. The individual risk does not take into account how many people that may be affected by the accident. The aim of this measure of risk is to ensure that individuals are not exposed to unacceptably high risks.

The *societal risk* is the probability (often expressed as the frequency per year) that a certain number of fatalities will result from exposure to a certain risk. The societal risk takes into account the density of population, in other words, it is a measure of the consequences in terms of the number of people affected by the accident scenario.

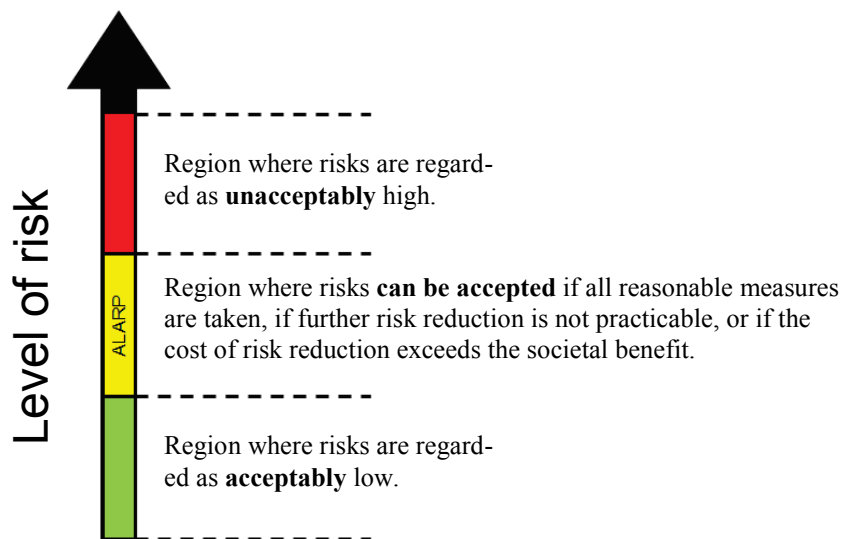


Figure 4. A principle for risk assessment when using quantitative measures of risk.

2.3 Risk acceptance criteria

The general visions regarding safety described above do not include any concrete suggestions for risk acceptance criteria for individual risk or societal risk, and do not provide any support in the application of quantitative risk measures. Some help has been provided by the Swedish Civil Contingencies Agency (MSB) [18] and the Stockholm County Administrative Board [19]. This means that responsibility for taking a stance regarding the effects of risk is borne by the person or operator involved, or those responsible for a particular project.

A lack of risk acceptance criteria also leads to difficulties in determining whether the level of risk is appropriate or not. It is thus difficult to obtain an indication of whether further safety-improving measures are necessary using risk analysis as a tool. This was pointed out by an independent expert committee in an early review of the bus terminal project [20], and by The Greater Stockholm Fire Brigade [21] during the planning process.

Stockholm City Council has not taken a stance regarding the general specification of requirements [22] drawn up together with the Greater Stockholm Fire Brigade, which stated that: “it should be clear

whether the risks are acceptable from the point of view of both the individual and society". The question of actual levels of risk are not dealt with in strategic documents governing comprehensive urban planning [23], the accompanying assessment of the environmental impact [24], or Stockholm City Council's Safety and Security Programme [13]. The lack of both national and local standpoints means that the way in which the risk of accidents is described and evaluated can vary from one case to another. This applies to risk management throughout the whole planning process – from the assessment of whether the risk of accidents can cause significant effects on the environment, to the evaluation of the need for additional risk-reduction measures, and the final assessment and compromises made between the risk of accidents and other interests.

No explicit risk acceptance criterion is given in the Stockholm County Public Transport Authority's safety target, but it can be interpreted as promoting the principle of continuous improvement in a similar way to the vision of zero deaths in road traffic accidents in Sweden [25].

Despite the fact that no explicit criteria are provided in the planning process regarding the effects of risk, decisions are made continuously by, for example, the Stockholm County Administrative Board, as to whether the detailed plan should be reviewed, where the effects of risk are part of the general assessment. The County Administrative Board also approves assessments of the environmental impact of, for example, planned road and rail infrastructure, which also include the effects of risk as part of the general assessment. The basis for the Board's assessment in such situations is not always completely transparent, and may vary from one project to another.

2.4 Risk-reduction measures

The principle of risk reduction (Figure 4) means that measures must be taken if the level of risk is in the region regarded as being unacceptably high, in order to ensure that a certain safety target is fulfilled. All reasonable measures must be taken to reduce the level of risk when risks are in the ALARP region, bearing in mind the cost-benefit perspective. The aim of these measures is to reduce the degree of risk in one way or another. Based on the definition of risk used in this context, it follows that risk-reduction measures can be directed towards reducing the probability (or frequency) of an incident, or reducing the consequences of that incident, or both, as illustrated in Figure 5.

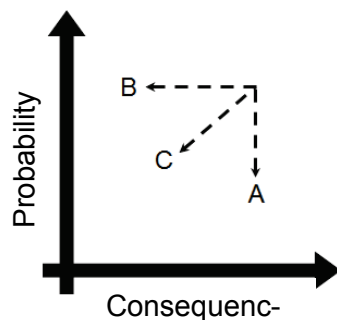


Figure 5. The principle of risk-reduction measures when the probability of the incident is reduced (A), the consequences are reduced (B), or when both are reduced (C).

2.5 Risk perception

Risks and the level of risk perceived to be tolerable by society can be valued differently. The kind of factors that affect how we perceive risk, and what kind of risk is acceptable in society may be technical/mathematical, ethical, political or societal. Some of the factors that have the greatest effect on people's perception of risk are described below. This is by no means a complete list, but according to research in the field [26] [27], these factors dominate to such a degree that they give a good representation of what governs risk assessment, and why it is that there are such large variances in the levels or targets accepted by society for different risks. This also explains indirectly why different parties are differently inclined to invest in measures to further reduce the level of different kinds of risk.

People find it easier to accept a risk when they perceive a clear benefit of being exposed to the risk associated with a certain activity [28]. Many perceive driving or travelling in a car to be a beneficial

activity. However, road traffic is associated with a level of risk that would not necessarily be acceptable in other technical systems; the benefit of such technical systems may be less clear to people, and are therefore regarded as more hazardous.

Another related aspect can be considered here, namely people's knowledge of risks. The ability to recognise and understand the risks associated with various activities affects how we assess them, as well as our ability to actually control the risk. There may be such differences between someone working in an underground bus terminal, and a member of the public, e.g. a passenger. These two individuals have quite different knowledge regarding the nature of the activity in question, its risks, the protective measures implemented, early warnings signals, and how the extent of an accident can be limited, if this is possible.

Whether or not an activity is undertaken voluntarily is another factor that affects how risks are perceived. We find it easier to accept the risk of a voluntary activity such as rock climbing, than one we are required to carry out, for example, working in the chemical industry [28]. Similarly, people who either live close to a route along which dangerous goods are transported, or who work within a hazardous facility, do probably not want to be in the vicinity of these risks, but they accept the situation. For a household to move may be possible, but this depends on other factors, apart from the voluntary nature of the activity. Another aspect is that many in the public can be unaware of the risk exposure they are subjected to, i.e. the (un)knowledge of risk.

The degree of vulnerability may vary among those exposed to a certain risk. Differences in vulnerability can be discussed in the context of several factors, such as age and mobility. Public transport is intended for all to use, but the number of more vulnerable people may vary depending on which part of the system is being considered. The ability to escape from a dangerous situation is also related to vulnerability. In order to be able to escape from a dangerous situation one must first become aware of it, then react to it, and finally evacuate. All of these steps can be affected by age and mobility, but the individual's knowledge concerning the source of the risk is also important.

The duration of the exposure to a risk varies depending on the type of risk and how long or how often a person is in the vicinity. There will be differences between people who use public transport regularly to commute to work, and those who use it more seldom. Similarly, the exposure to risk resulting from an industrial plant where hazardous materials are used will be quite different for someone living in the area and someone simply passing through the area.

The potential for catastrophe is another factor affecting risk acceptance that describes how people perceive the possibility that the source of the risk may lead to a major disaster, e.g. very severe consequences. Enclosed spaces are often perceived as a factor that can increase the potential for a catastrophe. Examples of this are tunnels and underground spaces, as well as large underground train or bus stations, which can also constitute totally or partially enclosed spaces, and thus have a greater potential for catastrophe than open ones.

The amount of attention directed by the media to a source of risk can vary depending on the location of the risk; e.g., whether it is an open area, or close to a school. The kind of consequences that could arise can also be assessed differently; the release of many small emissions are not given as much media coverage as a single large emission.

Finally, people's perception of risk can depend on whether the source is manmade or natural. A tunnel is perceived as being a manmade construction, and may lead to an increased concern, despite the fact that technical equipment has been installed to detect hazardous events and reduce their consequences.

3 METHODS FOR THE QUANTIFICATION OF SAFETY TARGETS

Based on the principles for the construction of safety targets given in Figure 3, it can be deduced that risk acceptance criteria for the risk measures individual risk and societal risk should constitute a central part of the safety target for the bus terminal in question. Risk acceptance criteria can be used to determine whether the level of risk is acceptable or not, or whether further measures are required. A number of approaches for estimating a reasonable level for such risk acceptance criteria are presented

in Section 3.1. The method chosen for application to the commuter bus terminal in Katarinaberget, Stockholm is then presented in Section 3.2.

3.1 Possible approaches to define the acceptance level

Table 1 lists a number of well-established approaches that can be used to determine the level of risk acceptance criteria in the bus terminal.

Table 1. Possible approaches to setting the level of risk acceptance criteria.

	Description of method	Comments
A	Apply current best practice regarding risk acceptance criteria for underground bus terminals.	The use of buses running on CNG in underground facilities is a relatively new phenomenon, both in Sweden and internationally. No standards or best practice where the novel risks are considered explicitly, nor applicable risk acceptance criteria, could be identified.
B	Use current data (accident statistics) for existing comparable facilities and evaluate whether the risk acceptance criteria should be the same as, higher or lower than historical outcomes.	No sufficiently comprehensive accident statistics are available for similar vehicles in an underground facility. However, there are examples of accidents on the open road that show that various scenarios with potentially serious consequences can arise.
C	Compare with risk acceptance criteria applied to other kinds of facilities in other sectors, in Sweden or internationally.	A number of acceptance criteria have been applied to other sectors in Sweden and internationally. Comparisons should take into account the different conditions, i.e. perception factors, prevailing in the evaluation of the different acceptance criteria.
D	Compare with the general death rate in the population (e.g. natural background risks or risks associated with transportation) and base acceptance criteria for the facility in question on this level.	The application of this method as the only basis for acceptance criteria is deemed to be complicated if large uncertainties in the results are to be avoided. Comparison with natural background risks is deemed to be useful provided a plausibility check is performed, and the chosen levels are discussed.

3.2 Proposed method for the quantification of the safety target

The method deemed to be suitable for the current conditions is to apply method C, and then to use method D as a plausibility check. This means that a comparison is made between risk acceptance criteria applied to other kinds of facilities and activities in other sectors, in Sweden and internationally. This comparison should take into account the differences in the conditions prevailing when those criteria were established. The risk perception factors described above should also be compared to ascertain whether there is a need to increase or decrease the level of safety in the bus terminal in relation to the level or levels identified as being applicable. The plausibility check can be carried out as a comparison with both background risks and the fatality rate associated with other kinds of transport and activities.

3.2.1 Individual risk

An activity-based risk measure, i.e. the probability of death each time a passenger enters the bus terminal, is used to evaluate the individual risk. A location-specific risk measure is not deemed as relevant in a situation where the flow of people is a more dominating principle than the fact that a person is in a specific place for a certain time. An activity-based risk measure allows comparison with a number of other modes of transports where similar conditions prevail, and can be used for a plausibility check, as described in Chapter 6.

3.2.2 Societal risk

As accidents involving CNG have the potential to affect numerous people, the societal risk must be included in the safety target. In most sectors, the societal risk is usually expressed in terms of F-N curves or the average risk [18].

Depending on the sector used as the reference, it may be necessary to normalise or scale the criterion for application to the bus terminal in a proportional way. This can be done, for example, by taking into account the size of the area where the risk exposure is evaluated with the criterion or the number of people exposed to risk. For example, comparing the case of the bus terminal with the nationwide transport sector will not be as relevant as comparing with a single terminal or a set distance approximating the size of the terminal, e.g. one kilometre.

4 ANALYSIS

This chapter describes the analysis based on the method proposed above. An inventory of national and international risk acceptance criteria is made, followed by a comparison of the risk perception factors associated with an underground bus terminal and other areas of application.

4.1 Inventory of national and international risk acceptance criteria

Quantitative acceptance criteria are used to describe safety targets in a number of sectors. We have surveyed national and international acceptance criteria in order to obtain an idea of the levels used. Figure 6 shows a number of examples of the levels employed in various sectors, in a number of European countries [17] [29].

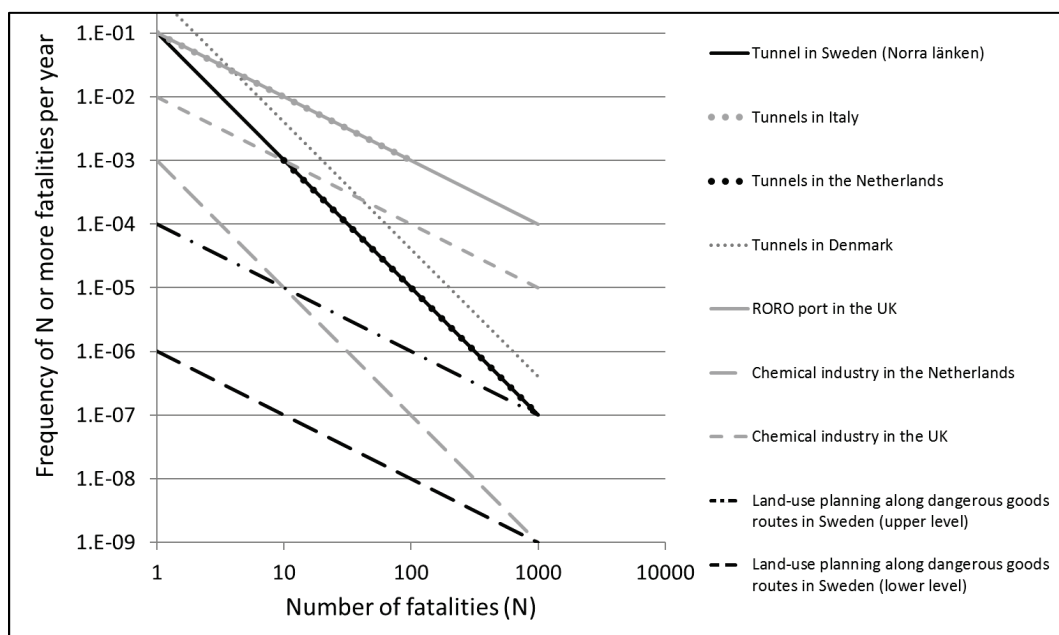


Figure 6. Examples of quantitative risk acceptance criteria in different sectors in different countries.

It can be seen that there is considerable variation between different countries within the same sector. There is also significant variation between different sectors in the same country. This means that there is a broad range of acceptance criteria, making the choice of criterion appropriate for the current facility challenging.

In order to establish a suitable level, the two Swedish cases included in Figure 6 are considered, and a comparison is made between the important factors affecting the tolerated risk in society between the bus terminal and these two cases.

The first example (case) is a risk assessment for a Swedish modern road tunnel (Norra länken) included in the submission from The Swedish Transport Administration (Trafikverket) for approval to the

The Swedish Transport Agency (Transportstyrelsen). Although there is a legal demand for such a risk assessment, there are as yet no relevant guidelines on applicable levels. Information on the acceptance criteria in this case was obtained by requesting the relevant documentation from the Swedish Transport Agency [30]. The road tunnel gained approval, which makes the risk levels used for verification of the tunnels safety concept in this case relevant as precedent.

The second example concerns land-use planning and development adjacent to dangerous goods routes in Sweden. Common practice in Sweden in this case is to use the risk criteria proposed by DNV (Det Norske Veritas) [18]. Even though these criteria is not formally stated in regulations, e.g. in PBL [3], the are referenced to in guidelines issued by several County Administrative Boards, e.g. in Stockholm [19].

4.2 Comparison of the factors that affect risk perception

As there is a significant difference between the two Swedish examples, the factors affecting risk perception, discussed in Section 2.5, are considered. The table below presents a comparison between the present case of the bus terminal, and those regarding road tunnels and development adjacent to dangerous goods routes or close to hazardous facilities, i.e. chemical industry. A simplistic assessment is made of whether the risk perception factors lead to a higher or lower acceptance of risk in the present case.

Table 2. Comparison of the factors affecting risk perception in the case of the bus terminal, and the two Swedish cases described above.

Factor affecting risk perception	Road tunnel (urban dual carriageway) vs. bus terminal	Land-use planning adjacent to dangerous goods routes vs. bus terminal
Possibility of knowing about the risk	/	/
Possibility of being able to affect the risk	/	-
Benefit of the hazardous activity	/	-
Voluntariness	/	-
Vulnerability of those exposed	/	-
Possibility to evacuate the hazardous area	/	/
Potential for catastrophe	/	/
Media coverage	/	/
Natural or manmade risk	/	/

+ Higher risk acceptance than in the bus terminal

- Lower risk acceptance than in the bus terminal

/ Similar risk acceptance as for the bus terminal

5 SUGGESTED RISK ACCEPTANCE CRITERIA FOR THE UNDERGROUND BUS TERMINAL IN STOCKHOLM

The analysis presented in the previous chapter shows that the risk acceptance criteria used in the case of modern road tunnels in Sweden can be appropriate for the underground commuter bus terminal in Katarinaberget, in Stockholm. This conclusion was based on the levels of risk applicable to Swedish conditions, which are in line with those applied in other European countries, and an evaluation of the most important factors affecting the perception of risk. Sections 5.1 and 5.2 explain how the risk acceptance criteria for individual risk and societal risk can be expressed so as to represent the corresponding level of risk for the bus terminal.

5.1 Suggested individual risk criterion

The individual risk level is obtained by estimating the probability of fatality as a result of commuting to work through a modern road tunnel. The estimate is based on information on the risk acceptance criterion taken from the documents submitted to the Swedish Transport Agency [28] for approval in the case of the road tunnel in question:

- Total distance travelled: 170 000 000 person·km/year.
- Maximum average risk according to the criterion for the facility: 0.46 fatalities per year¹.
- Distance travelled in a tunnel by a commuter travelling to work 200 days/year: 800 km/year (assuming a one-way journey of about 2 km).
- Maximum individual risk (probability of fatality) as a result of commuting in a modern road tunnel on an urban dual carriageway: $2.2 \cdot 10^{-6}$ /year.

5.2 Suggested societal risk criterion

The suggested societal risk criterion for the bus terminal is presented as F-N curves in Figure 7.

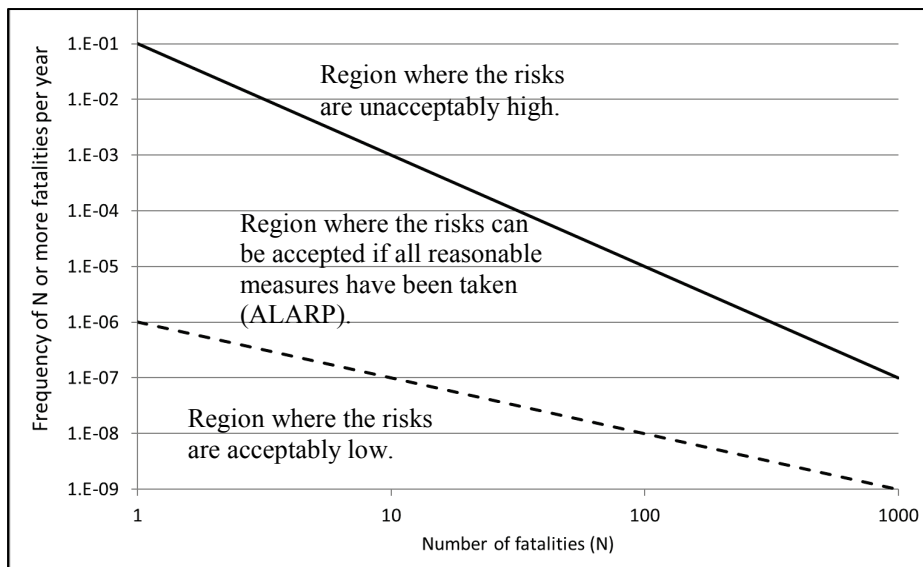


Figure 7. Suggested societal risk criterion in terms of upper and lower F-N curves for the underground bus terminal.

It may be necessary to scale or adjust the risk acceptance criterion for application to the bus terminal. In the example with the road tunnel, the length of the tunnel was assumed to be about 1 km and during heavy traffic conditions this means about 600-700 people will be exposed in each tunnel tube at any one time.

The corresponding distance in the underground bus terminal, which in many key safety aspects can be regarded as being similar to a tunnel, is 800 m, and it is estimated that about 1000 people will be in or close to the areas used by the buses. It is here assumed that the areas used by the buses are separate from the areas used by passengers while waiting, i.e. people in the waiting room are not exposed to

¹ Both the F-N curve and the probability of fatality in the Swedish road network (0.0027 fatalities per million vehicle·km) are included in the acceptance criterion for the road tunnel. Assuming 170 000 000 person·km per year in the tunnel gives 0.46 fatalities per year (i.e. $3.3 \cdot 10^{-2}$ per km per year). The maximum expected number of fatalities taken from the F-N curve for the upper risk level is equivalent about 10 fatalities per year in the tunnel. Both these criteria must be fulfilled, i.e. neither the average risk of 0.46 fatalities per year nor the upper F-N curve may be exceeded.

risk from the buses. This implies that the fire compartmentation and structural elements of the waiting room must be designed to withstand the overpressure in the event of a CNG explosion or a jet flame.

Based on the above assumptions, the bus terminal corresponds roughly to a 1 km tunnel, and the number of people using the facilities and exposed to risks is about the same. We therefore consider it unnecessary, at this stage, to scale or adjust the societal risk criterion.

As a complement to the F-N curves, we suggest a maximum average risk of $3.3 \cdot 10^{-2}$ fatalities per year, which leads to a similar level of safety as on the Swedish open road network, as in the case of the acceptance criterion derived for the recently approved and opened for operation Swedish motorway tunnel Norra länken.

In the criterion used for the road tunnel, only an upper level is given with an F-N curve. This means that the case only specifies that the risk is unacceptably high above a certain level. Bearing in mind the basic principles for safety targets discussed in Section 2.2, we deem it appropriate to formulate criteria that allow the application of a plausibility check, and to emphasize the principle of continuous improvement.

This can be done by defining an ALARP region (see Figure 4). The principle of continuous improvement means that it is appropriate to set a relatively low lower limit in this region. We therefore suggest that this level be set at the lower level of the DNV criterion [18], which is often used in cases concerning the exploitation of land close to routes for the transportation of dangerous goods.

6 PLAUSIBILITY CHECK

This chapter presents a plausibility check of the suggested risk acceptance criteria for the individual risk and societal risk in the underground bus terminal.

6.1 Individual risk

In order to compare the activity-based risk acceptance criterion for the individual risk, a comparison can be made with other activities in order to gain an idea of their size. It is important to bear in mind that the level of risk acceptable to the individual and society is governed by the perception factors discussed above.

Another relevant comparison is to study travelling by other modes of transport that corresponds to a probability of fatality of $2.2 \cdot 10^{-6}$.

- Riding a motorbike for 21 km [31]
- Walking 58 km [32]
- Cycling 32 km [33]
- Travelling 798 km in a car [31]
- Travelling 3460 km in a jet aircraft [33]
- Travelling 21 000 km by train [31]

In order to place this in relation to other risks, the risk of fatality as a result of various background risks and activities is given in Table 3. It can be seen that an individual risk level of fatality of $2.2 \cdot 10^{-6}$ /year is below the level to which many people are normally exposed during the course of a year.

Table 3. Examples of the annual individual risk of fatality due to various background risks and modes of transport [34].

Cause of death	Individual risk of fatality per year
Natural background risks	
Being struck by lightning	$1.0 \cdot 10^{-7}$
Fire	$1.4 \cdot 10^{-5}$
Workplace accident (fulltime workers)	$1.3 \cdot 10^{-5}$
Accidents in the home and during leisure activities	$2.2 \cdot 10^{-4}$
All causes, individuals aged 20-40 y	$1.0 \cdot 10^{-3}$
All causes, individuals aged 60 y	$1.0 \cdot 10^{-2}$
Other modes of transport, gender, age range¹	
Car, male, 15-24 y	$8.2 \cdot 10^{-5}$
Car, male, 65-84 y	$7.4 \cdot 10^{-5}$
Car, male, 25-64 y	$5.1 \cdot 10^{-5}$
Car, female, 65-84 y	$3.2 \cdot 10^{-5}$
Car, female, 15-24 y	$2.4 \cdot 10^{-5}$
Walking, male, 65-84 y	$2.3 \cdot 10^{-5}$
Cycling, male, 65-84 y	$2.1 \cdot 10^{-5}$
Car, female, 25-64 y	$1.9 \cdot 10^{-5}$
Walking, female, 65-84 y	$1.3 \cdot 10^{-5}$
Motorbike, male, 25-64 y	$1.3 \cdot 10^{-5}$
Moped, male, 15-24 y	$1.0 \cdot 10^{-5}$

¹Only groups for whom the risk is greater than $1.0 \cdot 10^{-5}$ are included

6.2 Societal risk

F-N curves can be difficult to interpret and compare as the scales are often logarithmic and the curves may have different gradients. To facilitate comparison between the different levels of risk identified and represented by F-N curves, the so-called average risk, i.e. the expected number of fatalities per year based on the level of risk, is presented in the table below for various cases in a number of countries, in decreasing order of risk.

Table 4. Maximum expected number of fatalities per year (average risk) based on the risk acceptance criteria (F-N curves) for various cases in different European countries.

Country and case	Maximum expected number of fatalities/year (average risk)
UK RORO port (per vessel)	$6.9 \cdot 10^{-1}$
Italy, tunnels (per km)	$4.6 \cdot 10^{-1}$
Denmark, road tunnels (per km)	$4.0 \cdot 10^{-1}$
UK, chemical industry	$6.9 \cdot 10^{-2}$
Sweden, modern road tunnel (Norra länken) (per km)	
- upper level F-N curve	$9.9 \cdot 10^{-2}$
- average on Swedish open road network	$3.3 \cdot 10^{-2}$
Netherlands, road tunnels (per km)	$9.9 \cdot 10^{-3}$
Netherlands, chemical industry	$9.9 \cdot 10^{-4}$
Sweden, development of land adjacent to dangerous goods routes (per km) upper level	$6.9 \cdot 10^{-4}$
Sweden, development of land adjacent to dangerous goods routes (per km) lower level	$6.9 \cdot 10^{-6}$

It can be seen that the average risk corresponding to the upper F-N curve for the societal risk acceptance criterion corresponds to $9.9 \cdot 10^{-2}$ fatalities per km per year in the road tunnel, while the corresponding value for the Swedish road network is $3.3 \cdot 10^{-2}$ fatalities per km per year in the road tunnel. If the F-N curve criterion is used in the same way as in the Netherlands, where only accidents with 10 or more fatalities are included, the value obtained is $9.9 \cdot 10^{-3}$ expected fatalities per km per year. It is thus deemed that the suggested risk acceptance criterion is of the same order of magnitude as that in tunnels in European countries such as the Netherlands, Italy and Denmark. However, the average risk is higher than those applied in the chemical industry and in the land-use planning adjacent to dangerous goods transport routes.

7 CONCLUSIONS

Although there are no explicit safety targets for the kind of facility considered in this study, we have presented a specific value for the proposed underground commuter bus terminal in Katarinaberget, in the city centre of Stockholm.

The safety target was quantified using risk acceptance criteria for measures of the individual risk and societal risk. The value obtained was based on comparisons between the risk acceptance criteria for other types of facilities and activities in various sectors, both nationally and internationally. A plausibility check was made showing that the risk level of the safety target is lower than, or similar to, that for many other kinds of risk in society, for example, other forms of transport.

The suggested risk acceptance criterion consists of an upper and a lower F-N curve. The highest tolerable risk level is equivalent to the individual and societal risk in a modern Swedish road tunnel. In order for this suggestion to live up to the basic principles discussed in Section 2.2, continuous improvements will be necessary to reduce the level of risk. The suggested criterion includes a so-called ALARP region, within which such improvements are required. Examples of the type of improvements are administrative and organisational controls, or technical measures aimed at the fleet of buses. The lower limit in the ALARP region corresponds to the risk level that is considered acceptable in the exploitation of land close to transport routes for hazardous goods in Sweden. As a complement to the F-N curve, we suggest a maximum average risk of $3.3 \cdot 10^{-2}$ fatalities per year, which is equivalent to the level of safety on the Swedish road network, and similar to the acceptance criterion applied for a modern Swedish road tunnel.

The safety target proposed in this study has been deemed appropriate by the head of administration of the Stockholm County Public Transport Authority [35] and has also formally been approved by the Stockholm Municipal Council in the detailed land-use planning of the underground bus terminal [36]. No objections regarding the safety target have been raised by either The Stockholm County Administrative Board or The Greater Stockholm Fire Brigade. The presented safety target has been a central component in both the planning and design process for the bus terminal when developing the safety concept and evaluating the acceptability of the residual risk [6].

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