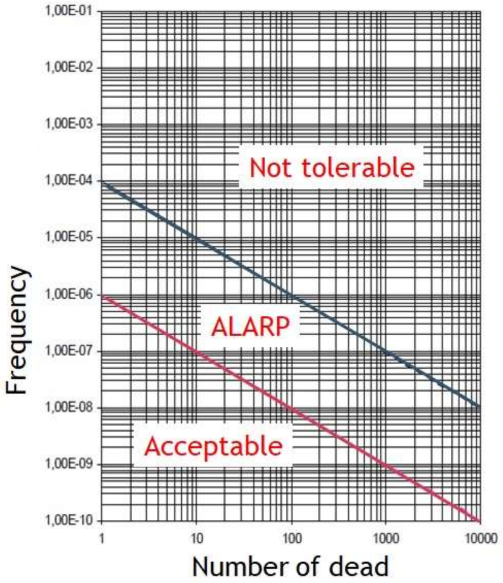

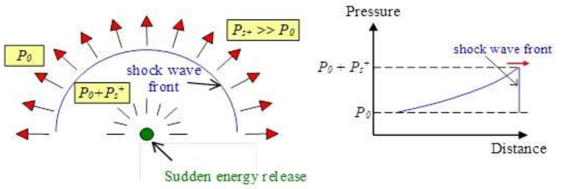

Inventory of knowledge needs, with regard to explosion loading, in a densified urban environment

Master's thesis in the master's program Structural engineering and building technology

EMMA DAHLÉN

Department of Architecture and Civil Engineering
Division of Structural engineering
Concrete structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Master's Thesis ACEX30-19-58
Gothenburg, Sweden 2019

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Cover:
Explosion loads in densified urban environments. Shock wave distribution from an explosion. From Johansson and Laine, 2012a. ALARP curve for risk evaluation. From Räddningsverket 1997.

Department of Architecture and Civil Engineering
Göteborg, Sweden, 2019

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ABSTRACT

In densified environments there is a need to build closer to roads where the buildings get more exposed to risks like explosions from dangerous goods traffic. It has been discovered that when a risk analysis is performed for buildings close to such roads the risk of explosions is treated differently from case to case. Furthermore, structural engineers are not always used to work with dynamic loads and therefore the knowledge about how to handle explosions in calculations are generally low. Because of this, there is of interest to find out what knowledge needs there are in the building sector for handling of explosions. The aim of the thesis was to highlight problems with how explosions are handled in the construction process today and search answers for what type of knowledge that is needed to improve the handling of explosions.

Literature studies have been made to find out how risk analyses are made, what load properties that are obtained from an explosion and how to calculate the structural response of a building exposed to an explosion load. Reviews of risk analyses have been made for several projects in Sweden to find similarities and differences in how explosion risks are treated. It was discovered that there was no common procedure for how to handle explosions and there were many uncertainties in the analysis, especially concerning statistics of dangerous goods traffic and statistics about what the consequences will be in case of an accident.

To illustrate the potential effect of an explosion a parametric study of a wall is made. It can be concluded that to have a plastic response and high mass are valuable for a good resistance.

A significant part of the study was interviews with people treating explosion risks in their daily work. The key questions in the interviews was how to improve the handling of explosions. Improved statistics of dangerous goods transports, increased information about how explosions events work, increased collaboration between stakeholders, more investigation about the risk reducing actions and standards for how explosions should be treated and evaluated was the main things that was brought up as suggestions for improvement during the interviews.

It was concluded that since the charge weight have a large impact on the structure it is important that the information about explosions is correct and that the risk of explosions is evaluated in a reasonable way. To have a common accepted view which should be reflected in codes and guidelines for evaluation of explosion risk is important.

Keywords: Explosions, explosion risk, explosion loading, risk analyses, handling of explosions, structural response

Undersökning av kunskapsbehoven gällande explosionslaster i en förtätad stadsmiljö

Examensarbete inom masterprogrammet Konstruktionsteknik och byggnadsteknologi

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SAMMANFATTNING

I samband med att samhällen förtätas finns det ett behov av att uppföra byggnader närmre transportleder där farligt gods fraktas. I och med detta utsätts byggnaderna för en större risk för explosioner från till exempel farligt gods olyckor. I samband med att byggnader byggs nära vägar görs riskanalyser och det har upptäckts att dessa sällan hanterar explosioner likvärdigt. Det är dessutom så att konstruktörer oftast inte har så stor erfarenhet av att arbeta med dynamiska laster och därav har liten kunskap av att i byggnadsdesignen hantera explosionslaster. På grund av detta har det bedömts finnas ett intresse av att undersöka vilka kunskapsbehoven är inom explosionsområdet. Denna rapport kommer belysa problem med hur explosioner hanteras idag och besvara vad som behövs för att förbättra situationen.

Litteraturstudier har genomförts för att ta reda på hur riskanalyser ska genomföras, hur lasten av en explosion ser ut och hur beräkningar för byggnadens respons genomförs. Det har också gjorts en undersökning av flera riskanalyser där likheter och skillnader har undersökts. Det upptäcktes att det inte fanns ett standardiserat sätt för hur explosioner skulle hanteras och att det var många saker som var osäkert i riskanalyserna, speciellt gällande statistiken för farligt gods samt för vilka konsekvenserna kunde bli av en explosion.

För att illustrera vilken potentiell effekt en explosion kan ha har en parameterstudie utförts på en vägg. Från denna analys kunde slutsatsen dras att en plastisk respons samt en hög massa hade stor betydelse för hur väl väggen stod emot en explosion.

En mycket viktig del av studien har utgjorts av intervjuer med personer som i sitt arbete hanterar explosionsrisker. Tanken med dessa intervjuer var främst att ta reda på vad de ansåg behövdes för att förbättra hanteringen av explosioner. Att förbättra statistiken, informationen om explosionsförloppen, samarbetet mellan olika parter, informationen om riskreducerande åtgärder samt få en samsyn och standard på hur explosioner ska hanteras togs upp som viktiga åtgärder för att förbättra hanteringen av explosioner.

Sammanfattningsvis så är det av stor betydelse att informationen om explosioner är korrekt och att explosionsrisken är utvärderad på ett rimligt sätt eftersom explosionen har stor inverkan på byggnaden. Det är också av stor betydelse att det finns en samsyn kring hur explosioner ska hanteras i en förtätad stadsbebyggelse.

Nyckelord: Explosion, explosionsrisk, explosionslast, riskanalyser, explosionshatering, strukturrespons

Contents

Preface

This study about the knowledge needs in a densified urban environment regarding explosions has included a literature study, risk analysis reviews, calculations of explosion loads and structural response, and interviews. The thesis has been carried out at Norconsult between January 2019 to June 2019. The thesis is a part of a pre-study made for Trafikverket in collaboration with Norconsult, Chalmers and KTH, where the goal is to find out what areas regarding explosions that has a need of increased knowledge. The idea is that this study will lead to a PhD project in the area which this study finds to be needed the most.

The thesis project has been carried out with Morgan Johansson as supervisor and examiner and I would like to thank him for his large interest in the study and his supervision throughout the project. As interviews has been a large part of the result of the thesis, I would like to thank all the interviewees for their participation. Thanks to Herman Heijmans from Norconsult, Erik Egardt from MSB, Henric Modig, Ulf Lundström and Maria Nilsson from Trafikverket, Mathias Lööf from Projektstaben, Marie Sjölander form Spetsprojektledning Marie Sjölander AB and Rebecka Thorwaldsdotter and Patrik Jonsson from Länsstyrelsen. I would also like to thank Johan Hultman, risk analyst at Norconsult, which answered a lot of questions about risk analyses.

Göteborg June 2019

Emma Dahlén

Notations

Roman upper-case letters

A	Area
E	Modulus of elasticity
E_k	Kinetic energy
F	Force
F_b	Force on beam
F_k	Characteristic force
I	Second moment of area
I	Impulse
I_k	Characteristic impulse
P	Pressure
Q	Equivalent static load
R	Capacity
T	Period time
W	Charge weight
W	Work
Z	Scaled distance

Roman lower-case letters

a	Acceleration
b	Width
c	Damping
c'	Concrete cover distance
d	Distance to reinforcement level
c_b	Damping of beam
i	Impulse intensity
k	Stiffness
l	Length
m	Mass
q	Load
r	Distance
t	Time
t	Duration
t_l	Load duration

u	Deformation
$\dot{u}$	Velocity
$\ddot{u}$	Acceleration
κ_k	Transformation factor regarding stiffness
κ_F	Transformation factor regarding force
κ_m	Transformation factor regarding mass
κ_{mF}	Transformation factor regarding mass and force

Greek letters

Λ	Reflection coefficient
α	Constant
γ	Heat capacity ratio
γ_I	Correction factor
δ	Displacement error
ω	Angular frequency

Index

+	Positive phase
-	Negative phase
0	Ambient air
a	Arrival
b	Beam
c	Concrete
k	Characteristic
e	External
el	Elastic
ep	Elastoplastic
eq	Equivalent charge weight
i	Internal
k	Kinetic
k	Characteristic
mod	Modified charge weight
pl	Plastic
r	Reflected shock wave
s	Unreflected shock wave

s	Steel
tot	Total

Companies and authorities

	Boverket	National Board of Housing, Building and Planning
DNV	Det Norske Veritas	
FOA	Försvarets forskningsanstalt	The Swedish National defense research institute
GÖP	Göteborgs översiktsplan	Gothenburgs city plan
KTH	Kungliga Tekniska Högskolan	Royal Institute of Technology
MSB	Myndigheten för samhällsskydd och beredskap (tidigare SRV)	Swedish Civil Contingencies Agency (earlier SRV)
RIKTSAM	Länsstyrelsen i Skånes riktlinjer	The county administration board in Skånes guidelines
RIVM		National Institute for public health and environment
	Räddningstjänsten	The emergency services
SCB	Statistiska centralbyrån	Statistics Sweden
SIKA	Statens institut för kommunikationsanalys	The National Institute for Communication Analysis
	Socialstyrelsen	National Board of health and welfare
SRV	Svenska Räddningsverket	Swedish rescue service agency
	Länsstyrelsen	The county administration board
	Sjöfartsverket	Maritime Administration
TRAFA	Trafikanalys	Traffic analysis company
	Trafikverket	Transport Administration
	Transportstyrelsen	Transport Agency
VTI	Statens väg- och Transportforskningsinstitut	The Swedish National Road and Transport Research Institute
ØSA		Øresund safety advisor

1 Introduction

1.1 Background

In several cities in Sweden there is a need to densify the city environment. There is a need for building houses closer to each other but also closer to transport routes. In some larger cities like Stockholm and Gothenburg there are also plans on decking over large roads and build houses over them. However, when the distance between a road and a building decreases, the latter gets more exposed to accidental events, e.g. explosions which can take place on the roads. In those places where dangerous or explosive goods are transported, the risks are even higher. With an increased risk the demands on the nearby buildings also increases. How an explosion will affect a building and what accidental scenarios are possible, is something that there is a need of knowledge further.

When a building is constructed close to a road a risk analysis should be made. However, it has been noted that depending on which company that makes the risk analysis it can be large differences in the result. The calculation procedure can also differ between different people at the same company which can affect the result. Some guides from MSB (the department for protection and preparedness) are available for how a risk analysis can be done but there are no rules that is followed by everyone. To not have a standardized procedure can be a problem. Whose prediction of the risk is good enough? Different risk analyses will contribute to different demands on the building which will result in different safety for the people inside of the building. It can also affect the construction costs.

Once an explosion source and a position has been defined by the risk analyst it is possible to determine which explosion load that a building should be able to withstand. However, one problem is that most structural engineers are not used to work with dynamic loads and generally the knowledge about explosion loads are low.

Norconsult believes that there is a need of investigating in which areas more knowledge regarding explosions in a densified environment is needed. A pre-study is initiated in the topic at Chalmers and KTH. This thesis, which was done in cooperation with Norconsult, is a part of this study. This thesis will contribute to an increased understanding of how explosion loads are handled by risk analysts and engineers today in Sweden, and where there is need of increased knowledge. This thesis will be the start for more in-depth research projects in the future.

1.2 Aim

The thesis will find out in which areas more knowledge is needed about explosions. Different stakeholder’s challenges when handling explosions in the built environment will be highlighted. The stakeholders of interest are in the whole building sector, from municipalities to the risk analysts. The thesis should give an overview of how the explosion risks in a densified environment are handled in early stages. The idea is that this thesis will contribute to inputs for further research in the area.

Questions that the master thesis aim to answer are:

- How are explosion risks handled by risk analysts and engineers today?
- What differences and similarities are there between different projects concerning explosion risk evaluation?
- What kind of rules and recommendations exists concerning explosion loads and how are they followed/used?
- How will a wall react to different explosion loads depending on the design of it?
- In which areas are there a need of increased knowledge?
- How can the knowledge be increased?

1.3 Limitations

This master thesis has been limited to concentrate on interviews for analyzing the stakeholders discovered problems regarding handling of explosions and how this should be improved. Interviews was made but no surveys. Furthermore, the interviews were mainly with contacts acquired by Norconsult in different projects. Interviews were limited to mainly focus on risk and early stages of a project. Hence, no interviews with structural engineers or contractors where made even though this would have been interesting.

The thesis was limited by looking at the situation in Sweden, and not include other countries in the analyses. However, it would have been interesting to see how they handle explosions and what Sweden can learn from them.

1.4 Methodology

The first part of the project included a literature study. This was done in order for the writer to increase her knowledge in the explosion topic and to collect information needed for the reader to understand the investigation done in the thesis. The literature study was divided into three parts. Firstly, it was analysed how risk analyses can be made, thereafter the load situation at an explosion was analysed. Lastly, the structural response for buildings exposed to an explosion load was analysed and described.

The second part of the project included a review of several risk analyses. Risk analyses from different parts of Sweden were included. In order to get a wider comparison several companies were included and there were also projects from different years. However, it was also of interest to see if the risk analyses were done similar or different if they were done by the same company. Therefore, some risk analyses from the same company was included. Since the idea was to look at how explosions were considered in the risk analyses all projects picked out were analysing risks from a road or a railway were dangerous goods were transported.

In addition to the quantitative review of the risk analyses a review of some risk analyses in Gårda in Gothenburg was made. Since such an analysis was partly done by risk analysts at Norconsult the result from their analysis was included and discussed. However, since the focus of this thesis is explosions an additional analysis of how explosions were handled in these risk analyses were made. In the risk analyses where the calculated risk level was presented a comparison of the result of the risk analyses was made as well.

The result from the reviews of the risk analyses provided a base to the interview questions. These were also formed from what the writer discovered as possible problems in the handling of explosions from the literature study.

The interviews were carried out as a discussion where the interviewee had large possibilities to present their own thoughts about how explosions are handled today and what is needed in order to improve the handling of explosions. If one interviewee highlighted a problem in the situation today this was also brought up in the rest of the interviews to see if there was an agreement about if it was a problem.

In addition, an analysis of what impact different parameters had on a wall structure´s ability to resist an explosion was made. This was done by using calculation sheets provided by Morgan Johansson at Norconsult. Graphs with comparisons of different parameters were produced. This chapter was included in the thesis to be able to illustrate what effect an explosion may have on a building. By including these comparisons of how the building handle different sizes of explosions one will more easily understand how an insufficient handling of explosions throughout the construction sector may be a problem.

Finally, a discussion of the result of the literature study, the review of the risk analyses, the interviews and the calculations of the structural response was made. From this discussion suggestions of possible things to improve and make more research about was suggested.

1.5 Overview of content

The first chapter in the literature study, Chapter 2, is about the risk analysis and it describes how a risk is evaluated. It also explains what a risk analysis are, why it is important and what purpose it serves. Further, the typical steps in the analysis are presented. Thereafter the critique about today's methods is presented and the situation today regarding risk analysis work is described. Finally, the chapter also includes information about possible events at an explosion.

Secondly, the load from an explosion is described. Chapter 3 will explain the explosion and the load that the explosion will result in. The difference between a static load and an impulse load is explained and the influence on the load due to the surrounding is described. Furthermore, this chapter explains explosions from explosives and includes information of how to determine the dynamic load from gas.

The last part of the literature study, Chapter 4, is about the structural response. This chapter describes how a structure behaves when it is subjected to an impulse load. Firstly, the general behaviour of an impulse loaded structure is described and to some extent compared to the behaviour of a statically loaded structure. Thereafter, one simple way of calculating the response of an impulse loaded structure is presented. This is an accepted way of calculating structural response of dynamic loads. The idea is to give a description of how the behaviour of a dynamically loaded structure works.

Furthermore, some examples of how a building can be constructed with a better resistance to explosions is given.

In the literature study some references have been of large importance. In Chapter 2 information from Räddningsverket (1997) has been very valuable since they have some guidelines for how a risk analysis can be performed. Räddningsverket, which sometimes is written as SRV (Statens Räddningsverk) transformed into MSB (Myndigheten för samhällsskydd och beredskap) in 2009. In some places it is referred to Räddningsverket and in other places to MSB; however, it is the same authority. Moreover, for the other two literature chapters, Chapter 3, about explosion load and and Chapter 4 about structural response, Johansson and Laine (2012a) and Johansson (2014) are important sources. There are other sources available which has been used in their reports, but the useful information is well described in these two references.

The following two chapters, Chapter 5 and 6, describes how explosions have been handled in various risk analyses studied. In Chapter 5, a comparison between different risk analyses are made. Similarities and differences between the risk analyses are highlighted. Possible problems with how explosions are handled are brought up and discussed. During 2017 a comparison of eight risk analyses in Gårda, Gothenburg, was made by Norconsult. Parts of this comparison has been included in the report in Chapter 6 together with further comparisons with a larger focus on how the explosion risk has been handled. This comparison has been of interest in order to point out differences in how explosions are handled in risk analyses. This comparison has also been valuable to find suggestions for improvement in future analyses.

In risk analyses it is common that the explosion scenario considered is different from one analysis to another. Therefore, it may be difficult for someone, for example the risk analyst to know what impact the explosion load will have on the building. To give a picture of what impact explosions of different sizes will have on a wall several comparisons have been made in Chapter 7.

After discovering possible problems in how explosions were handled in the building industry interviews were made to see if people working with explosions in different ways had encountered similar problems. Chapter 8 presents the results of the interviews. The interviewees were from Norconsult, MSB, Trafikverket, Projektstaben, Länsstyrelsen and Spetsprojektledning Marie Sjölander AB. The interviewees contributed with knowledge about how explosions are handled in the construction sector and opinions about what is needed in order to improve the handling of explosions.

Chapter 9 contains a discussion where teachings and discoveries from the previous Sections are summarised, analysed and discussed. In Chapter 10 conclusions, suggestions for improvements and further studies are presented based on what was discovered in the thesis.

Chapter 11 presents the used references in the project. Lastly, in Appendices some information about statistics collection, an investigation about the possibilities of improving the existing statistics and input data and result for the calculations of the wall is included.

2 Risk analyses

2.1 Definition of risk

A risk is defined as the probability for something to happen multiplied with the consequence if it happens, see Figure 2.1. To identify the risks and objects in need of protection is the first steps of making a risk analysis. Firstly, an inventory of the risks is made. The inventory is done on a general level where the risks and areas of protection like schools, hospitals and other buildings where people commonly gathers are pointed out. The next step is to make this on a detailed level. This is called risk identifying. The documents, in form of maps, tables or diagrams that the risk identification provides will be a support when forming future environmental plans, rescue plans, traffic plans, etc (Räddningsverket, 2003). Some examples of risks that can be considered in risk analyses are:

- Processes and transports
  - Industries
  - The public sector
  - Transports
- Natural disasters
  - Landslip
  - Flooding
  - Earthquake
- Fire
- Explosions

(Räddningsverket, 2003).

$$\text{Risk} = \text{Probability} \cdot \text{Consequence}$$

Figure 2.1 Definition of risk.

Risks can be divided into categories depending on what type of risk it is or how large the consequence of the risk is or to what extent it can happen. One division is by technological risks, risks for the nature or social risks. Risk can also be divided into deterministic risks, random risks with large variations in occurrence, and catastrophes. *Deterministic risks* are risks which have approximately equal occurrence every year. An example of it is traffic accidents in a country, which only has small variations from one year to another. However, if decreasing the area of study to municipality level the number of traffic accidents will be more of a *random risk with large variation* between years. To describe the third category, *catastrophes*, it is an accident with large consequence, however the probability is low.
(Räddningsverket, 2003).

The risk inventory and risk identifying are followed by the risk analysis which is a much more detailed analysis which estimates the probability and the consequence of a specific risk (Räddningsverket, 2003). The risk analysis will be described in detail in Section 2.2.

2.2 Risk analysis

2.2.1 General principles

When evaluating a risk, one need to look at both possibility and consequence. Regarding the consequence it is of importance to take different groups into consideration. The individual and the health of that person is important, so are the environment, the surrounding areas, the business and the functions of the society (Räddningsverket, 1997).

According to Räddningsverket (2003) there are three ways of evaluating the possibility for something to happen. One can look at data from earlier years if there is enough data to get something out of it. This is called *empirical studies.* A second alternative is to model the event to get a *logical analysis* of what can happen. The third way of evaluating is by taking help of experts in the area. Normally a combination of these methods is used.

Generally, some principles are followed when analysing risks, evaluating them and decide if they are acceptable:

1. Plausibility principles
2. Proportions principles
3. Distribution principles
4. Principles for avoidance of catastrophes

(Räddningsverket, 1997)

The *plausibility principle* means that if there are risks which easily can be avoided technically and economically, they should be avoided. The *proportion principles* mean that if an activity result in risks, the risks should not be large compared to the benefit from the activity. Moreover, the *distribution principles* mean that the risks from an activity should not be larger for one category of people than for another; i.e. the risk should be evenly distributed between people. Lastly, the *principles for avoiding catastrophes* refers to that it is preferable to have risks with smaller consequences over risks that may lead to catastrophes (Räddningsverket, 1997)

2.2.2 The purpose of the risk analysis

The risk analysis is made to get knowledge about what kind of risks there are, how large the possibility and consequence of them are and, as a result of this information, be able to present some recommendations for how the risks should be handled or avoided. This should be done to satisfy both the ones being exposed to the risk and the ones getting a benefit from the activity that includes risks. This does not necessarily have to be the same persons (Räddningsverket, 2003).

The risk analysis will be basis for giving permissions, making sure that security measures taken are good enough and to investigate incidents and accidents. The risk analysis will give answers to if e.g. a new building could be constructed close to a road, if and which types of actions are needed to reduce risks that the new building come with. It will also help to decide which actions that will have the largest effect on reducing the risk. Sometimes it is of interest to know which other activities that can be allowed close to each other, the risk analysis will give an answer on this too.

Moreover, the risk analysis should give a picture of all possible risks, as well as it should take earlier experience from several areas into consideration (Räddningsverket, 2003).

A risk analysis should be done in cases where changes are made in the processes or a new material or product is used (Försvarsmakten, 2011). When something is to be built close to transport routes one need to do a risk analysis. The large cities in Sweden have a need for densifying and by then using areas closer to routes where dangerous gods are transported. The transports can be both on railways and on roads. Densified cities are also an important reason why the risk analyses have become of larger importance for the society (Länsstyrelserna Skåne län, Stockholms län and Västra Götalands län, 2006)

2.2.3 Important steps in a risk analysis

General steps
According to Räddnigsverket (2003) the risk analysis always follows some general steps:

- definition of goals and limitations
- inventory of risks and identification of them
- analysing the risks and evaluate them regarding possibility and consequence

The general steps can be described by Figure 2.2.

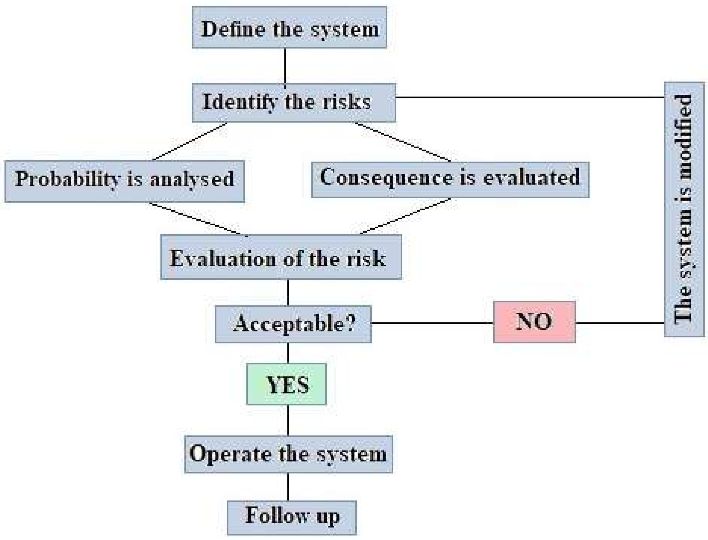


Figure 2.2 General steps for a risk analysis. Based on Räddningsverket (1997).

Purpose and limitations
The first step is to identify what the purpose of the risk analysis is. One need to identify what information that the risk analysis needs to give and what decisions that will be taken with the risk analysis as support. Additionally, limitations of time, risk, magnitude, and degree of detailing needs to be decided and described. The limitation needs to be done so that the level of details is enough to give a valuable result (Räddningsverket, 2003).

Risk identification

The second step, which is one of the most important steps of the analysis, is to identify all possible risks. Some events are more important to include than others. Events that has happened before is an obvious part of the risk analysis as well as events that has happened during similar activities. One need to look at the activity in detail and take into consideration possible risks that has to do with the specific activity. Furthermore, combinations of events have to be considered. In order to further improve the analysis, it should also include combinations of events that have not happened before and events that normally are avoided with systems, routines and maintenance (Räddningsverket, 2003).

Qualitative and quantitative analyses

Risk analyses can be categorized into qualitative and quantitative analyses, both begin with a definition of the purpose of the analysis. Afterwards, the risks are identified. Thereafter, the methods are a bit different. In the *qualitative method* the risk identification as well as the risk evaluation regarding probability and consequence is to a large extent based on experience. The *quantitative analysis* is different because it is not based on experience at the same level. The quantitative analysis uses several models for analysing the effect of accidents and the probability is based on generic data and from this the risk is calculated (Räddningsverket, 1997).

There are pros and cons with the models. The quantitative model can easier be used to compare different risks and solutions with each other since almost all possible events are handled. It is with the quantitative model easy to find costs for different solutions. If the model is detailed and correctly made it will give a risk analysis with a high quality. There are some disadvantages with the quantitative method as well. Since the quantitative analysis takes a lot of things into account it makes them complex and they become difficult to understand. Furthermore, the analysis is based on generic data and this needs to be evaluated if it's applicable to the new conditions. The method is also criticised for not considering human mistakes well enough (Räddningsverket, 1997).

Statistics

After the possible risks have been identified, one need to find reliable statistics for how probable it is for the accident to occur. Also, statistics for how probable it is for different consequences to occur needs to be calculated or assumed. As an example, one need to find statistics for what categories of dangerous goods that are transported on a road as well as the number of transports in order to get a good risk analysis for a building close to a road. In Appendix A some sources of statistics concerning dangerous goods on roads are presented.

Risk presentation

The risk can be presented in different ways. One can analyse the individual risk or the risk for the society. The individual risk is the risk for one specific person which is in the area. The individual risk will present the effect on one person depending on the distance from the accident. The risk for the society includes the number of people that use to be in the area and for how long time. The risk for the society can be described by so called FN-curves (Frequency of accidents versus Number of Fatalities) or by PLL (Potential Loss of Life). An example of a FN-curve is given in Figure 2.3. From the curve one can read that the risk of an accident resulting in 10 or more dead people is 10^{-5} (the black curve). The curve will always have a slope similar to the curve in the figure. With a flatter slope, like the red curve in Figure 2.3, the risk of accidents with many dead is almost as big as the risk of an accident with one dead. If the slope is steeper, as the blue curve, the risk of many deaths decreases faster. Flatter slopes are therefore worse than steeper slopes of the FN-curve. (Räddningsverket, 1997).

Figure 2.3 Example of FN-curves. Based on Räddningsverket (1997).

A common way of describing risks are by using a risk matrix. The concept for that are shown in Figure 2.4. If both the probability and the consequence are low the risk may be acceptable, and it has no need for risk reducing actions. However, for risks with high probability and consequence they have need for acute actions. For cases in between, risk reducing actions will be needed (Boverket and Räddningsverket, 2006).

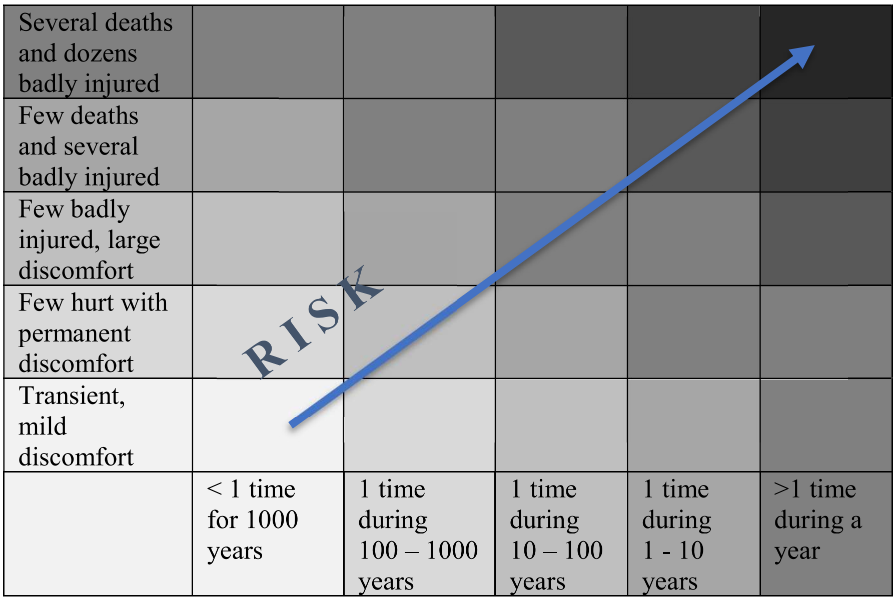


Figure 2.4 Risk matrix. Based on Boverket and Räddningsverket (2006).

Risk evaluation

When the consequence and the possibility is calculated the risk needs to be evaluated. The evaluation needs to be done in an objective way. One need to consider both how the society will be affected and specific individuals (Räddningsverket, 1997).

The person making the risk analysis and decides if the risk is acceptable or not needs to have large knowledge about the activity and the risk that comes with it. When evaluating risks, one should consider the plausibility principles, proportions principles, distribution principles and principles for avoidance of catastrophes, further described in Section 2.2.1. One should also try to increase the safety in the society and do so in a cost-efficient way (Räddningsverket, 1997).

The evaluation can be done from several perspectives. The *deterministic* way is based on the consequences and looks at both worst case scenarios, which are less probable, and designing risks. What the designing risk should be is difficult to decide and the deterministic method is therefore somewhat problematic. If one should use the worst case as the designing case this can result in that unnecessarily large cost are put on risk reducing actions. Another way is to analyse the risk from a *probabilistic* perspective, where focus is on the probability for different consequences as a result of the accident. The probabilistic analysis can focus on an individual perspective or the society's perspective, both of high importance. Beyond probabilistic and deterministic evaluations one can compare risks with each other. This is difficult and there may be many things that are different for the various risks that could make the result from such a comparison strange. This will be described more in Section 2.5. Safety distances is another way of expressing the risk and thereby comparing them. Rules and regulations can be used as a tool for evaluating different risky activities (Räddningsverket, 1997).

There are several guidelines for how to evaluate a risk and several recommendations are given for what should be used as acceptable and tolerable risk level. Some commonly used guidelines in Sweden are presented in Section 2.3 together with recommendations regarding distances to different types of buildings.

Risk reducing actions

After the risks have been identified and evaluated the next step is to look at what actions that needs to be made to reduce them. The actions can be divided into categories depending on where in the process they will be used. The first alternative is to start with actions which reduces the risk in an early stage, so that less accidents with large consequences occur. If this is not possible, the second alternative is to use preventing actions to reduce the consequence if an accident happens. If nothing of the above is made the third alternative is to only reduce the consequences after an accident have happened. Best is to use all three alternatives. (Räddningsverket, 1997).

The first method is to have inherent safety. The idea is to reduce the possible sources of risks and accidents. Some general examples of inherent actions are:

- Substitution – the dangerous substance used are exchanged to a less dangerous
- Intensifying – smaller volumes of the dangerous substance are used
- Storage – the dangerous substance is stored in a safer way
- Limit the effect – the effect of an accident is limited
- Simplification – the process is simplified to reduce both technical and human mistakes

(Räddningsverket, 1997).

The first method is also connected to reducing the probability for accidental events. There are several ways of doing this. Some examples are to work with education and better instructions for how things should be used or how things should be done. In addition, systems which monitors the processes and systems which can correct errors can be used (Räddningsverket, 1997).

The second step are to reduce the consequences *if* an accident happens. Alternative ways of doing this is by e.g. establishing protective walls or using fire protection systems to reduce the consequence in case of fire. This are done in beforehand and are called preventative actions. The last method is to make acute actions after the accident has occurred (Räddningsverket, 1997).

Often it is not obvious which actions will have the largest effect. Even if inherent actions are made and the risk is reduced it is still possible that an accident will happen. And if it does, it is necessary to have damage limiting actions as well. The way of prioritizing different actions of reducing the risk may differ between different cases. One way of evaluating the risk reducing actions are by a cost/benefit analysis. By comparing the cost for the action with the benefit it will give different actions can be ranked (Räddningsverket, 1997).

In addition to the risk reducing actions it is worth mentioning that together with having these risk reducing actions it is important that the conditions used in the risk analysis are kept constant. For example, that the risk analysis assumes that the maintenance work for a certain object are at a good level. If this is not the case and the maintenance work are falling behind it may result in much higher risks than what the risk analysis claims (Räddningsverket, 1997).

Documentation

Not to forget is the documentation of the risk analysis. The risks that have been identified should be described in the documentation and the actions to reduce the risks should be described here as well. Equally important is to keep the risk analysis updated. When changes affecting the risk level are made these needs to be included so that the risk analysis represent the reality (Försvarsmakten, 2011). A good documentation is achieved if all details of importance is presented, if it is possible to control what has been done, and if it is repetitive. A good level of documentation is according to Räddningstjänsten, Storgöteborg (2004) reached if:

- assumptions are presented and they are argued to be reasonable
- the method used are presented
- calculations involved are included
- the calculations can easily be updated
- tools used are presented
- sources used are presented correctly

Uncertainty analysis

In a risk analysis there will always be a number of things that one will be uncertain about and it is always important to take the uncertainty into consideration. Boverket and Räddningsverket (2006) brings up some examples of where the uncertainty may be large and where it can have effects on the result:

- Mistakes in the identification and evaluation of possible risks
- Mistakes in the evaluation of what might happen in case of different accident
- Wrong or inadequate input data
- Inadequate calculations or models
- Misjudgement of what effect the risk reducing actions will have

Review of the risk analysis

The final step of the risk analysis work is to review the risk analysis. This is an important step in order to get a sufficient quality of the risk analysis. The review is done in three steps. Firstly, a check is done by the persons who made the analysis, secondly an internal check is made and third an external review is done (Räddningsverket, 2003).

2.3 Rules and recommendations

2.3.1 General rules regarding personal safety in the environment

There are rules saying that risks that may have an effect on the personal safety and health needs to be considered and reduced. The Swedish laws Plan- and building law (Plan- och bygglagen, PBL1995:1197, PBL 1998:839) and the environmental laws in Miljöbalken (MB) points at the importance of this. The risk analysis will be a document that will support the decisions made regarding safety (Länsstyrelserna Skåne län, Stockholms län and Västra Götalands län, 2006). According to Räddningstjänsten, Storgöteborg (2004), there are lot of documents which is called risk analyses but a lot of them are at a detail level that is too low to make decisions from it.

Some of the rules that have an influence on the risk analysis are brought up in Räddningsverket (2004). The Plan- and building law (PBL) is said to be the most important of the rules. The law says that risks that one should consider when building something should be presented in the general city plan. Other laws of importance are:

- The law about protection against accidents (Lagen om skydd mot olyckor) which handles preventing activities, rescue work and follow up work to protect human life and health as well as properties.
- The law about activities to prevent and reduce the result of severe chemical accidents (Lagen om åtgärder för att förebygga och begränsa följderna av allvarliga kemikalieolyckor)
- The law about flammable and explosive subjects (Lagen om brandfarliga och explosiva varor)
- The zero vision (Nollvisionen), meaning that one should aim to have zero accidents.

2.3.2 Recommendations for safety distances and acceptable risk levels

Although the laws say that risks need to be considered it is not specified how the risks should be evaluated and how small a risk needs to be to be on an acceptable level. For many risky activities there are rules regarding e.g. safety distances from a business to residential areas. It is often the case that the given safety distances also consider noise, smells and other annoying things that not necessarily have to be dangerous for people. These rules of safety distances result in that large areas cannot be used for residential areas or other businesses (Räddningsverket, 1997). The guidelines in Boverket (1995) recommend having not less than 200 m safety distance for industries. For industries with increased risk the distance needed can be of 1000 m or more. Regarding railways and roads where dangerous gods passes the recommended distance is 100 m.

In PBL some guidelines are given regarding how areas at different distances from a road or railway with dangerous gods should be used. The distance from zero to 150 m are by Länsstyrelserna Skåne län, Stockholms län and Västra Götalands län (2006) divided into three zones where the closest zone should be for activities where people will not be during most of the time. The middle zone is for activities like offices, shops and industries. Furthest away from the risk source is building which is of high importance for the society like hospitals, schools and residential areas. This is presented in Figure 2.5. Although Länsstyrelserna Skåne län, Stockholms län and Västra Götalands län (2006) divided the area in zones, no distances for where the zones start and end are specified because it may vary depending on the area. However, according to Länsstyrelsen Stockholm (2016) some recommended distances for these zones can be given, see Figure 2.6.

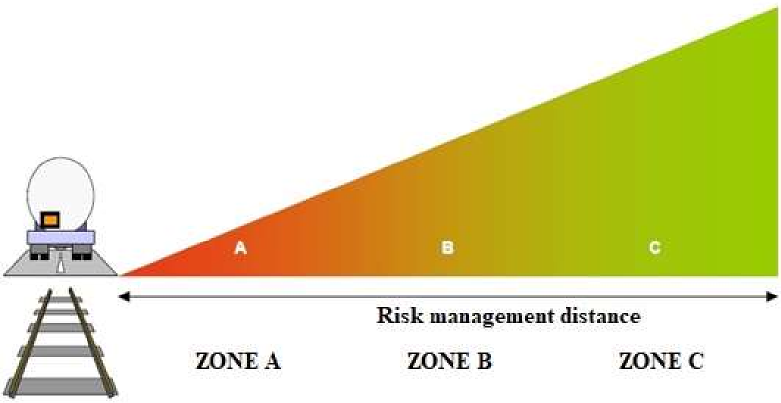


Figure 2.5 Recommended distances for different activities and buildings. From Länsstyrelserna Skåne län, Stockholms län and Västra Götalands län (2006).

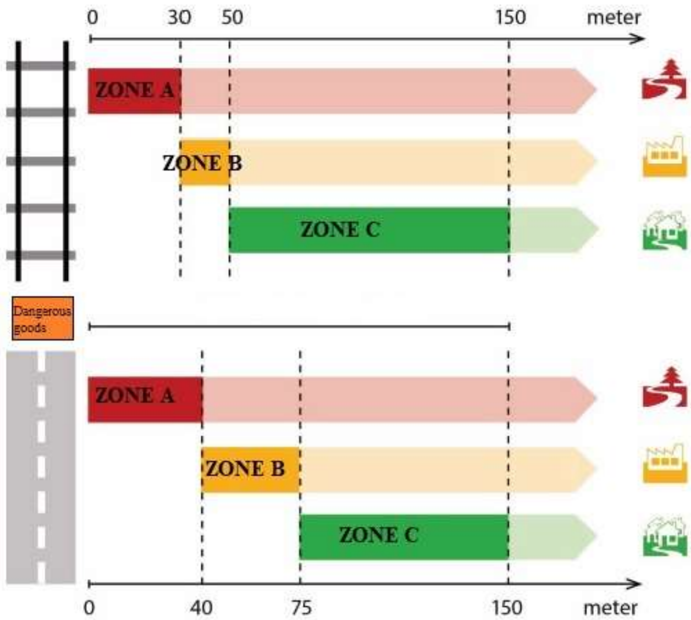


Figure 2.6 Zones for different activities. From Länsstyrelsen Stockholm (2016).

Beyond the recommendations for safety distances mentioned above, e.g. Gothenburg city have some regulations for at what distances they recommend to have different types of buildings and where one should have building free areas (Norconsult, 2015). Their recommended distances are shown in Figure 2.7. If comparing the distances given in Figure 2.6 and Figure 2.7 one can see similarities even if the exact distances are not the same. Together with the recommended distances it is also given some recommended risk levels (Cowi, 2017a). These are presented in Figure 2.9 where it is also compared to the recommendations given by DNV which is described below.

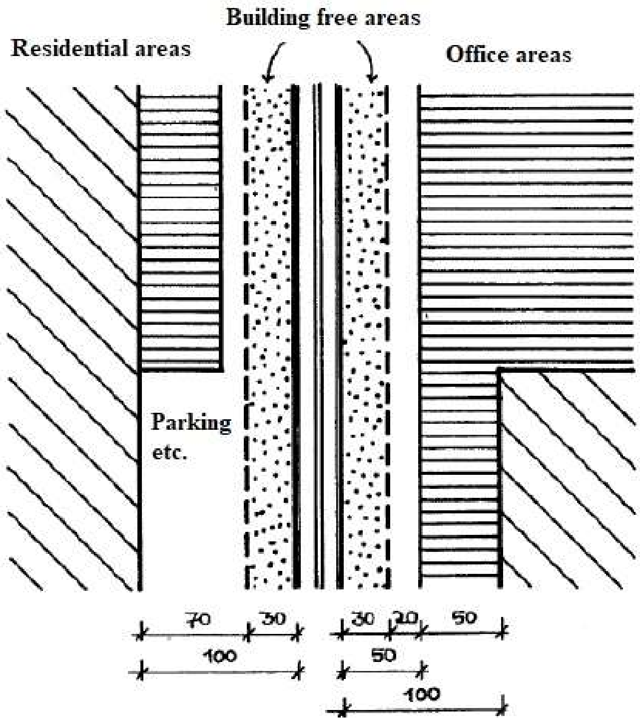


Figure 2.7 Recommended distances in meters. From Göteborg (1997).

Some criteria for what levels that can be seen as acceptable for risks are given in Räddningsverket (1997). Concerning the risk for the society two lines are given in the FN-diagram. In Figure 2.8 the recommended risk levels from DNV (Det Norske Veritas) are presented. These recommendations are commonly used in the building sector. The criteria presented are for a 1000 m long distance and for buildings on both sides of the road. The upper line (blue) represents the limit for where a risk above the line cannot be accepted and risk reducing actions needs to be done. The lower line (purple) represents the limit below which the risk can be seen as so low so that no actions are needed to reduce the risk. The lower limit is called the acceptable level and the upper the tolerable level. The area in between the lines is called ALARP (As Low As Reasonably Practicable). If the risk level is in the ALARP area risk reducing actions should be analysed and they should be used if it is economically reasonable.

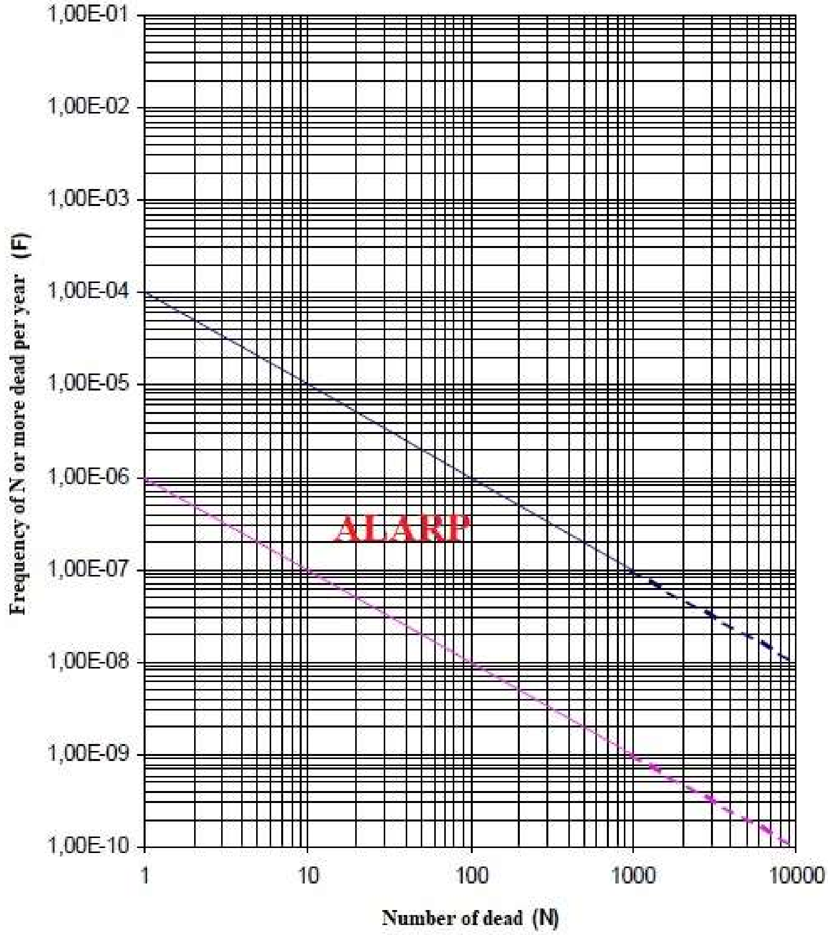


Figure 2.8 Suggestions by DNV for criteria for risk for society. From Räddningsverket (1997).

Concerning the individual risk level, the criteria given by DNV are that it can be acceptable with a risk level below 10^{-7} per year and that it can be tolerable with a risk level lower than 10^{-5} per year (Räddningsverket, 1997).

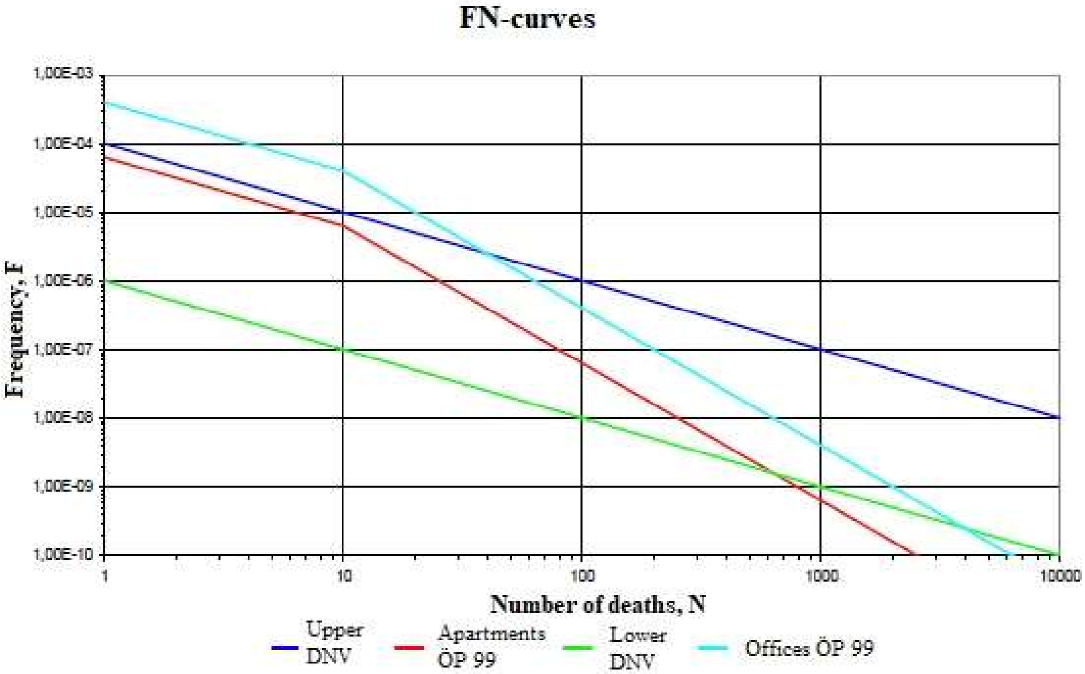


Figure 2.9 A comparison between the risk level criteria from DNV and from GÖP. From COWI (2017).

2.3.3 Recommendations of risk reducing actions concerning explosions

Boverket and Räddningsverket (2006) gives several examples of risk reducing actions that could be used in order to reduce the risk from various accidents and events. In the document it is also described what effect the risk reducing action will have, and other aspects such as costs, uncertainty and possibility to regulate it with the zoning.

Concerning explosions, the recommendations that is given to reduce the risk is presented in Table 2.1. The X marks that the action will reduce the explosion risk concerning the shock wave, explosion debris or collapsing or moving constructions parts or subjects. For further information about the explosion event see Chapter 3.

Table 2.1 Recommendations for risk reducing actions concerning explosions. From Boverket and Räddningsverket (2006).

Risk reducing action	Shock wave	Debris	Construction parts and subjects
Pool / embankment	X	X	
Safety distance	X	X	X
Vegetation trees	X	X	X
Mound	X	X	X
Wall	X	X	X
Disposition of the area	X	X	X
Dig down the risk source	X	X	X
Strengthening of the building frame	X	X	X
Reduction of window area		X	X

2.3.4 Guidelines for reviewing risk analyses

By Räddningsverket (2003) a checklist is produced in order to help in the external review. The list is long and only the general parts that needs to be checked is presented below. All the parts need to be analysed from several perspectives.

1. Planning and implementation
   1.1. The composition of the analysis group
   1.2. Internal check
   1.3. Time
   1.4. Requirements from authorities
2. Content and extent
   2.1. Purpose, precision and extent
   2.2. Limitations
   2.3. Description of the surrounding
   2.4. Analysis method
   2.5. Presentation method and method for evaluation of risks
   2.6. Identification of accidents
   2.7. Probability calculations
   2.8. Consequence calculations
   2.9. Presentation of risks
   2.10. Risk evaluation
   2.11. Uncertainty calculations
   2.12. Transparency
   2.13. Recommendations
   2.14. References
3. Quality of documentation
   3.1. Are all needed parts included in the analysis?

2.4 The situation in Sweden and international

2.4.1 The situation and development in Sweden

Räddningsverket (1997) described that by 1997 no general guidelines for risk analysis were used. It was also described that it would be valuable to have a standardized way to identify, analyse and evaluate the risk. Models of documenting were available, but not widely used by then. With standardizations of risk analyses Räddningsverket (1997) described that probably:

- it would be easier to review the risk analyses
- a larger uniformity would be achieved
- more risk analyses would be performed
- the experience feedback would increase
- the communication would be better

(Räddningsverket, 1997).

By 2006 there was still no general, or by the government, decided requirements for what should be included in a risk analysis or how it should be performed. Although some handbooks and recommendations has been published by Räddningsverket to support the risk analysis work (Boverket and Räddningsverket, 2006)

According to Länsstyrelserna Skåne län, Stockholms län and Västra Götalands län (2006) the need for making good risk analyses has increased. This is linked to the fact that large cites wants to become more densified. The cites are growing and more areas needs to be used as residential areas or offices. This means that areas closer to roads needs to be used as well and by that the risks increases.

2.4.2 Investigation of similarities and differences in risk analyses

During 2016 a study was made by Alvarsson and Jonsson which analysed how risk analyses regarding dangerous goods transports were made in Stockholm, Västra Götaland and Skåne. What was discovered in the study was that it can be large differences in how the risk analyses are made and in what assumptions that are made in the risk analyses (Alvarsson and Jonsson, 2016).

It was discovered that it can be differences in what categories of dangerous goods that is included in the risk analyses. Assumptions of what risks that will not have a large consequence are made. However, the same assumptions are not made in different risk analyses. Therefore, it was suggested that a commonly accepted guideline for what should be included in a risk analysis could be needed (Alvarsson and Jonsson, 2016).

Regarding consequences from an accident there were large variation in calculation models, and this was considered to be a large problem. It was concluded that it is a need for a standardized model for how consequence calculations should be performed (Alvarsson and Jonsson, 2016).

What was also discovered to have a large impact on the risk level in the risk analysis was how assumptions regarding the amount of people in the studied area was made. It could be large variations in assumptions for how many people that will be inside buildings or outside of it. Since the society risk level is what is evaluated when deciding if the risks are tolerable or not these assumptions have a large impact (Alvarsson and Jonsson, 2016).

When it comes to suggestions for risk reducing actions the effects of them were mostly qualified guesses. Furthermore, the difficulty of knowing what actions that would have the largest impact and how they affect the risk level was discovered as a problem. In most cases general suggestions of risk reducing actions were given and why they were suggested was not very well motivated (Alvarsson and Jonsson, 2016).

Due to this, some suggestions for improvement were given in Alvarson and Jansson (2016). According to them improved statistics of the transports of dangerous goods is needed. In addition, there was need of increasing the knowledge about the consequences. Further suggestion was to increase the communication between different parts by having forums or interest associations for risk handling. Lastly, it is suggested that rules or regulations may be needed for how to make frequency and consequence calculations. In order for this to be done Alvarsson and Jonsson (2016) argues that an increased collaboration between companies and authorities are needed.

2.4.3 Methods for risk analyses used in the Netherlands

In the Netherlands a method called RBM2 is used for risk analyses. The method was produced at request from the government. They saw that there was a need for having a standardized method for evaluations of risks connected to transportation of dangerous goods. The standard which is now used in the whole country is valid both for transports on roads and railways. By using these standards, they get quick analyses which gives the risk level both for the individual and for the society (Norconsult, 2009).

The method RBM2 uses methods and guidelines from some books, often referred to as the yellow book and the purple book. The TNO Yellow Book includes calculation methods for the physical effect while the TNO Purple Book. See Van den Bosch and Weterings (2005) for the yellow book and Uijt de Haag and Ale (2005) for the purple book. These documents include some guidelines for calculations of the quantitative risk assessment (Norconsult, 2009).

The RBM2 method includes risks from flammable gases, flammable liquids, toxic gases and toxic liquids. Other categories of dangerous good are either transported in small amounts or not considered to be deadly. The categories which is included in the model is 2.1, 2.2, 3 and 6.1. Information about the categories are found in Section 5.4. Explosives and radioactive substances, category 1 and 7 are transported in very small amounts while category 4, 5, 6.2, 6.3, 8, 9 are not as dangerous so that it will have deadly effects on some distance from the accident (Norconsult, 2009).

In the RBM2 method a number of things are considered. One is looking at the number of transports passing the area analysed. The number of people that will be in the area is included in the analysis. There are also possibilities to take into consideration variations over day and night as well as weekdays and weekends both for the transports and the population (Norconsult, 2009).

Furthermore, the amount of goods transported is considered. Additionally, the type of road gives variations in statistics for number of accidents and what consequences an accident will result in. If the road has several lanes it can also be included the variations in number of accidents for the different lanes. Also, the consequence might be different depending on what lane the accident occurs in (Norconsult, 2009).

When all information needed is collected the risk can be calculated by using event tree analyses as the one in Figure 2.10. By summarising the risks from different events, a curve can be presented in a FN-diagram where it can be compared to the guidelines for acceptable risk criteria (Norconsult, 2009).

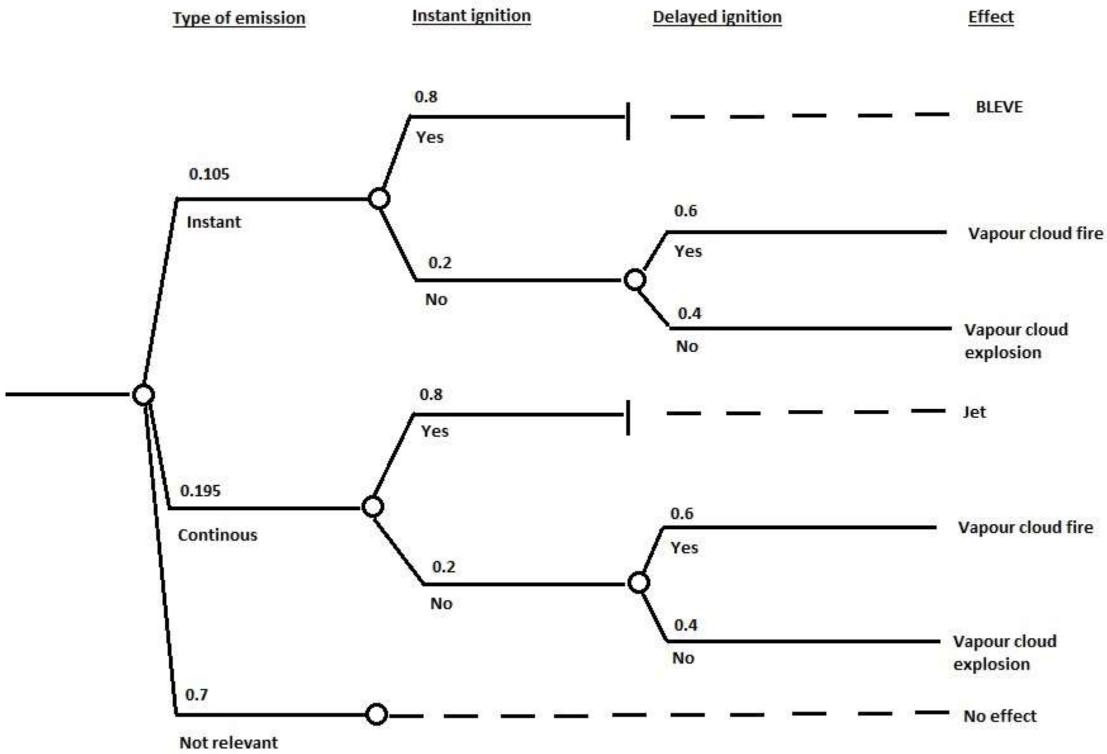


Figure 2.10 Event tree analysis of emissions of flammable gas. Based on Norconsult (2009).

2.5 Quality and critique

Lack of standardized methods

According to Boverket and Räddningsverket (2006) some guidelines and standards for risk analyses are available over the world. Although, the quality of risk analyses in Sweden varies a lot. They believe that with increased standardisations and increased requirements on the analyses the quality would increase. For example, requirements of the used method, documentation and competences could be set in order to get a better quality and usefulness of the analysis.

How probability and consequence are calculated

To make a risk analysis can be difficult and the work and methods are often criticized for many reasons. In Räddningsverket (2003) some critique against the commonly used methods are brought up. The probability of an event is something that people argues is impossible to evaluate. There will be uncountable numbers of possible events in combination with each other and people are unpredictable and don't follow all rules, as they are assumed to do in the risk analysis. Because of this, the risk analysis will be an underestimation. The risk also includes the consequence. In a risk analysis the consequence can be measured in economical perspectives which some claims to be wrong. They mean that it is impossible to put an economical value on human lives and suffering. Furthermore, risk analyses are criticised since they are measuring events that do not exist or have not happened. Therefore, the risk analysis will only be a result of how the risk analyst evaluate the risk and it is because of that not fully representing the reality (Räddningsverket, 2003).

Insufficient knowledge
It is brought up by Försvarsmakten (2011) that the quality of the risk analysis is connected to how much knowledge the one doing the analysis has about the activity that is analysed. If the person does not have enough knowledge about the analysed activity it is important that other persons can be a part of the risk analysis work to ensure that the quality of the analysis is good enough.

Risk evaluation methods
One method may be used to evaluate the risks is to compare them with each other. However, this is not a method that is commonly used when evaluating risks for buildings close to roads. This method may often be complicated and there are several mistakes that can be made in such comparisons. There are several ways of analysing how large the individual risk from an accident are. The methods cannot simply be compared with each other. Another mistake is that some risks from different events are compared where one of the events may be optional and the other one is not. Problems can arise when trying to compare what is worst case between several small accidents or one large. It may also be a problem if risks to the whole society are compared to risks that only parts of the society are exposed to. Even though comparisons are complicated it can be a start of evaluating the risks (Räddningsverket, 1997),

If comparisons between risks are made there are some things that one can consider making the comparison more valuable. One should have a clear purpose of the comparison. If the risks are more well described the comparison will be easier to understand and better. It is important that even though one risk is ranked as worse than another, none of the risks may be acceptable. Lastly, one should remember that the comparison is just a comparison and does not necessarily represent true facts, therefore the uncertainty involved should be highlighted (Räddningsverket, 1997).

How safety distances are used
Boverket and Räddningsverket (2006) criticizes how safety distances are used to make sure that a risk is low enough. According to them the safety level is not very well connected to the distance from the risk source. In many cases risk reducing actions will have much more effect than just placing the building hundreds of meters away. Using these safety distances, which in some cases are really large, will result in that a lot of areas which could have been used gets unused. Boverket and Räddningsverket (2006) also comments that in most cases it will not be enough to use one risk reducing action. A combination of actions will often have the largest effect on reducing a risk.

Uncertainty analyses to increase the quality
One way to get a higher quality of the risk analysis is by looking at the uncertainty. Räddningstjänsen, Storgöteborg (2004) gives some guidelines for how this could be done. At first it is important to have in mind that the risk analysis will not be based on completely true facts. One need to look at uncertainty in the resources which affects the project definition. Furthermore, one need to think about the uncertainty regarding the decisions and assumptions that are made, did the model for the risk analysis work good on the specific situation, and if the data used in the analysis was correct and representative.

2.6 The explosion risks

2.6.1 Explosion sources

There are several reasons why explosions occur. It can be by accidents, or by purpose. Accidental events like traffic accidents can result in fires and in a worst case scenario an explosion. Large explosions can be criminal actions or terror attacks. The threat of these type of things are increasing in Sweden and there is a vulnerability in the society towards these types of actions. In case of wars explosions of higher magnitude can occur. Explosions connected to wars or terror attacks are not what a building normally should be designed to withstand. However, it is of interest to know how buildings and constructions respond to loads from explosions from accidents and terror (Johansson and Laine, 2012a).

2.6.2 Possible consequences

Consequences in case of an explosion from explosives
A large explosion can result in a shock wave with a large pressure. The increased pressure might result in direct damage on the human body. People might also get hurt by parts of buildings which gets destroyed by the shock wave. The shock wave might also result in that buildings collapses which may lead to that people get hurt or dies (Norconsult, 2009).

Consequences in case of emissions of flammable gases
Several consequences are possible in case of emissions of flammable gases. If the gas ignites immediately the result can be a jet flame. If it takes some time before the ignition, the gas cloud gets time to spread over a larger distance and depending on the direction of the wind in might spread over surrounding buildings. The result of a delayed ignition could be a flash fire or a vapour cloud explosion. Third, it is possible to get a BLEVE (Boiling Liquid Expanding Vapour Explosion). This takes between 5 – 20 minutes before it can occur. What is happening is that liquid expands to gas which results in that the entire tank explodes. The result is a large fire ball which can have a diameter of 80 meters (Norconsult, 2009).

Consequences in case of emissions of flammable liquids
If emissions of flammable liquids occur the damage is often more local than it is for gas emissions or explosions. What possibly will happen is that a puddle fire occurs on the road and the damage will be limited to some dozen meters (Norconsult, 2009).

Consequences in case of accidents with oxidizing substances
In most cases oxidizing substances will not contribute to large consequences. In order for large consequences to happen the oxidizing substances needs to be mixed with oil or petrol. If it is mixed however, the result might be an explosion of the same size as if it was an explosion of explosives (Norconsult, 2009).

2.6.3 AMRISK, a method for analysing the explosion risk

AMRISK is a risk analysis method described in Försvarsmakten (2011). The method is used to analyse explosives and the amount of explosives that can be acceptable. The method is mainly used by Försvarsmakten when analysing the risk from storage of explosives. Hence, it is not used in the risk analyses which has been reviewed in this report. An important difference in these two cases are that the storages for explosives have a permanent risk. However, this is not the case for buildings located nearby roads where dangerous goods is transported. Special for this method is the way of considering accidents with large consequences. An aversion factor is multiplied with the actual risk to get a value of how the accident will be experienced by the society if it happens. When looking at an example with ammunition storage the following things are considered, see Figure 2.*11*. The course analysis will look at the amount of explosives as an equivalent amount of TNT. This part considers the probability for an accident. The analyse of the effect looks at how large the explosion will be as an impulse, the forces and the spalling effects. Moreover, the probability for people to be on the affected area is considered. In the exposure analysis the risk is analysed by individual risks, collective risk, the experience of the risk and if there are other objects, like buildings of high importance, that has need for extra protection (Försvarsmakten, 2011).

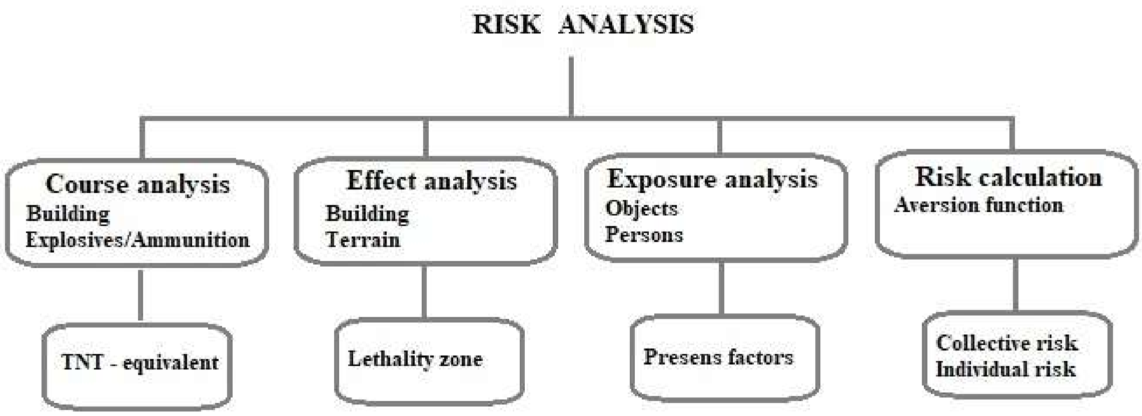


Figure 2.11 AMRISK risk analysis method. Based on Försvarsmakten (2011).

3 Explosion load

3.1 Orientation

An explosion is a large expansion of matter happening during a short time. An explosion can come from e.g. gas or explosives such as TNT. Explosions might be of different strength, and chemical explosions are often divided into detonation and deflagration. Detonation is a fast reaction that takes some microseconds while the time for deflagration to develop may be much longer. Detonation results in more intense loading, with high pressure and short duration, compared to deflagration. An explosion from an explosive such as TNT is always a detonation while an explosion from gas most often is a deflagration (Johansson and Laine, 2012a).

In an explosion, a lot of energy will be released during a short period of time. The pressure will increase, and shock wave will spread from the centre of the explosion and outwards. This happens in a speed faster than the speed of sound. In front of the shock wave front with high pressure, there will be ambient air pressure. During a short time, the pressure will rise and shortly after, it will go back to normal again. Together with the increased pressure the temperature will rise. The phenomena of an explosion are described in Figure 3.1. Notice that the ambient air pressure P_0 is not zero, but about 101 kPa at a temperature of +15̊C. An air pressure of zero would correspond to vacuum (Johansson and Laine, 2012a).

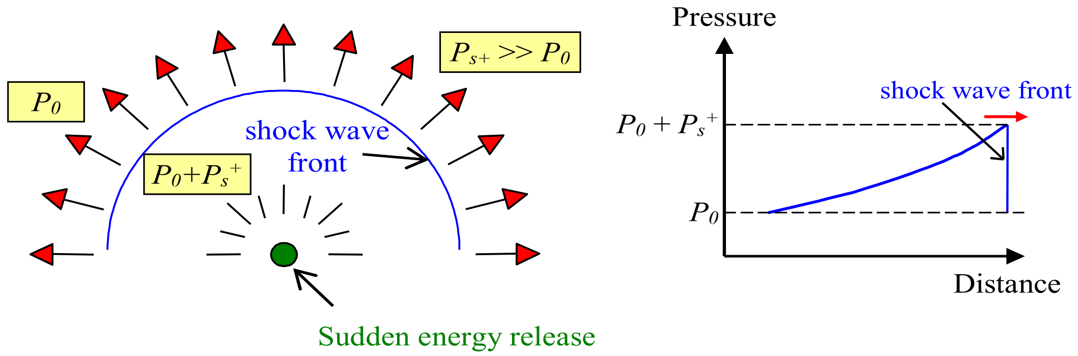


Figure 3.1 The pressure increases at an explosion. From Johansson and Laine (2012a).

3.2 Impulse loading

An explosion is an example of an impulse load, a load which is acting only during a short period of time. A structure subjected to an impulse load will react differently than if it was subjected to static loading. An impulse load is dynamic instead of static, see Figure 3.2. Collisions and progressive collapse are some further examples of impulse loads (Johansson, 2014).

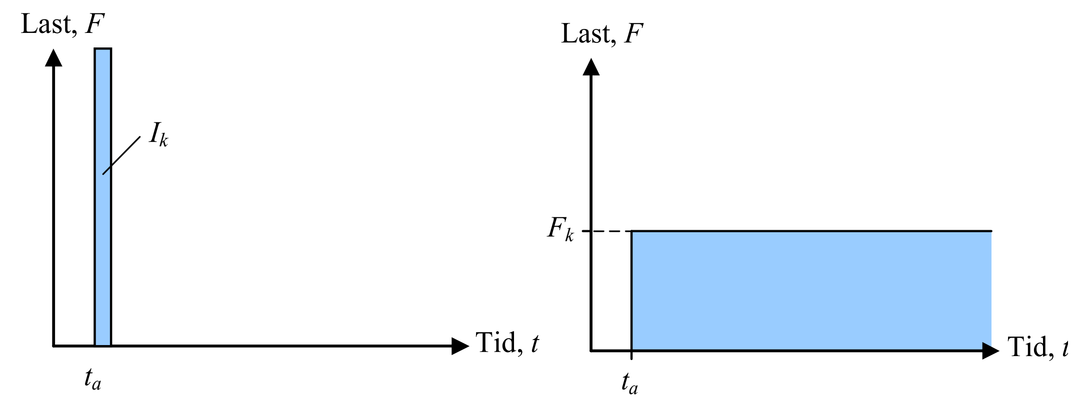


Figure 3.2 Characteristic impulse load (left) and characteristic force load (right). Based on Johansson (2014).

An impulse load can according to Johansson (2012a) be described as in Figure 3.3. The impulse i is a function of pressure P and time t, which for an explosion from explosives may be described by Equation (3.1). The impulse intensity i^+ of the positive phase can be calculated according to Equation (3.2) where the pressure-time relation $P(t)$ is calculated with Equation (3.3) and α is a factor which can be solved from the Equation when the other factors P^+, t^+ and i^+ are known (Johansson, 2012a).

$$i = \int_{t_0}^{t_1} P(t)\mathrm{d}t \tag{3.1}$$

$$i^+ = P^+ t^+ \left[\frac{1}{\alpha} - \frac{1}{\alpha^2}(1 - e^{-\alpha})\right] \tag{3.2}$$

$$P(t) = P^+\left(1 - \frac{t - t_a}{t^+}\right)e^{-\alpha(t - t_a)/t^+} \tag{3.3}$$

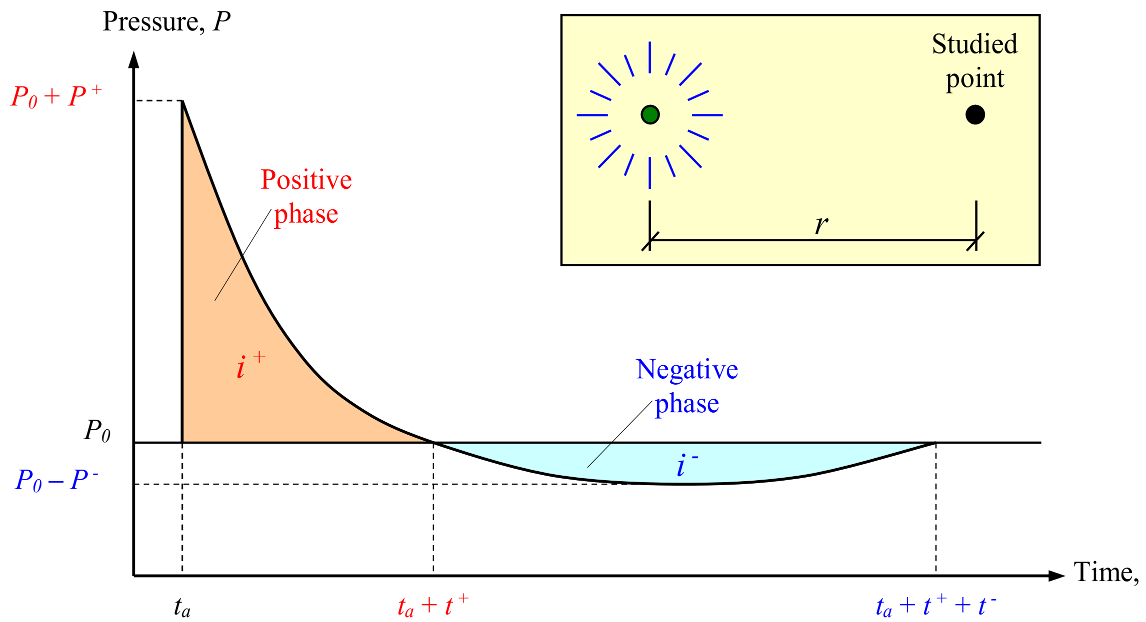


Figure 3.3 Positive and negative phase of an impulse load. Based on Johansson (2012a).

When studying a specific point of interest, the variation in pressure can be described by Figure 3.3. Initially, the point is just subjected to ambient air pressure P_0. Since the point is located with some distance from the explosion it takes until t_a before the explosion shock wave reaches it and the pressure in the point increases. The time of the increase can be assumed to be zero seconds and it can therefore be seen as a momentane increase of pressure. At some time after the explosion, $t_a + t^+$, the pressure reaches ambient air pressure again. After this, a negative phase follows, where the pressure level is lower than normal. After some further time, the pressure will be back at the ambient air pressure again. If integrating the pressure-time graph one will get the impulse intensity i^+ and i^- for the positive and the negative phase (Johansson, 2012a).

Sometimes, the pressure-time relation is assumed to be a linear relation instead of exponential in accordance with Equation (3.3). If calculating the duration of the impulse with this assumption the reflected and incident case will have different durations, which is incorrect. Figure 3.4 describes the difference in an incident and reflected case and how they can be simplified into linear relations. It can be seen that the pressure in the reflected case will be much higher (Johansson, 2012b).

$$t_1 = \frac{2i_1}{P_1} \tag{3.4}$$

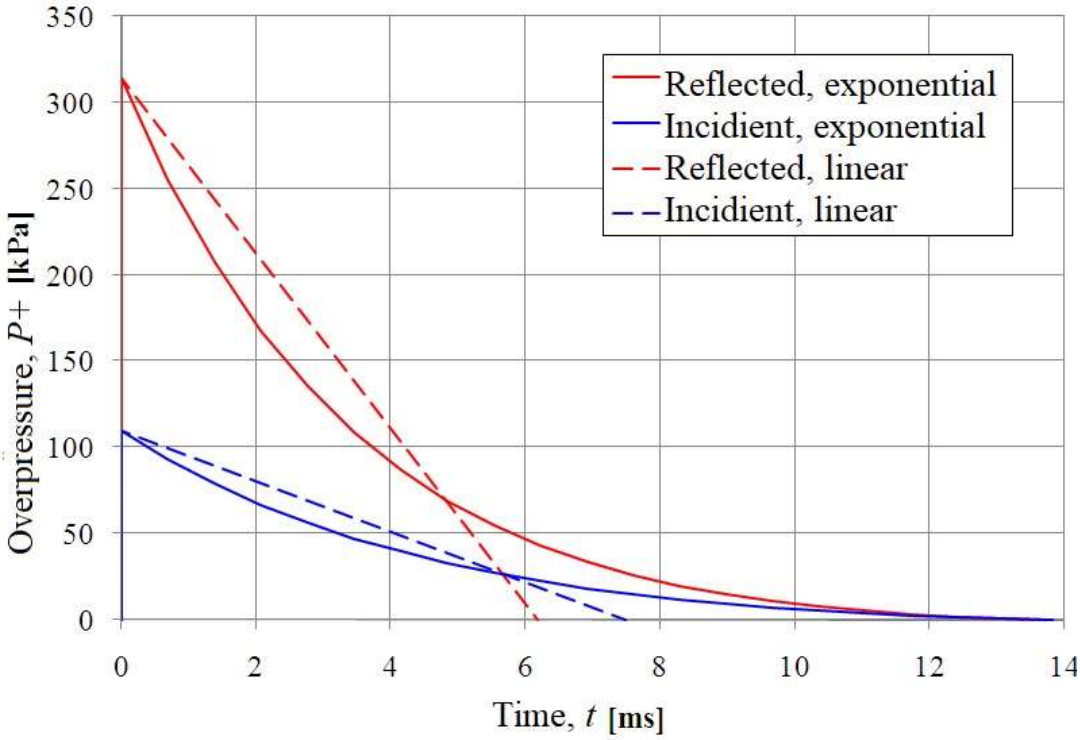


Figure 3.4 Overpressure for reflected and incident case, exponential relation and simplified linear relation. From Johansson (2012b).

3.3 Influence of the surrounding

3.3.1 Reflection

If the volume is restricted to expand in one or several directions or if it is reflected by the surrounding, the effect of the explosion will be affected. If subjected to several reflections, the overpressure will be higher, and the duration will increase. The difference with a reflected explosion is what is happening after the first wave of pressure. Smaller waves with lower pressure than the first will hit the point of study as schematically shown in Figure 3.5 (Johansson and Laine, 2012a).

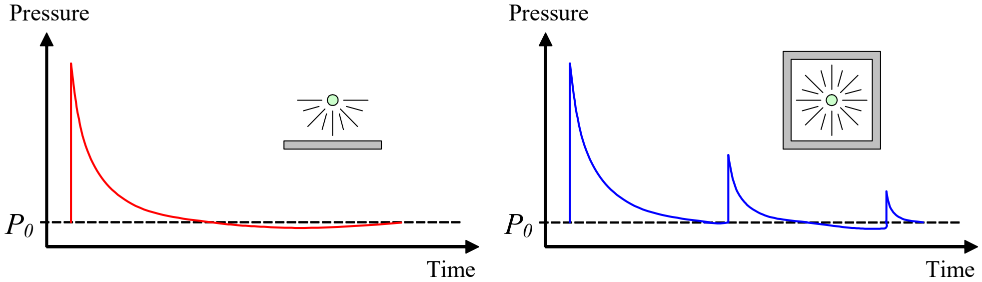


Figure 3.5 Pressure wave in the case of one reflection (left) compared to the case with several reflections (right). From Johansson and Laine (2012a).

In the case of a wave reflected perpendicular to the surface an increased pressure will occur close to the surface. This reflected pressure will be at least a factor 2 larger than the incoming pressure from the explosion. What is happening is described in Figure 3.6. In figure (a) the shock wave front is on its way to hit a surface. The pressure behind the wave front is $P_0 + P_s^+$ while the pressure in front of the wave front still are at ambient air pressure. The wave front is traveling with the speed U_s and the air particles inside the wave with the speed U_p. After the wave front has hit the surface in figure (b) the pressure between the wave front and the wall have the value $P_0 + P_r^+$. The reflected pressure can have a value that is more than double of the pressure in the wave front $P_0 + P_s^+$. The speed of the wave front is now changed to U_r as the air the wave is moving into has a higher pressure of $P_0 + P_s^+$ (Johansson and Laine, 2012a).

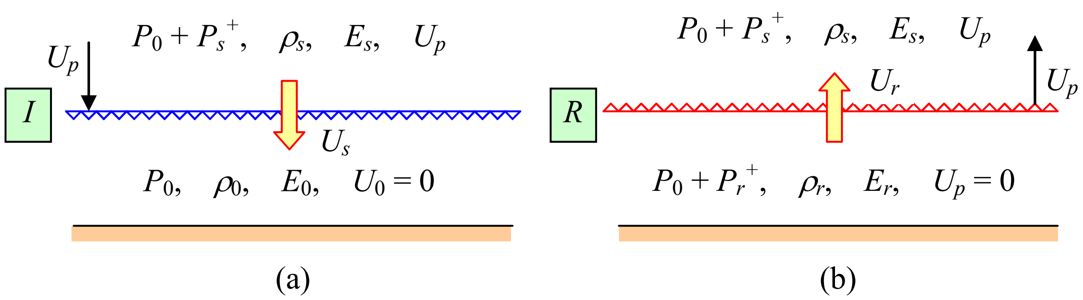


Figure 3.6 Reflection of a shock wave. From Johansson and Laine (2012a).

The reflected overpressure, P_r^+, is calculated by multiplying the incident overpressure by a reflection coefficient, Λ_p. The coefficient is a function of the incident overpressure and the ambient air pressure and is given by Equation (3.5). According to the equation a higher pressure will have a higher reflection factor and that the increase will be exponential. (Johansson, 2013). According to Johansson and Laine

(2012a) Equation (3.5) is valid for pressure up to 1000 kPa. For pressure higher than that, more info can be found in Johansson and Laine (2012a).

$$\Lambda_p = \frac{8P_s{}^+ + 14P_0}{P_s{}^+ + 7P_0} \tag{3.5}$$

3.3.2 Mirroring

One type of reflection is the so called mirroring effect. This will happen if there is an explosion close to the ground. Simplified it can be described as in Figure 3.7, where the energy intensity is doubled from what it would have been without the mirroring effect. This is described by almost double the charge weight from the explosion. This is not completely true, and a common estimation is to assume a value of 1.8 because some energy will be absorbed by the ground. However, 1.8 is not a value that will be correct for all different materials since they will absorb different amount of energy (Johansson and Laine, 2012a).

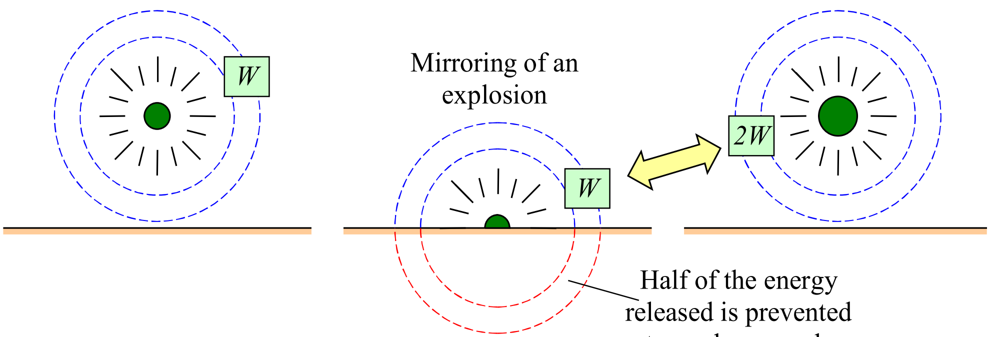


Figure 3.7 The effect of mirroring. From Johansson and Laine (2012a).

3.3.3 Diffraction

A third phenomenon is so called diffraction. This is the explanation to why all external surfaces of a building will be affected by an explosion. Figure 3.8 describes what is happening after different time, before the wave hits the first façade of the building, when the shock wave has reached the roof and when it has passed the building. Different air pressures will occur at the façade and the roof and the difference in pressure on different sides of the building is the reason why swirls is created around the building (Johansson and Laine, 2012a). For example, in figure b) the pressure in the reflected zone and after the wave front on the roof are much different and they will try to even out. This will create turbulence on the roof. In figure c) the wave front will bend instead of just continuing forward. This is also because of the pursuit of evening out the air pressure. This explains why all parts of the building gets affected by an explosion. The load on each side of the building is complicated to calculate. The diffraction effect is larger on an explosion with a bit longer duration. Diffraction can easier be understood if comparing the pressure wave with sound, which are much smaller pressure waves. If someone yells at one side of a building you will hear it on the other side, but just not as high (Johansson and Laine, 2012a).

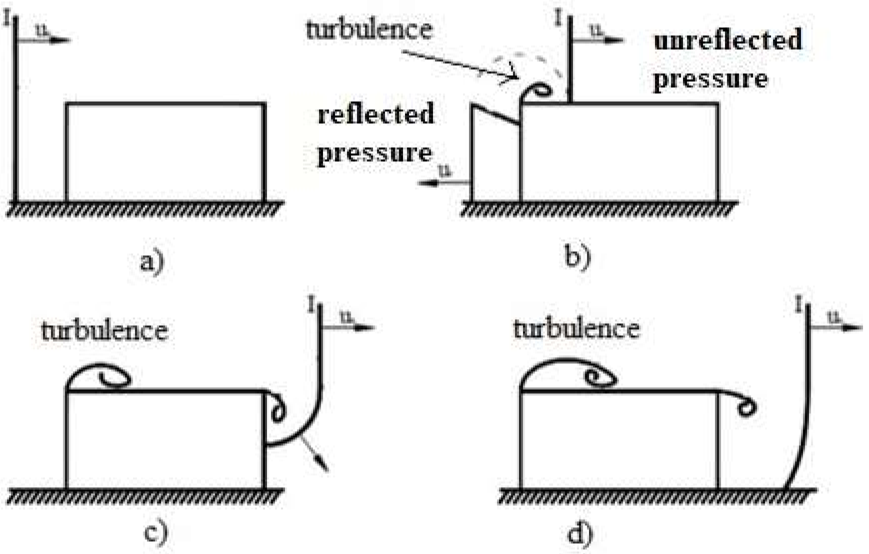


Figure 3.8 Diffraction. From Johansson and Laine (2012a).

3.3.4 Surrounding buildings

Furthermore, how the urban environment will affect the explosion effect may also be of importance. Looking at Figure 3.9 one will see two points A and B at equal distance from the explosion. The path between the explosion and A are blocked by a house. Assuming that the houses are very high, no shock wave will go over the buildings. Point A will be affected by the explosion due to diffraction and reflection. The load will be reduced both because of diffraction effects and by the increased distance. The reflected wave will affect the point A, but the wave fronts will not reach the point at the same time, giving a result similar to Figure 3.5 (right figure). Looking at point B and comparing the situation to an explosion on an open field, the situation in point B is worse. The pressure wave can initially only spread in two directions and hence the energy intensity behind the shock front is not reduced as fast, giving a worse effect on point B. The two examples are often called shielding (point A) and channeling (point B) (Johansson and Laine, 2012a).

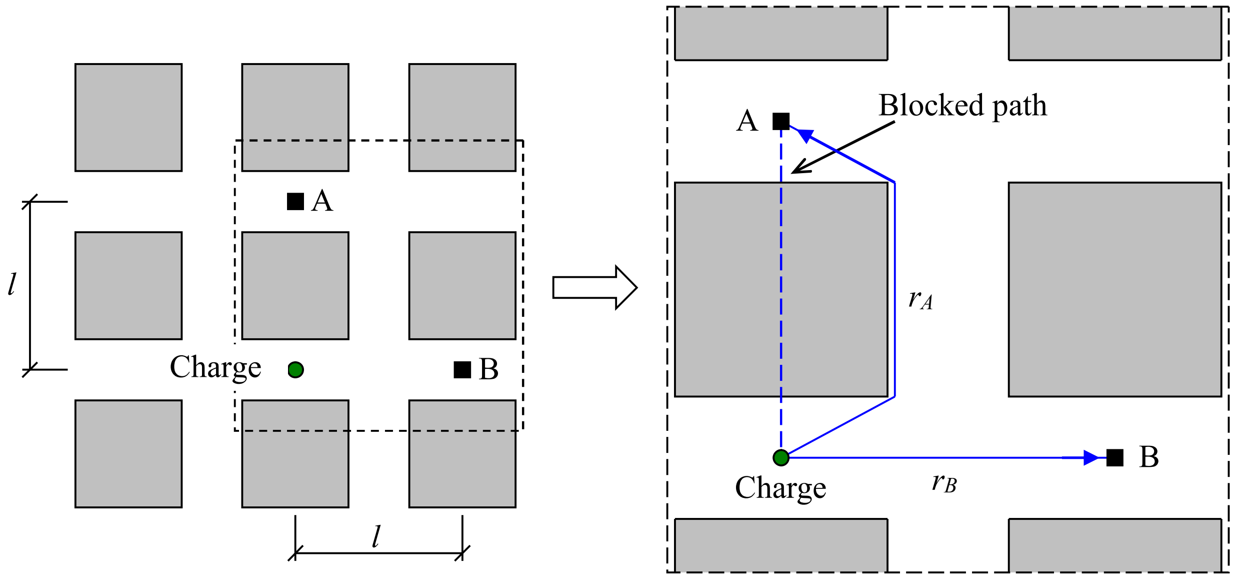


Figure 3.9 Explosion in an urban environment. From Johansson and Laine (2012a).

3.4 TNT explosions

3.4.1 Pressure, time, and distance relations

The influence of an explosion will vary with the distance. Therefore, some scale laws are used to compare the effect of the explosion at different distances from it. Looking at Figure 3.10 there are two cases. The first case shows an explosion load W at a distance r with the corresponding relation of pressure, impulse and duration. The second case is modified with a factor α. If multiplying the distance r by α and the load W by α^3 the overpressure will be the same. Meaning that at a doubled distance, $\alpha = 2$, an $\alpha^3=2^3=8$ times larger charge will give the same peak pressure. The relation is described by Hopkinson's scale law, see Equation (3.6) where the scaled distance Z is dependent both of the real distance r, and W which is the amount of TNT. In Figure 3.10 the overpressure P_s^+ and the scaled distance Z are the same for both cases. However, one should note that the duration as well as the impulse will differ when changing the distance or the load. An increased duration will result in a larger impulse (Johansson and Laine, 2012a).

$$Z = \frac{r}{W^{1/3}} \tag{3.6}$$

As described in 3.3.2, there will be a mirroring effect if the load is placed close to the ground and in such cases the amount of TNT needs to be modified. The modified value W_{mod} is calculated with Equation (3.7) using α as described in 3.3.2 (Johansson, 2012a).

$$W_{mod} = \alpha \cdot W \tag{3.7}$$

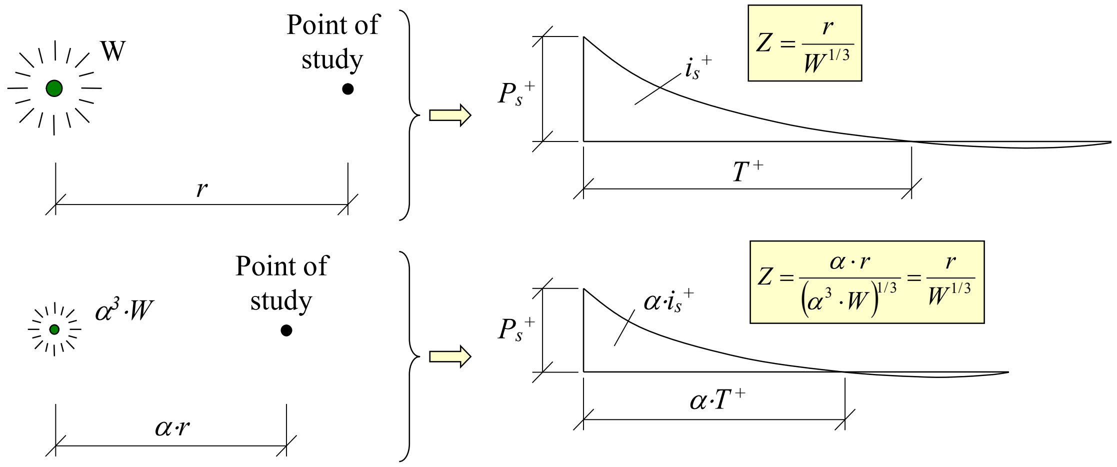


Figure 3.10 Hopkinson's scale laws. From Johansson and Laine (2012a).

For an explosion caused by the explosive TNT (trinitrotoluene) the pressure-time relation will schematically wary as shown in Figure 3.11. The three parameters pressure, impulse intensity and arrival time are all functions depending on the distance from the explosion to the point of interest. Often the scaled distance *Z* is used in the equations. As an example of how the distance has an influence one can look at the overpressure and the impulse intensity. Figure 3.11 shows how the pressure in the studied point varies with different distances and for the incident and reflected case. Similar, the impulse intensity will vary and decrease with increased distance, see Figure 3.12. The arrival time will instead increase with increased distance (Johansson, 2012a).

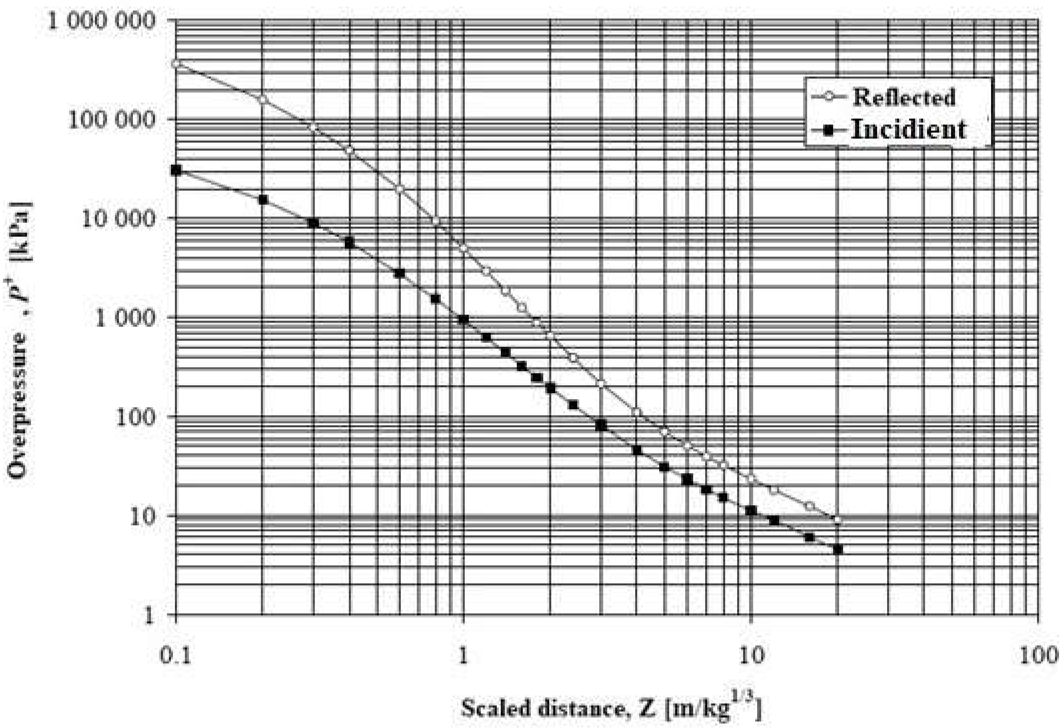


Figure 3.11 Overpressure depending on scaled distance for reflected and incident case. From Johansson (2012a).

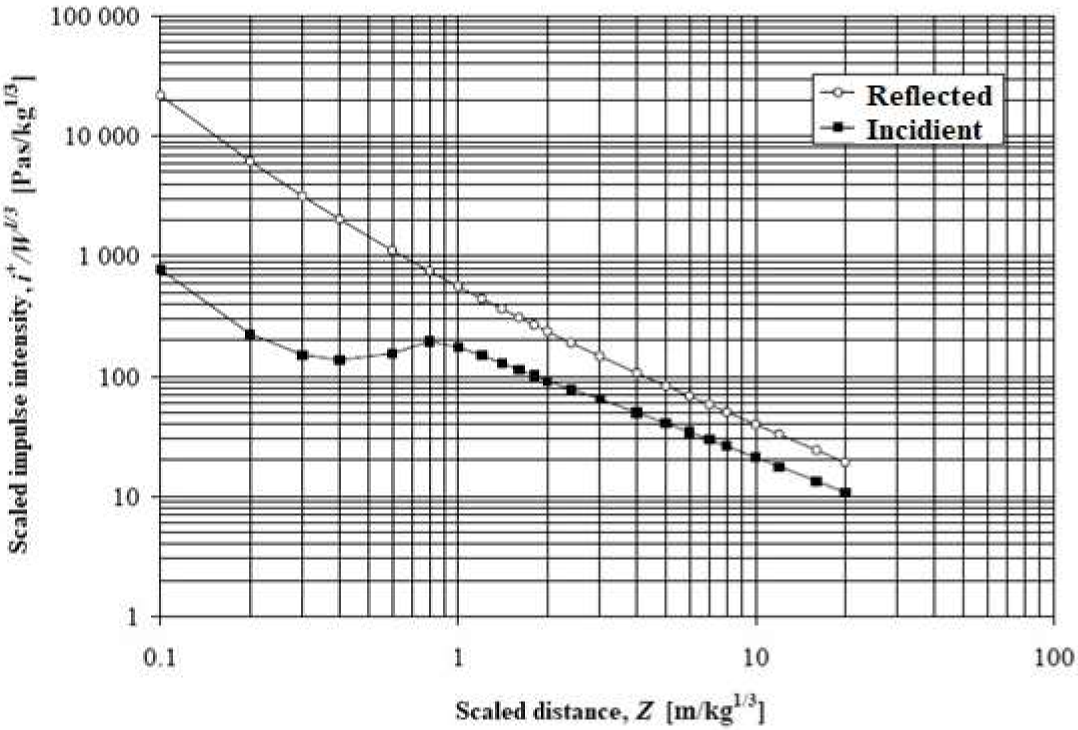


Figure 3.12 Scaled impulse intensity depending on scaled distance for reflected and incident case. From Johansson (2012a).

3.4.2 Effects of TNT explosions of different sizes

To be able to understand the huge effects that a TNT explosion can result in Table 3.1 gives some examples of how different amounts of TNT will affect a human ear, a building and glass sections in buildings. TNT is not the only explosive that exist, there are several others too. The reason for bringing up TNT is that other explosives are often recalculated to an equivalent amount of TNT. This could also be done with gas explosions. However, the relation between the generated overpressure and the impulse intensity might differ from TNT. That is why an explosive in most cases will have different equivalent TNT values depending on if the overpressure or the impulse intensity is studied, see Table 3.2. A method used in ConWep (1992), a software often used to determine the load from an explosion, is to use an average equivalent weight for pressure and impulse when defining an effective weight in TNT. (Johansson and Laine, 2012a).

Table 3.1 Effect from different amounts of TNT on humans, buildings and glass Sections. From Johansson and Laine (2012a).

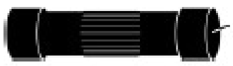
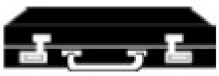
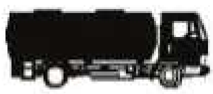
Source of explosion		Amount TNT (kg)	Smaller distances will result in damage on human ears (m)	Smaller distances will result in damage on buildings (m)	Smaller distances will result in damage on glass sections (m)
Bomb in tube		2.3	-	21	259
Bomb in a bag		23	-	46	564
Small car		227	30	98	457
Large car		455	38	122	534
Minibus		1818	61	195	838
Small truck		4545	91	263	1143
Truck		13636	137	375	1982
Truck and trailer		27273	183	475	2134

Table 3.2 Equivalent weight for several explosives concerning overpressure and impulse intensity. From Johansson and Laine (2012a).

Explosion source	Equivalent weight	
	Overpressure	Impulse intensity
ANFO	0.82	0.82
Composite A-3	1.09	1.07
Composite B	1.11	0.98
Composite C-4	1.37	1.19
H-6	1.38	1.15
HBX-1	1.17	1.16
Pentolite	1.42	1.00
RDX	1.14	1.09
TNT	1.00	1.00
Tritonal	1.07	0.96

3.5 Gas explosions

A gas explosion can, according to Johansson (2017), occur when a flammable gas ignites. A flammable gas is defined by that it at the temperature of 20℃ is a gas and that it can burn when it is mixed with air. All gases have a lower and upper limit of concentration when the gas can burn. The concentration depends on the temperature, amount of oxygen and the pressure. If the combustion of the gas creates an overpressure, the result can be that the gas explodes. The intensity of the explosion depends on several parameters such as to what extent the gas is contained, the size of the room, the speed of combustion and how the surrounding causes turbulence of the gas. Gas explosions are often of the type deflagration (Johansson, 2017).

Combustion of gas results in an increased temperature and volume. If the gas has small ability to increase the volume the pressure inside the container increases. At a high pressure a smaller speed of combustion is needed to cause an explosion. Since the expansion ability is strongly relevant it is common to divide gas explosions into various categories. The completely contained case is the worst case while the partly contained is somewhat better because of its possibilities of ventilating out the gases contributing to the overpressure resulting in an explosion. The best case is when the gas is not contained at all. If this is the case, and it is ignited by a small energy source, it might result in a so called flash fire instead of an explosion, thus resulting in only a minor peak overpressure (Johansson, 2017).

If the gas distribution is disturbed by irregularities in the surrounding, a turbulent flow can occur. The turbulence results in an increased combustion of the gas. It has been discovered that many small obstructions have a worse effect than one large obstacle. Furthermore, the placing of the obstacles has large influence too. When a gas starts to burn the flames spread laminar from the start. The speed of the combustion depends on the interaction with the unburned gas. As the flames get disturbed by the surrounding and start creating a turbulent flow the flame front gets corrugated. A larger area is now subjected to unburned gas and the speed of combustion increases.

With an increase in speed the pressure increases as well. This explains why turbulent flows are disadvantageous, resulting in stronger explosions, and why explosions in the open are less severe than if they are contained (Johansson, 2017).

3.6 Calculation models for gas explosions

Johansson (2017) explains that several models can be used when making calculations regarding gas explosions. Correlation models are the ones most frequently used but also phenomenological and numerical methods exist. Numerical models are the most powerful of the methods but since the information needed is large, the computation time is long, it is expensive, and the knowledge needs are high such method are not commonly used. The phenomenological method is a method which is something in between the two other methods. It tries to explain how the gas explosion behaves physically. Although the correlation method is simple and quick it is the method that is often used when making risk analyses in the process industry. Several correlation methods exist and here the TNO method will be described. For further information see van den Berg (1985).

In the TNO method the entire gas cloud is not considered to make up the source of the explosion; and the gas cloud can consist of many smaller separate explosions. It is said that only where the gas has limited ability to expand a strong explosion can occur. With this method, only parts which is considered to be prone to explode is taken into consideration in calculations of the explosion strength, see Figure 3.13 (Johansson, 2017).

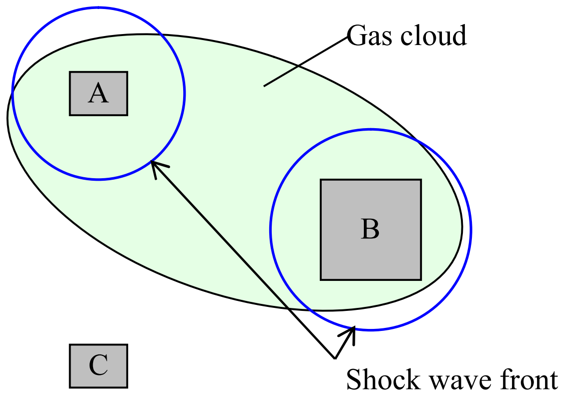


Figure 3.13 Two explosions inside the same gas cloud. Based on Johansson (2017).

For calculations, the gas is considered to be shaped as a hemisphere with a homogenous and stoichiometric mix of air and gas. As the explosion always is assumed to occur close to the ground, resulting in a mirroring effect where the explosion cannot spread downwards it is a good assumption with the hemispherical shape (Johansson, 2017).

An important part in the calculations using the TNO method is the strength factor, s. This factor can be complicated to decide although some guidelines are available, see Table 3.3. The first parameter of importance is the surrounding. In the case where objects are placed closely together the factor will increase as well as when the ability to expand is restricted in one or several directions. Pipes are a specific example of where the expansion is highly limited, and the risk of a large explosion increases. Furthermore, the reactivity of the gas and the energy at ignition has a large influence of the value of the strength factor (Johansson, 2017).

Table 3.3 Strength factor depending on ignition degree, degree of blocking and containment. From Johansson (2013).

Ignition energy		Degree of blocking			Containment		Strength factor, *s*
High	Low	High	Low	None	Yes	No	
•		•			•		10
•		•				•	10
•			•		•		7
•			•			•	6
•				•	•		6
•				•		•	5
	•	•			•		7
	•	•				•	7
	•		•		•		5
	•		•			•	3
	•			•	•		3
	•			•		•	3(1)

(1) If the reactivity of the gas is not high the strength factor, *s* can be assumed to be 2.

The strength factor can be correlated to a pressure level for the positive phase according to Table 3.4. A strength factor of 10 represent a detonation and factors lower than 10 will result in deflagration (Johansson, 2017).

Table 3.4 Pressure depending on strength factor. From Johansson (2017).

Strength factor	P_s^+ (kPa)
10	>1000
9	500
8	200
7	100
6	50
5	20
4	10
3	5
2	2
1	1

The way the overpressure varies with the different strength factors is described in Figure 3.14 and the duration varying with the strength factor is presented in Figure 3.15. Equations for these relations are presented in Johansson (2017).

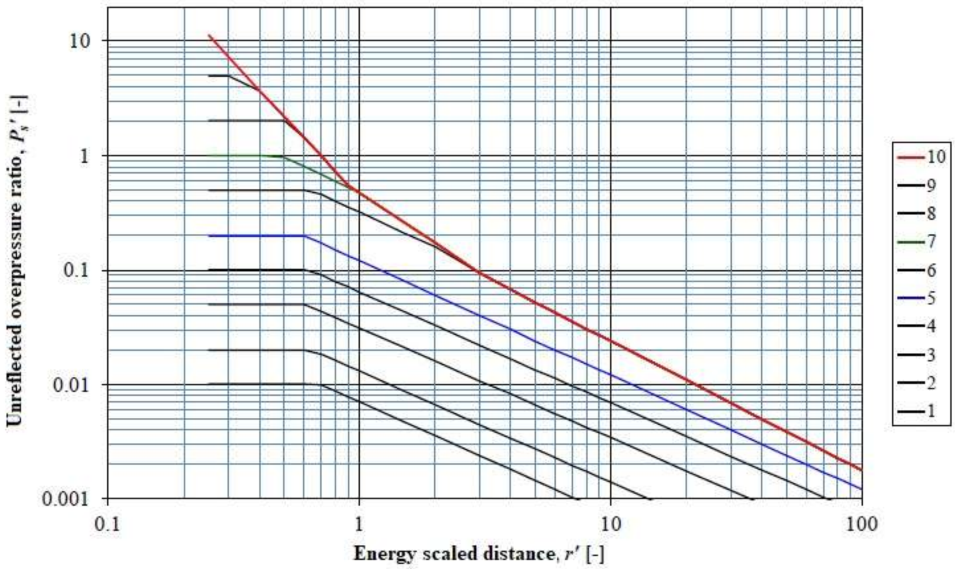


Figure 3.14 Incidient overpressure ratio and energy scaled distance depending on the strength factor. From Johansson (2017).

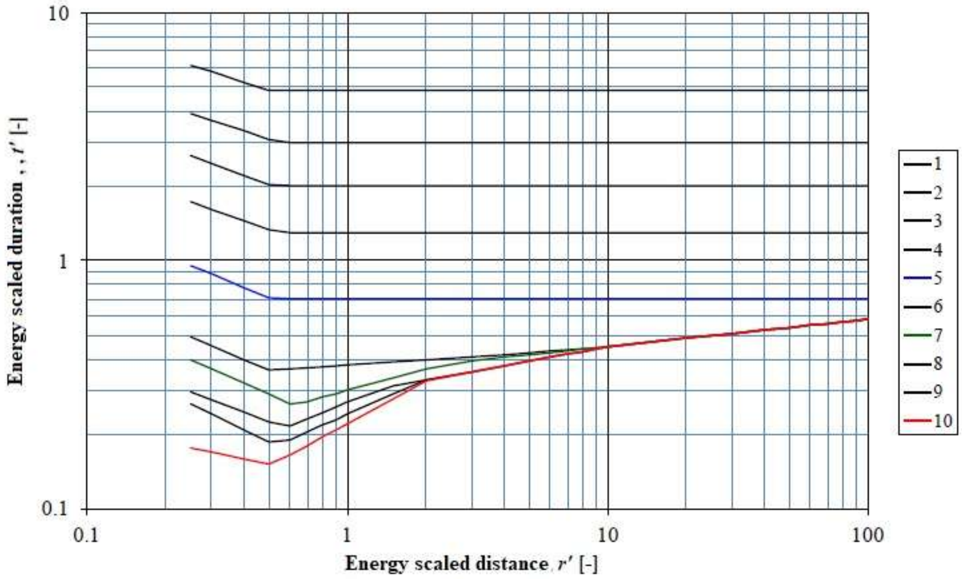


Figure 3.15 Energy scaled duration and energy scaled distance depending on the strength factor. From Johansson (2017).

The TNO method is relatively simple, but it has some disadvantages. As the TNO method claims that several explosions are possible in the cloud of gas it is reasonable to investigate what is happening is there is two explosions at the same time. How this could be done is further described in Johansson (2017). Another difficulty is how to choose the correct strength factor. Additionally, the method does not consider the negative phase of the explosion, see Figure 3.3. However, the positive phase and its overpressure and impulse intensity can be described well. The method can easily be customized to experimental data and compared to them (Johansson, 2017).

4 Structural response

4.1 The behaviour of the structure

The response of a structure that is subjected to an impulse load is different from the response from a static load. A lot is happening in the structure in the first milliseconds. The conceptual behaviour can be described by Figure 4.1 showing a civil defence shelter subjected to an explosion on the left side. Since it takes some time for the impulse load to travel through the structure it results in that the structure, will have time dependent support conditions. Here, the impulse is acting on the left side of the frame and during the first millisecond the right part is not affected at all by the impulse. That is why the frame is not reacting as a frame in the same way as during static loading. After some more time the information has reached the right end which can be shown in the lower right part of the figure (Johansson and Laine, 2012b). This wave propagation effect means that failure of the initially loaded part can occur before the other parts even have got any information about the load. Unlike a static loaded structure, where the response is directly related to the current load situation, this is not the case for impulse loaded structures. Further, the maximum load and the maximum deflection will normally not be synchronized (Johansson and Laine, 2012b).

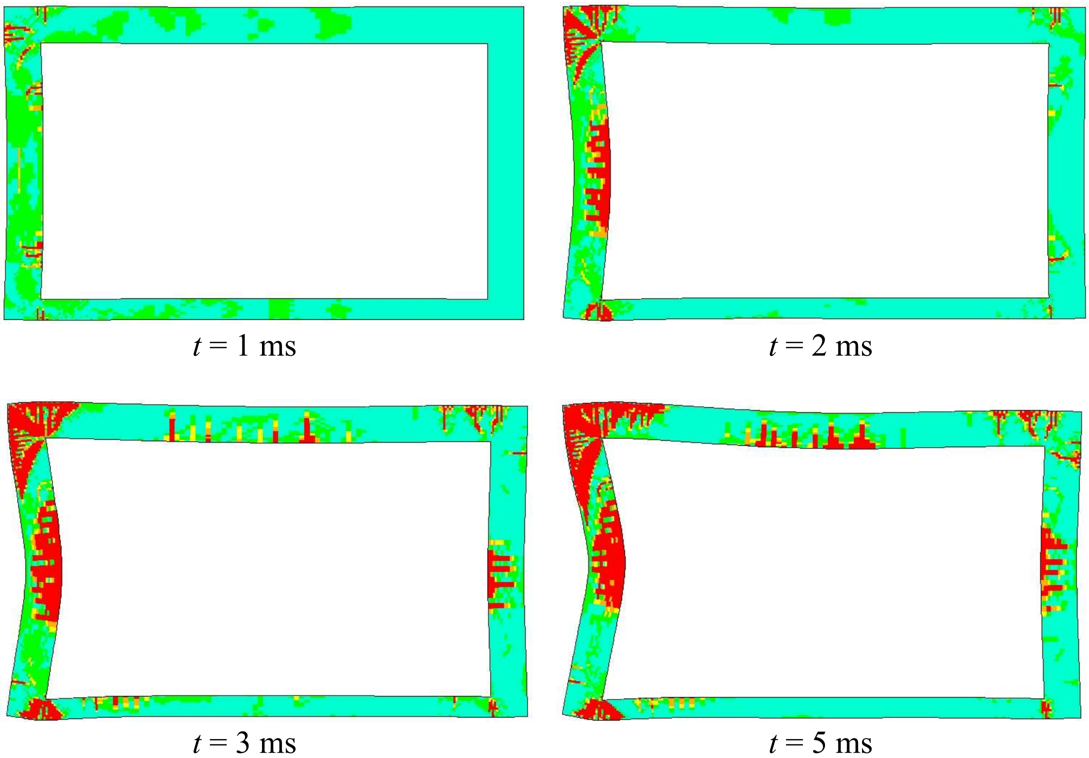


Figure 4.1 Structural response of a structure subjected to an explosion. From Johansson and Laine (2012b).

If looking at an example of an impulse loaded beam, see Figure 4.2, one can see that it takes time for the information to reach all parts of the structure. In the mid part on the beam the response during the first millisecond is the same as for a stiff body. After some time, the information about the supports reach the mid part of the beam and one can see changes in the behaviour. In Figure 4.2 the blue lines represent the deformation of the beam and the red dotted line the displacement of a rigid body without end supports. Both the beam in Figure 4.1 and the frame in Figure 4.2 show that the effect of the support conditions varies with time (Johansson and Laine, 2012b).

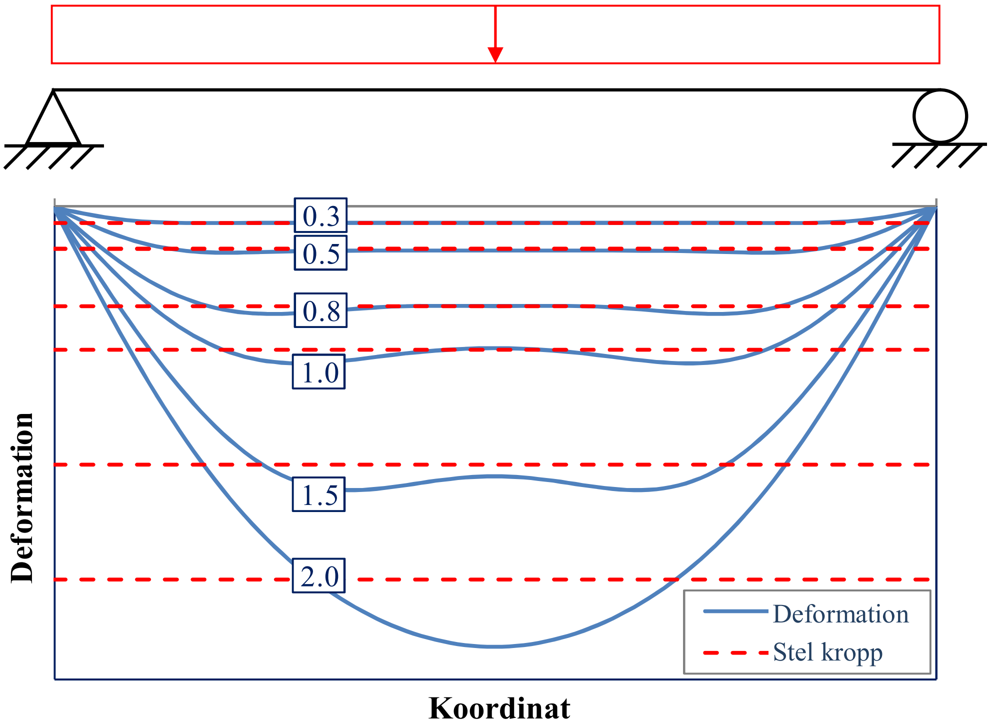


Figure 4.2 Response of an impulse loaded beam. Based on Andersson and Karlsson (2012).

4.2 Calculation of structural response

4.2.1 Single degree of freedom method

The method of analysing a beam subjected to an impulse that is described below is one way of calculating the structural response. In this Section it is described in a simplified way where a single degree of freedom system is used as well as other simplifications. An analysis of the structural response could be done more detailed by using several degrees of freedom or by using more advanced calculation tools. The method described below is an accepted method which is used and the method describes the overall concept and the behaviour of the structure.

When calculating a structure subjected to an impulse loading a single degree of freedom (SDOF) system can be used for simplification. The concept of SDOF are described by Figure 4.3. The SDOF system has some parameters which have influence on the capacity and response of the structure. The mass of the body m, the stiffness k, the capacity R, the impulse I, as well as the deformation u is important parameters (Johansson, 2014).

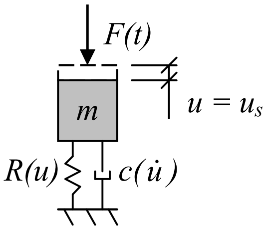


Figure 4.3 Single degree of freedom (SDOF) system. From Johansson (2014).

For this to be useful one need to understand how to transform a beam into a SDOF system. Looking at the beam in Figure 4.4, the beam has a constant mass m_b and stiffness EI_b and is simply supported. Here, the load $q(x,t)$ varies over the beam length l. If the deformed shape of the beam is shown the two systems can be compared by choosing a point on the length of the beam. Equation (4.1) gives the relation between force F_b, mass m_b, damping c_b and stiffness k_b of the beam as a function of deformation u. Comparing this to the SDOF system in Equation (4.2) one will find almost the same equation. To transform it one need to use some transformation factors κ-values for mass, stiffness and force. The damping is neglected here since it for an impulse loaded structure often has a small effect. By inserting κ-values, transformation factors, in Equation (4.3) and Equation (4.4), as well as using the relation in Equation (4.5), the beam may be transformed into a SDOF system. Which point that is chosen on the beam, the so called system point, is of no importance for the result if the characteristics such as stiffness and mass are constant over the length (Johansson, 2014).

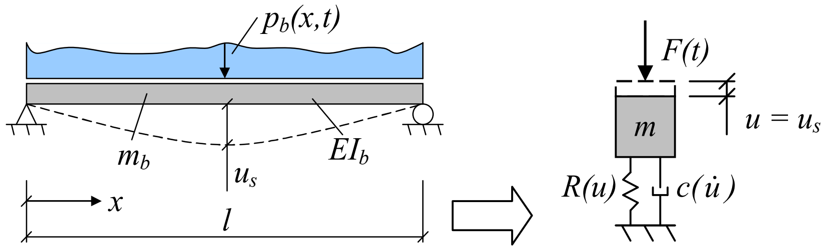


Figure 4.4 Transforming a beam into a SDOF system. From Johansson (2014).

$$m_b\ddot{u} + c_b\dot{u} + k_b u = F_b(t) \tag{4.1}$$

$$m\ddot{u} + c\dot{u} + ku = F(t) \tag{4.2}$$

$$\begin{cases} \kappa_m m_b\ddot{u} + \kappa_k k_b u = \kappa_F F_b(t) \\ \kappa_k = \kappa_F \end{cases} \tag{4.3}$$

$$\kappa_{mF} m_b\ddot{u} + k_b u = F_b(t) \tag{4.4}$$

$$\kappa_{mF} = \frac{z_m}{z_F} \tag{4.5}$$

4.2.2 External and internal work

When calculating the response of the structure, the external and internal work are important. The external work is described as force multiplied by distance. However, in our case the force is describes as an impulse *I* and therefore the external work is described as shown in Equation (4.6). The internal work, which is a function of stiffness, deformation ability and strength, represents the structure's ability to absorb energy. Unlike a statically loaded structure, the ability to deform when subjected to a load is a preferable characteristic for impulse loaded structures. As the internal work is an integral of the resisting force *R*, see Equation (4.7), a higher deformation capacity can sometimes result in a larger capacity of absorbing energy than a stiff structure would have (Johansson and Laine, 2012b).

$$W_e = \frac{I^2}{2m} \tag{4.6}$$

$$W_i = \int_0^u R(u)du \tag{4.7}$$

In Johansson and Laine (2012b) it is explained why a stiff structure can have a lower possibility to withstand an impulse load than a weak one, see Figure 4.5. Here, the blue area represents the internal energy of a structure with stiff and strong response but with limited deformation capacity and the pink area represent a weak behaviour with a high deformation capacity. In this example the weak behaviour results in a larger internal work and therefore a better resistance.

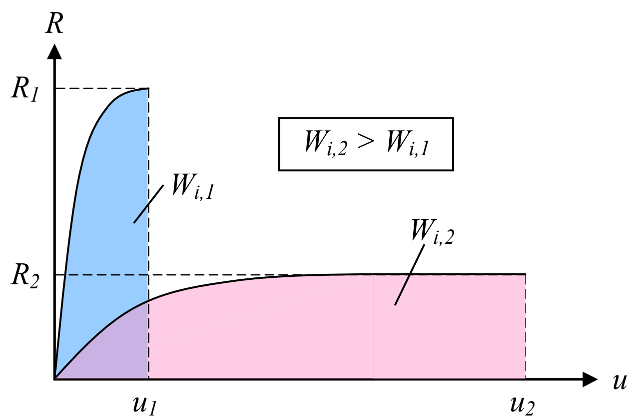


Figure 4.5 Comparison between a soft behavior (pink) and a stiff behavior (blue). From Johansson and Laine (2012b).

However, Johansson and Laine (2012b) explains that as a high stiffness often is an advantageous characteristic for statically loaded structures there is a conflict. The structure may in most cases be subjected to a static load but there might also be a risk of explosions or other dynamic loads. Moreover, the external work is a function depending on the impulse as well as the mass in movement, see Equation (4.6). The aim is to have an energy balance where the internal work equals the external work. From the Equation (4.6) one can understand that a large mass will give a smaller external work. It will then be easier to get the internal and external work equal. A large mass is therefore a good characteristic to get a good resistance for dynamic loading (Johansson and Laine, 2012b).

The internal work is dependent of the response of the structure. Commonly the response of a structure is divided into three categories, elastic, plastic and elastoplastic, shown in Figure 4.6. Apparent from the figures is that the way of calculating the internal work W_i (pink area) varies with the different cases. The response depends on the material. Timber has an elastic response while steel can have both elastic or plastic depending on the cross-section class of the structure. For concrete the response can be assumed to be elastic in the cracked stage if only small deformations are allowed. Assuming a plastic response of the concrete can be done if the reinforcement is yielding at the time of collapse (Johansson and Laine, 2012b).

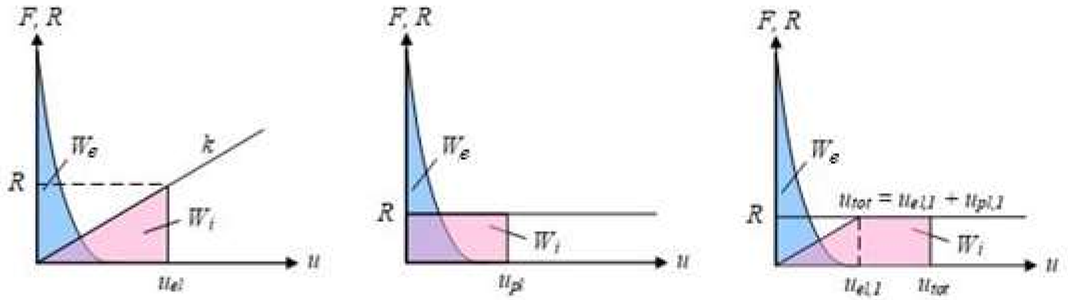


Figure 4.6 Elastic, plastic and elastoplastic response. Blue areas represent external work and pink areas internal work. From Johansson (2014).

To describe the difference in behaviour for a statically loaded structure and an impulse loaded structure one can look at the internal work and the deformations. Equations for the two cases are presented in Table 4.1 for characteristic force load and Table 4.2 for characteristic impulse loading, see Figure 3.2 for description of load cases. The equations given are simple and there are several ways of making them more precise. However, if the equations are used as they are described in their simple form the result will be on the conservative side (Johansson, 2014).

Table 4.1 External work, internal work and displacements from a characteristic force load for elastic, plastic and elastoplastic response. Based on Johansson (2014).

	Elastic response	Plastic response	Elastoplastic response
External work	$W_e = F_k u$	$W_e = F_k u$	$W_e = F_k u$
Internal work	$W_{i,el} = \frac{k {u_{el}}^2}{2}$	$W_{i,pl} = R u_{pl}$	$W_{i,ep} = R(\frac{u_{el,1}}{2} + u_{pl,1})$
Total displacement	$u_{tot} = u_{el}$	$u_{tot} = u_{pl}$	$u_{tot} = \begin{cases} u_{el}, F_k \leq \frac{R}{2} \\ \frac{R}{2(R - F_c)} \cdot u_{el}, \frac{R}{2} < F_k < R \\ \infty, F_k \geq R \end{cases}$
Elastic displacement	$u_{el} = \frac{2F_k}{k}$	–	$u_{el,1} = \frac{R}{k}$
Plastic displacement	–	$u_{pl} = \begin{cases} 0, F_c < R \\ \infty, F_c \geq R \end{cases}$	$u_{pl,1} = \frac{2F_k - R}{2(R - F_k)} \cdot u_{el,1}$
Equivalent static load	$Q_{el} = 2F_k$	–	$Q_{ep} = \begin{cases} R, F_k < R \\ -, F_k \geq R \end{cases}$

Table 4.2 External work, internal work and displacements from an characteristic impulse load for elastic, plastic and elastoplastic response. Based on Johansson (2014).

	Elastic response	Plastic response	Elastoplastic response
External work	$W_e = E_k = \frac{{I_k}^2}{2m}$	$W_e = E_k = \frac{{I_k}^2}{2m}$	$W_e = E_k = \frac{{I_k}^2}{2m}$
Internal work	$W_{i,el} = \frac{k {u_{el}}^2}{2}$	$W_{i,pl} = R u_{pl}$	$W_{i,ep} = R(\frac{u_{el,1}}{2} + u_{pl,1})$
Total displacement	$u_{tot} = u_{el}$	$u_{tot} = u_{pl}$	$u_{tot} = u_{pl} + \frac{u_{el,1}}{2}$
Elastic displacement	$u_{el} = \frac{I_k}{m\omega}$	–	$u_{el,1} = \frac{R}{k}$
Plastic displacement	–	$u_{pl} = \frac{{I_k}^2}{2mR}$	$u_{pl,1} = u_{pl} + \frac{u_{el,1}}{2}$
Equivalent static load	$Q_{el} = I_c \omega$	$Q_{pl} = R$	$Q_{ep} = R$
Angular frequency	$\omega = \sqrt{\frac{k}{m}}$	–	–

The displacement calculated with the equations given in Table 4.1 and Table 4.2 may be overestimated. To get a more exact solution some corrections can be made. Instead of assuming the characteristic impulse I_k to be the same as the actual impulse I_1 it can be corrected with a factor γ_I. The characteristic impulse can then be calculated by dividing the actual impulse by the correction factor, see Equation (4.8). The size of the correction factor depends of the shape of the force-time relation, see Figure 4.7, and the type of response of the structure. The error, when assuming $I_k = I_1$ can be calculated according to Equation (4.9). As the correction factor is dependent of the time ratio T/t_1, so are the error δ. Here T is the period time of the system and t_1 is the load duration. Table 4.3 shows the relation between how large the error of the displacement will be depending on the time ratio as well as the shape of the force-time relation for a structure with elastic response (Johansson, 2014).

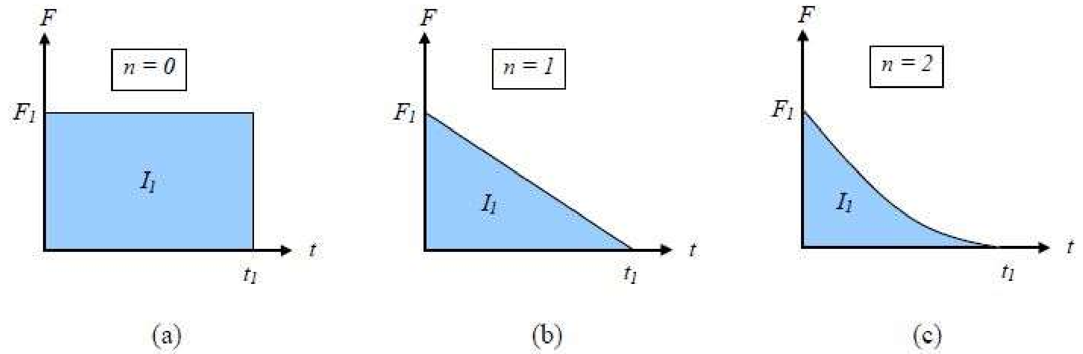


Figure 4.7 Force and time relations. From Johansson (2014).

$$\gamma_1 = \frac{I_1}{I_k} \tag{4.8}$$

$$\delta_{el} = \gamma_I - 1 \tag{4.9}$$

Table 4.3 The error and correction factor depending on the time ratio and the shape of the impulse for a case with elastic response. Based on Johansson (2014).

δ_{el}	γ_I	T/t_1	T/t_1	T/t_1
(%)	(-)	n=0	n=1	n=2
1	1.01	12.89	10.60	8.84
2	1.02	9.22	7.45	6.13
3	1.03	7.51	6.10	5.00
4	1.04	6.52	5.33	4.34
5	1.05	5.86	4.75	3.90
10	1.10	4.20	3.41	2.78
15	1.15	3.48	2.82	2.29
20	1.20	3.06	2.47	1.98
25	1.25	2.78	2.23	1.77
50	1.50	2.10	1.56	1.18
75	1.75	1.80	1.23	0.91
100	2.00	1.57	1.02	0.74
150	2.50	1.26	0.76	0.54
200	3.00	1.05	0.61	0.43
300	4.00	0.79	0.44	0.30
400	5.00	0.63	0.34	0.23
600	7.00	0.45	0.24	0.16
900	10.00	0.31	0.16	0.11

When looking at Table 4.3 one can see that for the case with a rectangular load, indicated by $n = 0$, the error is 10 % if the time ratio equals 4.20. Depending on the duration of the impulse the error varies. With increased load duration t_1, the error increases too. (Johansson, 2014) states that if the time ratio is small the error is so big that it will be better to assume that the load is a characteristic force load. Similar relations as in Table 4.3 can be given for the case of plastic response. However, for a general combination of $F(t)$ and $R(t)$, an elastoplastic response, it is preferred to solve the response numerically with central difference method (Johansson, 2012c).

4.2.3 Equivalent static load

A common way of handling impulse loads in the design of a structure is to first transform them into an equivalent static load. Since the external work is of importance for the response the impulse load is transformed into a static load which results in the same external work, this is what is called the equivalent static load. Several problems come with this transformation. The impulse load is acting only during a short time and it may have a huge pressure. When transforming an impulse load into an equivalent static load the force may be considerably reduced compared to its peak force. The principals of transforming the load into an equivalent static load is shown in Figure 4.8 where the blue curve represents the impulse and the orange curve the equivalent static load. Even though this method is commonly used, the behaviour of the structure in the different cases are different from each other (Johansson and Laine, 2012b). Furthermore, it is important to keep in mind that the equivalent static load comes from a dynamic load. Because of the fact that the structure will begin to oscillate as a reaction of the dynamic load, the equivalent static load needs to be considered not only in the direction of the force, but also in the opposite direction (Johansson, 2014).

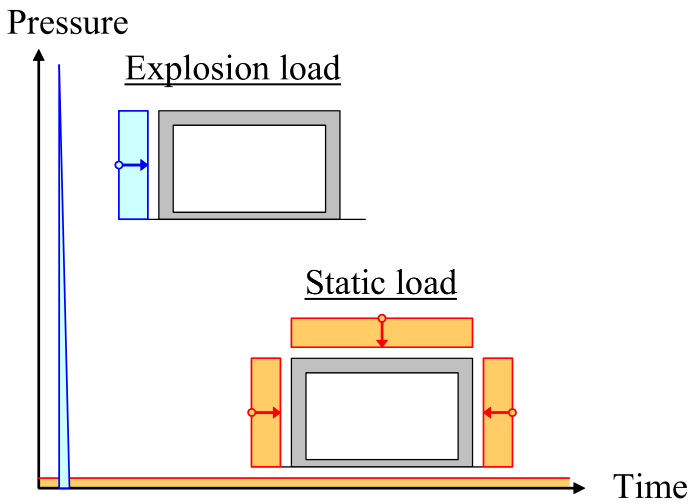


Figure 4.8 Equivalent static load. From Johansson and Laine (2012a).

4.3 How to build a structure with good resistance against explosions

The key parameters to build a safe structure concerning explosions is to build it either far from the explosion or to use protective mass. With an increased distance the energy released from the explosion is quickly spread out and the intensity decreases. A heavy structure does have a better protection because a heavy structure is more difficult to move. The mass has a large influence on the resistance. Why, can be understood by looking at Equation (4.10). The acceleration a is a function of force F and mass m. With an increase of mass, the result will be that the structure will not move as much (Johansson and Laine, 2012b).

$$a = \frac{F}{m} \tag{4.10}$$

Another way to create good resistance is to make sure that the structure has a high deformation capacity. This is a preferable characteristic since the ability to absorb energy W_i, is large but the capacity to carry load is not changed. Instead of building a structure that can carry large forces it is better to build a structure that can absorb the energy released in the explosion. If the structure is stiff the deformations will be low, but the forces are large. For the opposite case with a soft structure, the deformations are larger but the forces smaller. Since the resistance is related to the internal work, which is a function highly influenced by the deformation, a large deformation capacity is valuable. (Johansson and Laine, 2012b).

To receive a structure with a large deformation capacity, the structure should be able to plasticize and to form plastic hinges. At the plastic hinges the rotation will continue even though the maximum loading capacity is reached. The forces can redistribute in the structure because of this. Deformation capacity is a desirable quality for impulse loaded structures and with formation of plastic hinges the deformation capacity increases. For a concrete structure the ability of forming plastic hinges is related to the reinforcement. With a high difference between the ultimate strength in tension and the yield strength the reinforced concrete will show a soft behaviour (Johansson and Laine, 2012b).

With the knowledge about plastic hinges contributing to a better resistance against explosions it is understandable to have a structure where several plastic hinges can be formed. Comparing two cases in Figure 4.9, one containing several elements with moment free hinges and one continuous case, the latter can form five plastic hinges instead of three. The second case is therefore a better alternative due to its capacity of redistributing the forces (Johansson and Laine, 2012b).

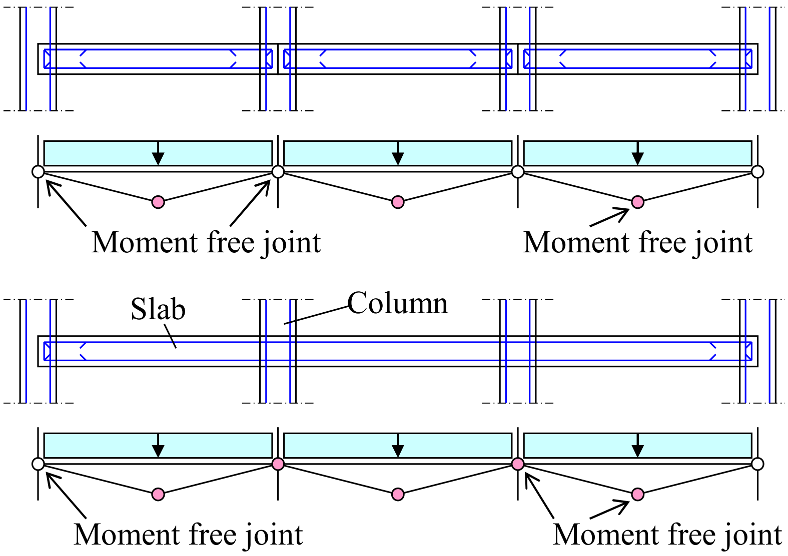


Figure 4.9 Continuity. Based on Johansson and Laine (2012b).

Redundancy is also a valuable capacity of the building. Redundancy is connected to the entire building and the fact that the entire building should not collapse if one element fails. To receive a redundant building, forces should have several ways to be led down to the foundation of the building. As an example, it is better to have a floor that is carried in two directions than in one (Johansson and Laine, 2012b).

5 Quantitative review of risk analyses

5.1 Orientation

Nineteen risk analyses have been reviewed and compared in this chapter. The picked-out analyses are all Swedish projects, but the projects are from different cities and are performed by a number of different companies. Some risk analyses are taken from the same company just to see if there is a continuity in the work and if the same methods are used. Similar for all the analyses are that they are analysing the risks connected to roads and railways where dangerous goods are transported. The risk analyses that are used in this chapter is presented in Table 5.1. The references to the risk analyses are found in the reference list by looking at the company name and the year. In further tables in this chapter the risk analyses are defined by the name in the first column.

The idea of this chapter is to review the risk analyses concerning how they handle explosions from different perspectives. Are there large differences between how the analyses have been performed and in the results? Is it a logical reason for the differences? Further, is it something in the methods that might be good to improve to get a better risk analysis? In an attempt to answer this, focus is put on six different areas all with explosion risks in mind:

1. Acceptable risk level
2. Statistics of transports of dangerous goods and accidents on the road
3. Included risks
4. Design explosion load
5. Position of the load
6. Recommended risk reducing actions

In Section 5.2 to 5.7 information from the nineteen risk analyses are presented in tables and in text. Moreover, in Section 5.8, the author of this report will discuss and comment on the similarities and differences between the risk analyses. Suggestions for improvement are given and it is discussed if there is need for increased knowledge in any part of the risk analysis work.

Table 5.1 Analysed projects.

Name	Place	Road	Railway	Company	Year
Getabrohult	Bollebygd	27/40		Norconsult	2014
Engelbreckt-området, Jakobsberg	Järfälla kommun	Viksjöleden		Norconsult	2017a
Stenungssunds centrum	Stenungssund	Väg 770	Bohusbanan	Norconsult	2017b
Veddesta Etapp 1	Järfälla kommun	Europaväg 18	Mälarbanan	Norconsult	2016
Gårda 2:12	Göteborg	E6/E20	Kust till kustbanan, Västkustbanan	Norconsult	2017c
Hallands län	Halland	E6, riksväg 25 och 26	Västkustbanan	COWI	2011
Lagaholm	Laholm	Väg 585, Lagavägen		COWI	2017b
Ullevigatan	Göteborg	E6/E20		COWI	2016
Lagerströms-platsen	Göteborg	E6/E20	Kust till kustbanan, Västkustbanan	COWI	2014
Täby park DP2	Täby kommun	E18/ Norrtäljevägen, Bergstorpsvägen	Roslagsbanan	Brandskydds-laget	2016
Krillans krog	Stockholm	Drottningholms-vägen		Brandskydds-laget	2013
Kv. Sicklaön	Nacka	Väg 75, Väg 260		Brandskydds-laget	2017
Gudebroleden	Tyresö kommun	Väg 260		Firetech	2017
Kållereds centrum	Mölndals stad		Västkustbanan	Wuz risk consultancy AB	2017
Strandängen	Jönköping		Jönköpings-banan	Briab	2018
Bromma center	Bromma	Ulvsundavägen		Sweco	2008
Floda Nova Sportcenter	Floda	E20		Ramböll	2018
Hornbergs-kvarteren	Stockholm	Essingeleden		RiskTec Projektledning	2017
Mölndalsåns dalgång	Göteborg och Mölndal	E6, riksväg 40	Västkustbanan, Kust-till-kustbanan, Götalandsbanan	WSP	2015

5.2 Acceptable risk level

To start with, the acceptable risk level was analysed to see if all the risk analyses had the same goal to aim for. In Table 5.2 acceptable risk levels are presented for all analyses. It is presented from what source the limits are taken and what level that is considered acceptable and tolerable at both individual and society level.

Table 5.2 Acceptable risk level.

	Individual risk level			Society risk level		
Name	Source	Acceptable	Tolerable	Source	Acceptable	Tolerable
Getabrohult	(1)	10^{-7}	10^{-5}	(1)	10^{-6}	10^{-4}
Engelbreckt-området, Jakobsberg	(1)	10^{-7}	10^{-5}	(1)	10^{-6}	10^{-4}
Stenungsunds centrum	(1)	10^{-7}	10^{-5}	(1)	10^{-6}	10^{-4}
Veddesta Etapp 1	(1)	10^{-7}	10^{-5}	(1)	10^{-6}	10^{-4}
Gårda 2:12	(1)	10^{-7}	10^{-5}	(1)	10^{-6}	10^{-4}
Hallands län	(1)	10^{-7}	10^{-5}	GÖP99, (1)	-	-
Lagaholm	(1)	10^{-7}	10^{-5}	(1)	10^{-6}	10^{-4}
Ullevigatan	(1)	10^{-7}	10^{-5}	**(1),** GÖP	10^{-6}	10^{-4}
Lagerströms-platsen	(1)	10^{-7}	10^{-5}	(1), GÖP	10^{-6}	10^{-4}
Täby park DP2	(1)	10^{-7}	10^{-5}	(1)	10^{-6}	10^{-4}
Krillans krog	SRV	10^{-8}	10^{-6}	SRV	10^{-6}	10^{-4}
Kv. Sicklaön	-	-	-	-	-	-
Gudebroleden	(1)	10^{-7}	10^{-5}	(1)	10^{-6}	10^{-4}
Kållereds centrum	**RIKTSAM**, (1)	(2)	(3)	**RIKTSAM,** (1)	10^{-7}	10^{-5}
Strandängen	-	10^{-7}	10^{-5}	-	10^{-6}	10^{-4}
Bromma center	(4)	(4)	(4)	(1)	10^{-6}	10^{-4}
Floda Nova Sportcenter	(1)	10^{-7}	10^{-5}	(1)	10^{-6}	10^{-4}
Hornbergs-kvarteren	(1)	10^{-7}	10^{-5}	(1)	10^{-6}	10^{-4}
Mölndalsåns dalgång	(1)	10^{-7}	10^{-5}	(1), GÖP	10^{-6}	10^{-4}

Bold text for project in the surrounding of Gothenburg.

(1) Värdering av risk, DNV

(2) Building free area 10^{-5},Less sensitive 10^{-6}, Normal sensitive 10^{-7}, Sensitive 10^{-7}

(3) Building free area 10^{-4}, Less sensitive 10^{-5}, Normal sensitive 10^{-6}, Sensitive 10^{-7}

(4) Included in the previous analysis

From Table 5.2 one can see that almost all the analyses use the same principles for evaluating the risk level. The acceptable and tolerable risk level is taken from the recommendations given in Räddningsverket (1997), (Värdering av risk), which can be found in the reference list. The values given in that report is taken from DNV (Det Norske Veritas) recommendations. The risk levels are presented both for individuals and for the society.

For the individual risk most have chosen that an acceptable risk level is below 10^{-7} deaths per year. Risks with a frequency larger than 10^{-5} is not tolerable and for these cases risk reducing actions are needed. For risks with a frequency of deaths in between the two levels risk reducing actions should be evaluated.

Regarding the society risk level all analysed projects have used the ALARP curves as presented in Figure 2.8. It is presented as an FN-curve with an upper limit of 10^{-4} and a lower limit of 10^{-6}. The curves have a slope of -1. For almost all the analysed projects the guidelines from DNV are followed. In the cases where the guidelines are not followed the acceptable and tolerable level is set stricter than the recommendations given by DNV, this by a factor of 10^{-1}.

In the risk analysis Kv. Sicklaön the acceptable risk level is not presented. Furthermore, in the risk analysis for Strandängen it is not stated from what source the acceptable risk levels are taken. Additionally, in some of the analyses one can read that GÖP are used for the risk level concerning the society. GÖP is a document which presents acceptable risk levels according to Gothenburg´s plan for land use. The risk analyses connected to Gothenburg and it´s surrounding is marked by using bold text. If it is stated which criterion that is used, in case of two given alternatives, this is marked with bold text.

A comparison between the criteria from DNV and from GÖP is made in Figure 2.9. The acceptable criteria from DNV are stricter than the criteria from GÖP for accidents up to 600 deaths. The reasoning has in some of the risk analyses, connected to Gothenburg, resulted in that the DNV´s criteria are the ones used for evaluation. This even though the DNV´s tolerable level is higher than the level given by GÖP for apartments. It is brought up, in some of the risk analyses, that it is strange that Gothenburg has its own criteria when it is common to use DNV criteria in the rest of Sweden. This has been the reason for in some cases not use the criteria from GÖP.

5.3 Statistics

The used statistics for the amount of traffic with dangerous goods, the statistics for what type of goods that is transported, as well as the number of accidents on the road may vary between the risk analyses. For the analysed projects the statistics used are presented in Table 5.3 and Table 5.4. In the cases where bold text is used two sources for statistics has been compared but the bold one is what has been used in the risk analysis.

Table 5.3 Statistics of transported load, assumed increase, division between classes of dangerous goods and statistics of accidents. Part 1.

Name	Road	Railway	Statistics transported load	Increase	Division between classes of dangerous goods	Statistics of accidents
Getabrohult	27/40		MSB (2013), **TRAFA (2013)**	Vägverket (2009) 2% per year	Räddningsverket (2006), ØSA (2004)	Vägverket (2008), Räddningsverket (1996)
Engelbreckt-området, Jakobsberg	Viksjöleden		No statistics available	Does not follow the general increase in Sweden	Investigation of the surrounding area	Trafikverket (2017b), Räddningsverket (1996)
Stenungssunds centrum	Väg 770	Bohusbanan	Bohusbanan: Trafikverket (2017a)	Bohusbanan: **Trafikverket (2016) Increase by 27% from 2014-2040**	Bohusbanan: ØSA (2004), SRV (2008)	Bohusbanan: Banverket (2001)
Veddesta Etapp 1	Europaväg 18	Mälarbanan	Europaväg 18: Räddningsverket (2006), Trafikverket (2017b) Mälarbanan: Räddningsverket (2006), **Trafikverket**	Mälarbanan: Trafikverket (2011) increase by 67% to 2030	Europaväg 18: ØSA (2004) Mälarbanan: Räddningsverket (2006), ØSA (2004)	Mälarbanan: Banverket (2001), Trafikverket (2017b), Räddningsverket (1996)
Gårda 2:12	E6/E20	Kust till kustbanan, Västkustbanan	E6/E20: No statistics available for the area, TRAFA (2014) Kust till kustbanan, Västkustbanan: Räddningsverket (2006)	E6/E20: Trafikverket (2013) Increase by 1.4 % per year Kust till kustbanan, Västkustbanan: Trafikverket (2015) Increase by 36 % from 2006-2030	Räddningsverket (2006), ØSA (2004)	E6/E20: Vägverket (2008) Kust till kustbanan, Västkustbanan: Banverket (2001)
Hallands län	E6, riksväg 25 och 26	Västkustbanan	Räddningsverket (2006)	Nothing mentioned	Nothing mentioned	Roads: Comparison between MSB, Statistics of civil protection, IDA,

Table 5.4 Statistics of transported load, assumed increase, division between classes of dangerous goods and statistics of accidents. Part 2.

Name	Road	Railway	Statistics transported load	Increase	Division between classes of dangerous goods	Statistics of accidents
Ullevigatan	E6/E20		Trafikanalys (2015), SIKA (2008), Räddningsverket (2006)	20 % increase from 2006-2030	Räddningsverket (2006)	MSB
Lagerströms-platsen	E6/E20	Kust till kustbanan, Västkustbanan	E6/E20: Räddningsverket (2006), SIKA (2008) Kust till kustbanan, Västkustbanan: Räddningsverket (2006), VTI (1994)	Trafikanalys (2010) 20 % increase from 2006-2030	Räddningsverket (2006)	MSB
Täby park DP2	E18/ Norrtäljevägen, Bergstorpsvägen		Trafikanalys (2015)	ÅDT-trafik_Täby_Park_revidering 160210	Trafikanalys (2015)	
Krillans krog	Drottningholms-vägen		SIKA (2008)		SIKA (2008), Räddningsverket (2006)	
Kv. Sicklaön	Väg 75, Väg 260		Trafikanalys (2015)	Vägverket (2004), Trafikverket (2010)	Räddningsverket (2006)	
Gudebroleden	Väg 260		Räddningsverket (2006)		Räddningsverket (2006)	STRADA
Kållereds centrum		Västkustbanan	Trafikanalys (2013)	Estimation is made	Trafikanalys (2013)	Fredén (2001)
Strandängen		Jönköpings-banan	Trafikverket (2011) personal communication	Trafikverket (2011) personal communication	Trafikverket (2011) personal communication	Räddningsverket (1996), Fredén (2001)
Bromma center	Ulvsundavägen		Forsén, R., Hägvall, J., (2005).			
Floda Nova Sportcenter	E20		Räddningsverket (2006)		Räddningsverket (2006)	
Hornbergs-kvarteren	Essingeleden		WSP (2016)			
Mölndalsåns dalgång	E6, riksväg 40	Västkustbanan, Kust-till-kustbanan, Götalandsbanan	Trafikkontoret Göteborg, Trafikanalytiker WSP	Trafikverket (2014) Personal communication	Trafikanalys (2010), SIKA (2009)	MSB, VTI

As can be seen in the tables the statistics used varies. In many cases statistics based on an investigation made by Räddningsverket (2006) is used. This investigation is further described in Appendix A. In the majority of the analyses the increase of traffic is included. Normally the traffic twenty years into the future is taken into consideration. The increase is based on predictions made by Trafikverket and it varies for different places in Sweden. The increase is around 2% per year according to the predictions. Concerning what type of dangerous goods that is transported information is collected either from Räddningsverket (2006), SIKA (2008) or Trafikanalys (2013) or (2014). Statistics or predictions for how many accidents that is probable to occur on the road is in most cases taken from a handbook from SRV 1996. A model called VTI-model has also been used in some of the risk analyses.

5.4 Included risks

According to Myndigheten för samhällsskydd och beredskap (2019) dangerous goods can be categorized into nine groups. This division is based on the consequence that may happen in case of an accident. Explosions, emissions of toxic gases or liquids and fires are the three consequences used to categorize the goods. The classes of goods are presented in Table 5.5.

Table 5.5 Division of categories of dangerous goods. From Myndigheten för samhällsskydd och beredskap (2019).

Class	Description
1.1	Explosives with risk of massive explosions
1.2	Substances with risk of debris and thrown pieces but not large explosions
2.1	Flammable gases
2.2	Not flammable, and non-toxic gases
2.3	Toxic gases
3	Flammable liquids
4.1	Flammable solids, self-reacting substances, polymerizing substances and desensitised explosives
4.2	Self-igniting substances
4.3	Substances that develops flammable gas in contact with water
5.1	Oxidizing substances
5.2	Organic peroxides
6.1	Toxic substances
6.2	Infectious substances
7	Radioactive substances
8	Corrosive substances
9	Other dangerous substances and subjects

When looking at what risks that is considered in the risk analyses one can clearly see a pattern, see Table 5.6. Normally, all possible types of dangerous goods are presented and considered in the beginning of the risk analysis work. By looking at statistics of what is normally transported on the road the relevant types of goods are identified. However, even though the number of transports of a specific category is few compared to another category, a category may be seen as important due to the consequence that an accident involving that category may cause. It is also possible that there are many transports of another category, but an accident of this type will not cause large damage and therefore it is deemed not necessary to be included.

Table 5.6 Considered risks in the risk analyses

Name	1		2			3	4	5		6		7	8	9
	1.1	1.2	2.1	2.2	2.3			5.1	5.2	6.1	6.2			
Getabrohult	X		X		X	X		X						
Engelbrecktområdet, Jakobsberg	X		X		X	X		X						
Stenungsunds centrum	X		X		X	X		X						
Veddesta Etapp 1	X	X	X		X	X		X	X					
Gårda 2:12	X		X		X	X		X						
Hallands län	X		X		X	X		X	X				X	
Lagaholm	X		X		X	X		X						
Ullevigatan	X		X		X	X		X						
Lagerströmsplatsen	X		X		X	X		X						
Täby park DP2	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Krillans krog	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Kv. Sicklaön	X	X	X	X		X	X			X		X	X	X
Gudebroleden	X	X	X		X	X		X					X	
Kållereds centrum	X	X	X	X	X	X	X	X		X	X		X	X
Strandängen	X	X	X		X	X	X			X	X		X	X
Bromma center	X		X		X	X		X						
Floda Nova Sportcenter	X		X	X	X	X		X	X					
Hornbergskvarteren	X		X		X	X		X	X					
Mölndalsåns dalgång	X	X	X		X	X		X	X					

The categories that most of the risk analyses has considered important are category 1.1, 2.1, 2.3, 3 and 5.1. These categories represent massive explosions, flammable and toxic gases, flammable liquids and oxidizing substances which also has a risk of explosion. These risks may result in large consequences for the surrounding close to the road. Explosives, oxidizing substances and gases can result in explosions with shock waves that can directly hurt humans or indirect hurt or kill them because of collapsing buildings. Gases and liquids can also result in large fires that spread up to around hundred meters. Some variations of these fires are puddle fire, jet flame and BLEVE. These are further described in Section 2.6.2. In three risk analyses all risk categories are included, and it is not further stated which risks that will contribute with the highest risks.

5.5 Design explosion load

In table Table 5.7 and Table 5.8 the considered sizes of explosions for risk calculations in class 1.1, gas explosions and explosions from oxidizing substances, are stated for the different risk analyses.

Table 5.7 Considered size of explosions for risk calculations.

Name	Explosives	Gas Instantaneous emission	Gas continuous emission	Oxidizing substances
Getabrohult	16 ton TNT	252x252 m pressure >0.3 bar	66x66 m pressure >0.3 bar	16 ton, 8 ton TNT
Engelbreckt-området, Jakobsberg	16 ton TNT	252x252 m pressure >0.3 bar	66x66 m pressure >0.3 bar	16 ton TNT
Stenungsunds centrum	Not described	330x330 m pressure >0.3 bar	95x95 m pressure >0.3 bar	Not described
Veddesta Etapp 1	16 ton TNT	252x252 m pressure >0.3 bar	66x66 m pressure >0.3 bar	16 ton, 8 ton TNT
Gårda 2:12	16 ton TNT	252x252 m pressure >0.3 bar.	66x66 m pressure >0.3 bar	16 ton, 8 ton TNT
Hallands län	Road: 50-1000 kg explosives, 16 ton explosives. Railway: 25 ton explosives	Not described	Not described	Not described
Lagaholm	1-16 ton, 25-1000 kg TNT	30 m 0.02 bar, 8 m 0.14 bar, 6 m 0.21 bar	Not described	200 kg explosives
Ullevigatan	1-16 ton, 25-1000 kg TNT	30 m 0.02 bar, 8 m 0.14 bar, 6 m 0.21 bar	Not described	200 kg explosives
Lagerströms-platsen	1-16 ton, 25-1000 kg TNT	30 m 0.02 bar, 8 m 0.14 bar, 6 m 0.21 bar	Not described	200 kg explosives
Täby park DP2	Risk calculations in appendix	Risk calculations in appendix	Risk calculations in appendix	Risk calculations in appendix
Krillans krog	16 ton, >2000 kg, 500-200 kg, <500 kg	Large, medium, small	Not described	Not described
Kv. Sicklaön	16 ton, 1 ton, <100 kg TNT	Not described	Not described	3 ton TNT
Gudebroleden	20 kg TNT, 2 ton TNT, 16 ton TNT	0.09 kg/s, 0.9 kg/s, 17.8 kg/s liquefied petroleum gas	Not described	Modelled as mass explosives

Table 5.8 Considered size of explosions for risk calculations.

Name	Explosives	Gas Instantaneous emission	Gas continuous emission	Oxidizing substances
Kållereds centrum	50 kg – 16 ton TNT	15-25 ton of different types of gases	Not described	25 ton explosives
Strandängen	Not described	Not described	Not described	Not described
Bromma center	16 ton TNT	Not described	Not described	2 ton TNT
Floda Nova Sportcenter	Not described	Not described	Not described	Not described
Hornbergs-kvarteren	<60 kg, 60-500 kg, 500-1000 kg TNT	Not described	Not described	1-4 ton TNT
Mölndalsåns dalgång	25 ton, 150 kg	Mass flow: 0.09 kg/s, 0.9 kg/s, 17.9 kg/s. Size >1500 kg, <1500 kg, 25 ton liquid petroleum	Not described	25 ton TNT

For most cases the amount of explosive considered in the risk analysis is defined. One can read that loads up to 16 ton of TNT (trinitrotoluene) is a commonly used amount. The argument for using 16 ton TNT is because this is the maximum allowed amount of explosives to transport on roads in Sweden. For transports on railway the allowed amount is 25 ton TNT. This is a very large amount of explosive and it is seldom transported. Some of the risk analyses has looked at different amounts of TNT and also considered how many transports with different amounts of explosives that statistically passes.

Furthermore, gas explosions are usually considered in the analyses. The sequence of events may vary for gas explosions, as an example it can be an instantaneous emission or a continuous emission. The spread of the gas will vary in the two cases. In some of the analyses the two types of emissions are mentioned and considered while in other analyses it is not described at all what size of a gas explosion that has been considered. From Table 5.7 one can read that the minimum pressure level at a distance often are given. The distance where the pressure is over 0.3 bar is in some cases described. 0.3 bar is the pressure limit at where a human will not survive.

The last type of explosions considered in the risk analyses is from oxidizing substances. For this type of explosions, the size considered varies from 200 kg TNT to 25 ton TNT. In some of the risk analyses the amount is not described.

The load which is considered when calculating the risk level may not be reasonable to design the building for. It is only in a few risk analyses the load which the building should be able to resist is described. This is presented in Table 5.9. It can be seen that 10 kg liquified petroleum gas has been used for gas explosions more than one time. The common factor for these analyses is that they are made by COWI. 100 kg dynamite which equals 60 kg TNT is a value that has been used for explosives. However, in most of the analyses nothing is mentioned about the resistance the explosions for the building. For the analyses where the design load is presented it is not the same that was used for the risk calculations.

Table 5.9 Design load for buildings close to road.

Name	Explosives	Gas	Oxidizing substances
Getabrohult	-	5 kPa static load	-
Engelbreckt-området, Jakobsberg	-	-	-
Stenungsunds centrum	-	-	-
Veddesta Etapp 1	-	-	-
Gårda 2:12	60 kg TNT (mirroring factor 1.8) (100 kg dynamite)	100 kg dynamite 1000 m^3 s=2 200 m^3 s=5 100 m^3 s=7 BLEVE 50 kg TNT (mirroring factor 1.8)	-
Hallands län	-	100 m3 gas cloud, 10 kg liquefied petroleum gas	-
Lagaholm	-	-	-
Ullevigatan	-	10 kg liquified petroleum gas	-
Lagerströms-platsen	-	10 kg liquified petroleum gas	-
Täby park DP2	2 ton explosives	-	-
Krillans krog	0 With rerouting of traffic 1 ton	-	-
Kv. Sicklaön	-	-	-
Gudebroleden	-	-	-
Kållereds centrum	-	-	-
Strandängen	-	-	-
Bromma Center	-	-	-
Floda Nova Sportcenter	-	-	-
Hornbergs-kvarteren	100 kg dynamite	100 kg dynamite	
Mölndalsåns dalgång	-	-	-

5.6 Position of the explosion centre

As described in Section 3.4.1 the peak pressure is depending on the distance from the explosion centre. Because of this the distance between the road and the building will have a large impact on the resulting risk level. Consequently, the position of the explosion centre on the road will also have a large impact on the result of the analysis. In Table 5.10 the position of the load is stated for the explosion caused by explosives, gas explosions and explosions of oxidizing substances. The number 1 to 6 indicates the position of the load, with the numbers representing the following, see Figure 5.1.

1. The edge of the road closest to the analysed building or area
2. In the middle of the closest lane
3. In the middle of the closest roadway
4. In the middle of the road
5. Other specified position
6. Not described

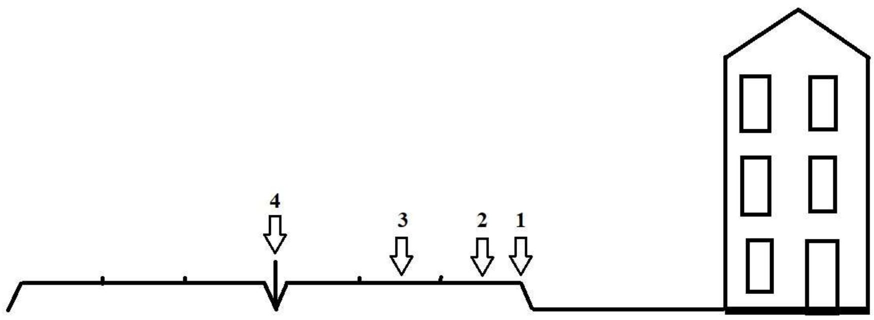


Figure 5.1 Alternative positions of the load placement.

It is only in a few cases that the position of the explosion load is specified. However, in some cases it is possible that it is further described in an appendix. When it comes to the position of a gas explosion it is a better described. It is pointed out, in the analyses by Norconsult, that it is possible that the vapor cloud spreads into the analysed area due to the wind direction. It is therefore said that the centre of the vapor cloud may be 33 m into the analysed area. Further, for oxidizing substances the position of the explosion is specified in none of the cases. However, a reasonable assumption could be that this will be at the same position as the TNT explosion.

Table 5.10 Position of the explosion load.

Name	Explosion						Gas explosion						Oxidizing substances					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Getabrohult						X				X	Momentaneous: on road Continuous: 33 m into the analysed area							X
Engelbreckt-området, Jakobsberg						X				X	Momentaneous: on road Continuous: 33 m into the analysed area							
Stenungssunds centrum						X					On the road for momentaneous 48 m from the railway for continuous							X
Veddesta Etapp 1						X					Momentaneous: on road Continuous: 33 m into the analysed area							X
Gårda 2:12	X								X		Momentaneous: on road Continuous: 33 m into the analysed area							X
Hallands län						X	X											X
Lagaholm						X					Close to the road							X
Ullevigatan						X		X										X
Lagerströms-platsen						X		X										X
Täby park DP2					On the road							X						X
Krillans krog			X						X						X			
Kv. Sicklaön						X						X						X
Gudebroleden						X						X						X
Kållereds centrum						X						X						X
Strandängen						X						X						X
Bromma center						X						X						X
Floda Nova Sportcenter						X						X						X
Hornbergs-kvarteren	X				Described on map		X				Described on map						Described on map	X
Mölndalsåns dalgång	X						X						X					

5.7 Recommended risk reducing actions

In the analyses some risk reducing actions are suggested. Some of them will be necessary to get a risk level under what is not acceptable, and some are suggestions for reducing risks in the ALARP area. Since the risks in all analyses are connected to what can happen on a road where dangerous goods are transported the suggestions are similar or identical to each other. Therefore, the risk reducing actions are presented as general suggestions for reducing the risk instead of presenting it for all the projects alone. The risk reducing actions are presented in Table 5.11.

Table 5.11 Examples of risk reducing actions.

Category	Risk reducing action
Building free areas	• Building free areas should not make people want to be there for long times
Barriers	• Barrier to stop fluids from the road • Protective mould • Collision protection • The ground should not have a slope towards the buildings, or protective ramparts should be placed between them • Sealed lower edge of the existing barrier prevent fluids from reaching the buildings • Shield reduce the spread of heavy gases
Ventilation	• Air intake should be placed as far from the road as possible and it should be possible to turn of
Exits	• Main entrances should be placed on the opposite side from the road • If main entrance is placed at the same side as the road glass areas should be avoided • Emergency exits should be placed on the opposite side from the road
Facades	• Non-burnable materials in facades • Resistant to fire EI30 glass • Gas explosions should not lead to collapse of windows • Large deformation capacity of the exterior walls is preferable
Building resistance	• Buildings should be designed to prevent progressive collapse
Other functions	• If a window breaks, sprinkler system should prevent fire, that by then reaches the inside the building, from spreading to other parts • Flame detection on the road connected to alarm inside the building
Distances	• No new buildings within 30 m from road • New offices and shops should not be placed closer than 45 m from road • New residentials should not be placed closer than 100 m from road • New hotels should not be placed closer than 130 m from road

5.8 Discussion

Acceptable risk criteria

In Section 5.2 the used risk criteria were presented. One could see that in almost all cases the risk criteria from DNV was used. Hence, it seems that DNV´s criteria are the standard to use all over Sweden. One may need to ask oneself if the criteria is reasonable and if they give a risk level that one can accept. One can compare to the risk level from a natural disaster or the risk of dying for the group of individuals that has the lowest risk of dying. If the risk criteria are at approximately the same level it can be considered to be an acceptable level.

What also could be seen in Section 5.2 was that special criteria were available for Gothenburg. These criteria were a bit different from DNV´s criteria, which could be seen in Figure 2.9. It could be argued for that it is strange that Gothenburg has its own recommendations that in some cases are stricter than DNV´s criteria when DNV´s criteria seems to be commonly used in the rest of Sweden. It seemed like it was not clear what criteria should be used and, in some cases, both DNV´s and Gothenburg's own criteria were used while in other risk analyses DNV´s were chosen. Since two different ways of evaluation are available there might be a need for evaluating which criteria is most suitable and what will give a reasonable risk level. To have a too strict level will result in more expensive buildings due to the fact that several risk reducing actions are needed. It can even be the case that the building cannot be build due to too large risks. On the other hand, if larger risks are accepted the building might be too unsafe for the people inside.

Used statistics for transports of dangerous goods

From Section 5.3 it was possible to see that many different sources of statistics for dangerous goods transports were used. In some cases, it is good that the statistics used are not the same, since there might be statistics available which is only valid for a specific road. However, if different statistics are used for nearby projects at the same road it is of interest to investigate why there are differences.

A source that is commonly used is SRV 2006. There are several reasons why this source will not give the true number of transports even if it will provide an estimate. Today this source is often used as an estimate for a whole year, even though it is stated in the reference that the statistics from the one month that was included in the study should not be recalculated to represent a whole year. It was also stated that more than one source should be used in order to get a good result for the statistics (Räddningsverket, 2006). Nevertheless, it is common that this source is used as the only source.

There might be a need for producing new data that is updated and that includes all roads where transports of dangerous goods are allowed. There might be a need of finding a way where the number of transports is calculated by a system instead of relying on voluntary surveys. An alternative way of doing this could eventually be to use existing cameras at the roads, i.e. a system similar to that used to register cars passing automatic payment stations, since this works well for registering cars which passes there.

For railways it is easier to get statistics than it is for roads since the train traffic is more controlled. Therefore, the statistics for railways may be seen as more reliable than the statistics for roads. For the statistics concerning train traffic Trafikverket and SRV (2006) are the two most commonly used sources for statistics. Further, the statistics may need to be updated continuously. It is possible that the increase of dangerous goods on railways are larger than was predicted. This as more transports of dangerous goods are disposed to railways rather than on roads.

In most cases an increase of the traffic is considered. To get the increase a prediction for the next 20-30 years traffic is used. It may be difficult to predict the increase of the traffic so far into the future. It is also possible that the increase of transports with dangerous goods will not increase in the same speed as the rest of the traffic. However, predictions are needed even though it is difficult. But to only consider the traffic 20-30 years into the future may not be enough. Buildings are designed to hold for a much longer period than that.

Included risks

In Section 5.4 it was presented what type of scenarios that were included in the risk analyses. And from this one can note that some categories were included more often. The included risks are the ones that will give large consequences in case of an accident. A category which won't have large effect on the nearby buildings will not be of any interest in the risk analysis. In some cases, risks with large consequences but very small probability has been neglected in the risk analyses. It may be difficult to set a limit for when a risk could be ignored and when it could not. It may be possible that there is an increased probability of that specific category which was ignored in the risk analysis. Then it is bad if this risk has been ignored.

To point out what risks will be of large importance in the risk analysis is good. Thereby, risk reducing actions could be specified to reduce these types of risk scenarios. It is important to know what risk that will have large impact on the risk analysis and what risk that may result in a too high risk level. It is also interesting to know what risk scenarios will not contribute to a high risk level so that a too large effort is not laid on reducing these risks.

Design explosion load

It was clearly visible in Section 5.5 that the used explosion load varied a lot. A common estimation was to use 16 ton TNT as the explosion load from explosives. This was based on the fact that this is the maximum allowed amount of explosives to transport on Swedish roads. However, it is extremely seldom these loads is transported. Hence, it seems that the risk analysts wants to be sure that they do not underestimate the risks. It may also be the case that risk analysts have too little knowledge about what effect an explosion of that size will have on a nearby building.

One approach that could be used is to use the maximum allowed explosives when calculating the risk level. However, it is often said that one risk reducing action is to prevent progressive collapse of the building. If 16 ton TNT is also used to determine the design explosion load the building would need extremely thick walls without any windows or it should be placed at a large distance from the road. Calculations for what distance that is needed to resist different sources of explosions are found in Chapter 7. It may be the case that 16 ton TNT is not the load used as design explosion load. Anyway, it is seldom very well described in the risk analyses what source that is assumed either for the risk calculations of for design loads for the building. This lack in information could lead to confusion and uncertainty of the structural engineer.

Another thing to reflect about is that in some risk analyses the difference between instantaneous and continuous emissions of gas has been considered while in some cases it has not. In addition to this there has been a lot of different ways of describing the gas explosions. In some cases, it has been expressed on what distance the pressure will be larger than 0.3 bar. To express it in this way will make it possible to calculate the risk level only if 0.3 bar is a lethal limit for a human. On the other hand, this information will not be very useful when designing a building since complete dynamic load data is not described.

Another way of describing the size of the gas explosion is by a mass of liquified petroleum gas. This may be a bit better since it, with help of calculation tools, could be recalculated to an equivalent amount of TNT and the needed building resistance could thereby be calculated. It might be so that the risk analyst not have enough knowledge to understand the connection between what is assumed in the risk analysis and what it will mean for the design of the building.

Furthermore, for explosives from oxidizing substances, the considered size of explosion charge varies between 200 kg TNT up to 16 ton. This is a huge difference. Since the risk analyses are performed for different locations in Sweden some differences are possible but to get these large differences is probably due to different assumptions rather that different amount of traffic.

As a conclusion, different assumptions have been made for the different risk analyses. It is possible that the person making the risk analysis has a lack of knowledge when it comes to what effect an explosion will have on a structure. That may be the reason why large explosions are considered. Hence, there is a need of clarifying to what and how the explosion loads are used. Is the 16 ton of TNT only for risk level calculation or is it the load that the building also should be designed to resist? There is need of discussing if it is reasonable to use the maximum allowed load or if an average value would be better. At least the reasoning about the assumptions made needs to be described better in the risk analyses.

The position of the explosion center

It is only in a few risk analyses that the assumed position of the charge is pointed out, see Section 5.6. An assumption is probably made in order to calculate the risk for the persons in the nearby building or outside of it. However, which assumption that has been made is in most cases not presented. When it comes to gas explosions the position is discussed somewhat more. It is mentioned in some of the risk analyses the probability for the gas cloud to move into the analysed area due to wind.

There is a problem if the load position is not defined. When the engineer should calculate the resistance of the building and design it to withstand progressive collapse, which in many cases are said to be needed as risk reducing action, the distance between the load and the building will have a large impact. If the position is not defined, an assumption is needed to be made by the engineer, who probably lacks deeper knowledge about risk analysis reasoning.

What position that should be assumed is difficult to say. Should the worst case be used, or is it more reasonable to place the load in the middle of the road since half of the traffic will go in the other direction further away from the building area? Or should something in-between these two alternatives be assumed. Different assumptions may be made and there might be a need of discussing this to come up with a correct solution.

Furthermore, something that could be interesting to consider is that the amount of traffic on different sides of the road may vary. It is possible that industries are placed so that transports in one direction is more common than in the other. With knowledge of this, a better estimation of the charge location could probably be done.

Risk reducing actions

When it comes to risk reducing actions, which is presented in Section 5.7, similar suggestions were given. A reason for this might be that the suggestions are taken from a document from MSB where risk reducing actions are presented for different types of happenings. In order to improve the risk analyses it could be specified in the analysis what effects that the risk reducing actions will have. It would also be good to point out what risk the action proposed will have an effect on.

Some of the risk reducing actions are often not very specific and it could therefore be difficult to know if the requirement is fulfilled. As an example of this it is said that the building should be designed to prevent progressive collapse and that windows should not break in case of an explosion. However, with the uncertainty about the charge size, and the position of it, it is difficult to know whether this criterion is fulfilled or not. If looking at Table 3.1 one can see that the distance between the road and the building, then needs to be very large. By choosing the charge weight 16 ton TNT, which was done in several risk analyses, the building needs to be placed at a distance of approximately 2 km. This is not reasonable. Therefore, it needs to be defined in the risk reducing actions what load the building actually should be designed to resist.

6 Comparison of risk analyses in Gårda in Gothenburg

6.1 Orientation

During 2017 a comparison of eight risk analyses, carried out in Gårda in Gothenburg, was made by Norconsult. This chapter will partly be based on that comparison, which is found in the reference list as Norconsult (2017d). If nothing else is mentioned the information in this chapter comes either from the comparison or from the eight risk analyses presented in Table 6.1. The risk analyses are from an area called Gårda in Gothenburg and they were performed between year 2002 and 2017. The idea of the comparison Norconsult did 2017 was to specifically analyse how explosion risks have been handled in the risk analyses. What can be learned from this review? How should further risk analyses be performed in the future?

In the review the risk analyses presented in Table 6.1 were analysed. They can be found in the reference list by looking at company name and year. The methodology was a bit different for the analyses, four of them was done as qualitative risk analyses while the others where quantitative analyses. In Figure 6.1 one can see the location of the eight projects. The projects marked with green colour are the ones that are made as quantitative analyses and the yellow are qualitative analyses. The colour marked areas in red, orange and yellow represent the distance to the road E6.

The projects marked with bold text in Table 6.1 are projects which has also been studied in Chapter 5. For Gårda 2:12 the same risk analysis has been studied. However, for Ullevigatan two different documents has been analysed.

Table 6.1 Reviewed risk analyses in a qualitative comparison.

	Project name	Company	Year	Type
A	Block Venus	Flygfältsbyrån (now COWI)	2002	qualitative
B	Gårda 18:25	GF-konsult (now Norconsult)	2007	qualitative
C	Gårda 3:3, 3:11, 3:13	Norconsult	2009	quantitative
D	Parkings at Johan på Gårdas gata	Norconsult	2010	qualitative
E	Gårda 18:23	Norconsult	2015	qualitative
F	**Gårda 2:12 etc.**	**Norconsult**	**rev. 2017c**	**quantitative**
G	Eken, Cedern and Lejonet	ÅF Infrastucture AB	2016	quantitative
H	**Ullevigatan**	**COWI**	**2017a**	**quantitative**

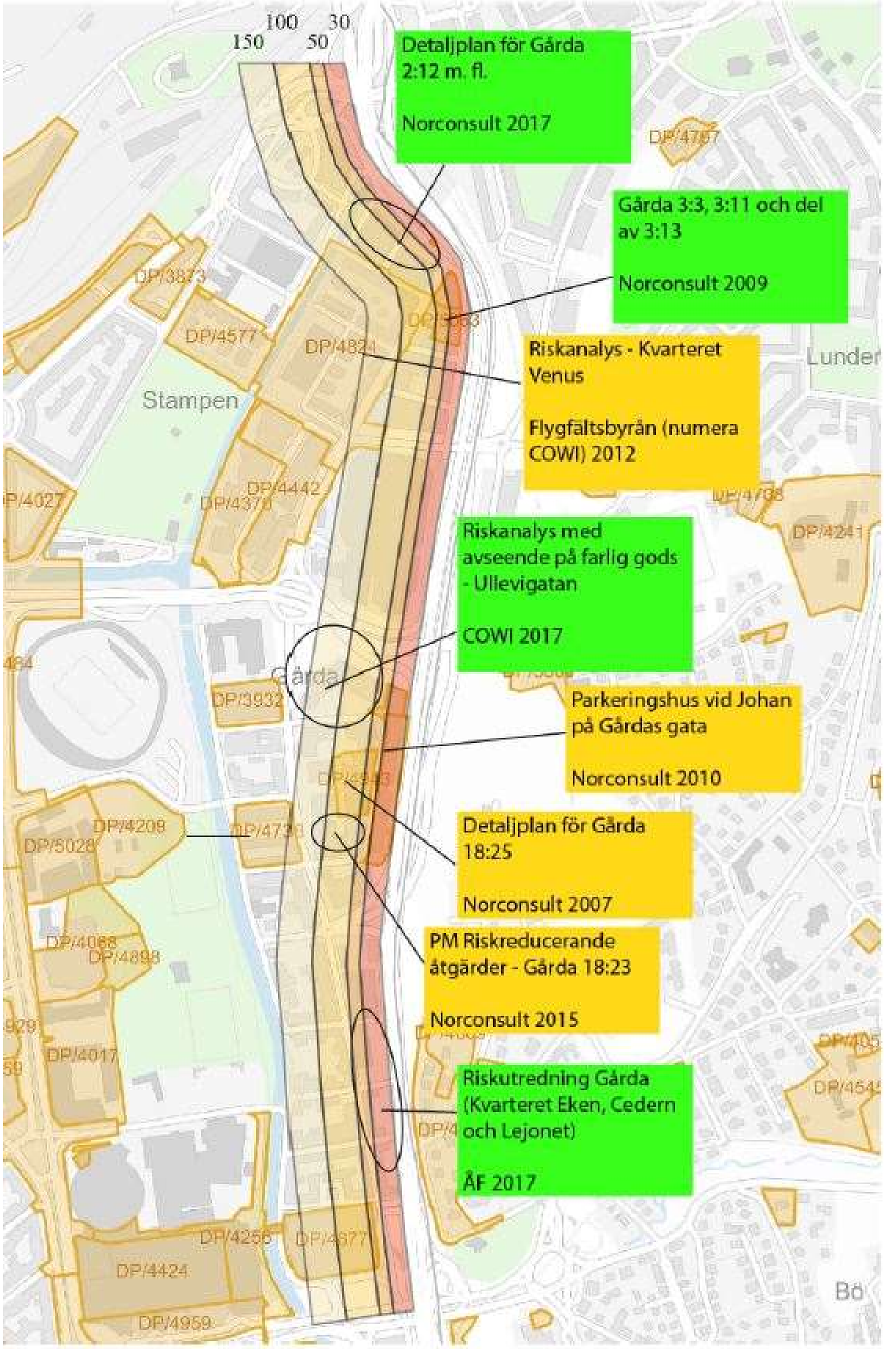


Figure 6.1 Analyzed projects in Gårda, Gothenburg. From Norconsult (2017d).

Comments of how the risk analyses has been performed and suggestions for improvement given in Section 6.2 to 6.4 comes from Norconsult, the county administration board or the emergency services and has been expressed in the report done by Norconsult (2017d). Because the focus of this thesis is on explosions a further investigation of how explosions has been treated in the risk analyses has been done by the author of this report. This is presented in Section 6.5. In addition to this a deeper comparison has been done of the result of the analyses. This comparison is found in Section 6.6. In Section 6.7 the author of this report discusses and presents some comments of how the risk analyses could been improved and gives suggestions for how risk analyses in the future could be done in order to increase their quality.

6.2 Acceptable risk level

As described in Section 2.3.2 there are two risk criteria that have been used in Gothenburg. The risk levels decided by Gothenburg city year 1999, presented in the document "Översiktsplan för Göteborg fördjupad för sektorn Transporter av farligt gods" which is often shortened as GÖP 99 is one of them. The other one is the recommendations by DNV (Det Norske Veritas). A comparison between the risk levels are found in Figure 2.9.

In the comparison of risk analyses it is noted that in risk analyses made year 2007 and earlier the criteria from GÖP was used. For analyses performed later DNV´s criteria were used instead, see Table 6.2.

Table 6.2 Used criteria for evaluation of risk

Analysis	Name	Used criteria
A	Block Venus	Gothenburg city plan, GÖP
B	Gårda 18:25	Gothenburg city plan, GÖP
C	Gårda 3:3, 3:11, 3:13	Gothenburg city plan, GÖP, and national criteria
D	Parkings at Johan på Gårdas gata	-
E	Gårda 18:23	-
F	Gårda 2:12 etc.	National criteria
G	Eken, Cedern and Lejonet	DNV and GÖP
H	Ullevigatan	National criteria, comparison with GÖP

A conclusion in the comparison is that a shift from using the GÖP criteria to using DNV´s criteria has been made. The county administration board, which reads though and reviews all risk analyses, has commented on that it is strange that Gothenburg's criteria are not followed in Gothenburg. However, the criteria form DNV has now been the standard which is used in the building sector. Therefore, Norconsult (2017d) argues that DNV´s criteria should continue to be used but still a comparison with GÖP criteria is recommended to be done.

6.3 Statistics

Depending on when the risk analysis is performed different statistics are used for the number of transports. For risk analyses performed before 2007 the statistics from Räddningsverket 1998 is used and for analyses made later the statistics from Räddningsverket 2006 are used.

In Table 6.3 the used statistics for transported dangerous goods are presented. From the table one can see that there are large variations in the statistics that is used. Even though the same source is used, for example in analysis F and G the number of transports is not the same. The difference is large, and some categories are skipped in analysis H which is included in analysis F.

Table 6.3 Used statistics for dangerous goods transports on E6 passing Gårda, divided into categories of dangerous goods.

	A	B	C	D	E	F	G	H
Source	(1), SRV 1998, 1999, 2000. SIKA 2000, 2001	Räddnings-verket 1998	Räddnings-verket SRV 2009	-	-	MSB 2006 south of Gothenburg, increase Trafikverket		Räddnings-verket SRV 2006
Year	1995	1998	2020	-	-	2030	2030	2030
What	Number of transports	ton	Fully loaded trucks			Number of transports	(2)	Number of transports
Category of dangerous goods								
1	-	800-2000	56	-	-	100	80	1
2	8068	60000-120000	9804	-	-	6300	7470	1643
3	33220	80000-200000	41000	-	-	50000	39600	29700
4	-	800-1600	1100	-	-	2600	1788	-
5	1898	20000-80000	100	-	-	500	590.2	443
6	-	2000-10000	140	-	-	260	372	-
7	-	-	-	-	-	12000	882	-
8	34169	40000-80000	2000	-	-	12000	13920	-
9	-	800-4000	630	-	-		13800	-

(1) Traffic calculation Åbromotet 1995
(2) Number of trucks loaded with 15 ton, except for explosives where the load is assumed to be 5 ton

To only use one source of statistics is common in the risk analyses even though this is not recommended by MSB. The statistics that MSB have is based on an investigation done during September 2006 and therefore it might not represent the reality well enough. For further information about this investigation see Appendix A. Furthermore, there is no statistics available for the part of E6 which passes Gårda. Statistics are available for the roads south and north of Gothenburg but not in the area where all of the projects analysed are located. An estimation for the part of E6 has therefore been done for all project.

It is argued for that due to the fact that there are restrictions for dangerous goods in Tingstadstunneln north of Gårda and at Oscarsleden the number of transports of dangerous goods that passes Gårda may be lower than what it is south and north of Gothenburg. How large this reduction may be is difficult to know and in most of the risk analyses a reduction is not considered.

Trafikanalys (2019) presents a number of transports with dangerous goods in relation to the total number of heavy transports. If the number of goods transports is known the national statistics can be used to calculate an approximation of the number of dangerous goods transports on the analyzed road. To get an approximation for the future an increase is assumed and the number of transports by 2030 is presented.

Additionally, it is highlighted that the analyses could consider the traffic by day- and nighttime. This could be an important factor which possibly could reduce the risk level. How much reduction depends on how the analyzed area should be used. However, this is only done in one of the eight analyses.

As a conclusion, since no investigation is made for the number of transports in Gårda this needs to be done. Together with more detailed estimations of the number of transports and by dividing the number of transports between day- and nighttime the risk analyses will contribute to more reliable information and reflect the actual risk level in a better way.

6.4 County administration board and the emergency services comments

The eight risk analyses have been reviewed by the county administration board in Gothenburg and by the emergency services which both has commented on the risk levels, the risk criteria and the suggested risk reducing actions.

Some comments and suggestions of improvement was presented by the county administration boards. Firstly, they have commented that they think that it is remarkably that the criteria given by GÖP has not been used in the cases where it is not used. They have also suggested that both GÖP´s criteria and DNV´s criteria should be used in the evaluation.

The county administration boards have also highlighted the importance that the risk reducing actions that is needed are well presented and precise so that it is not missed later in the building process. Connected to risk reducing actions they also comment on that it might be uncertainties in how much the risk reducing actions actually will decrease the risk level. If the risk level without risk reducing actions are above what is accepted according to DNV it is really important that the risk reducing actions are well described and that it is sure that they work as well as assumed.

The emergency services agree with the county administration boards about the fact that GÖP criteria should be used together with DNV´s criteria. In GÖP, criteria for apartments and offices are specified separately and the emergency services suggests that if apartments should be built the risk level should be compared with the criteria from GÖP.

In most cases the emergency services are satisfied with the suggested risk reducing actions. Some improvements are given and as an example they suggest that the pressure from an explosion should be investigated since it may result in that windows breaks and this could affect the people inside the building.

In addition to this the emergency services have also commented that the possibility for a rescue service operation needs to be considered in the risk analysis. In most of the risk analyses this is done sufficiently but this is something to have in mind for future analyses.

6.5 The handling of explosions

6.5.1 Analysis A: Block Venus

In this risk analysis, accidents with flammable liquids and gases are considered to be the two most important risks. This because they are often transported and that they can cause a lot of damage. From the used statistics it has been assumed that no transports of explosives are passing the analyzed area. However, there are other goods types that may lead to explosions which is considered in the analysis. In this analysis flammable gases and oxidizing substances have been included.

In the risk analysis it is described that possible consequences of an accident where flammable gas is included are jet fire, gas explosion or BLEVE. The type of consequence that is considered to contribute to the worst case with the greatest number of deaths is the BLEVE. Other happenings from accidents with flammable gases or liquids would not result in bad consequences.

When it comes to gas explosions it is also mentioned that it is possible that the explosion occurs at some distance from the accident. This due to the fact that the gas explosion will occur if the ignition of the gas is somewhat delayed. A detonation of the gas is said to be less probable than deflagration. What is said to be the most common case is a deflagration leading to a 20 ms long shock wave where the pressure is about 1 kPa. What will occur in case of an accident where flammable gas is included is of course highly dependent of the size of the leakage.

6.5.2 Analysis B: Gårda 18:25

When describing what is transported on E6 both explosives, flammable gases and oxidizing substances are presented. Also, other categories were included but these have no risk of explosions.

In the analysis a comparison is made for what difference it will be if moving the building to a distance of 44 m from the road instead of having it on the recommended distance of 50 m. When doing this comparison, the heat radiation and the explosion pressure has been compared for the two distances. The effect that the shorter distance will have concerning explosions is that the pressure from an explosion will increase by 25%. This according to FOA 1997. What pressure this actually correspond to is not presented. It is not presented what explosion load that is considered in the risk analysis.

When it comes to the recommended risk reducing actions concerning explosions the suggestion is that the façade and the windows should be built to withstand a higher explosion pressure than normal. This could be done by using prefabricated concrete elements in the façade. For the windows laminated safety glass could be used and the attachment of them could be improved. It is also said that a 2 meters high barrier is needed close to the road for protection for both liquids and explosions.

6.5.3 Analysis C: Gårda 3:3, 3:11, 3:13

In the analysis a calculation method called RBM2 is used for the risk calculations. The method, which comes from the Netherlands, has been customized to fit the

Swedish conditions. In RBM2 explosives and oxidizing substances are not included. To adjust the method to Swedish conditions risk concerning explosives has been added afterwards.

The risk categories that is considered to be of large importance in the risk analysis are mass explosives, flammable gases, toxic gases, flammable liquids and toxic liquids. It has been calculated that the risk contributing to the highest risk level is mainly flammable gases. Explosion from flammable gases are possible. It is noted that the worst type of accident from flammable gas is BLEVE.

To reduce the risk of a BLEVE it is suggested that the building should have better resistance against heat and pressure. The facade should resist a static pressure of 5 kP and the building should have a frame of concrete to better withstand an explosion. Another alternative is to have a protective wall which also will contribute to a reduced risk level outside the buildings as the wall will reduce the pressure and the heat. The wall will also reduce the ability for the gas to spread into the building area. Additionally, it is also pointed out that it is important that the exits are located on the opposite side of the building in relation to the road.

6.5.4 Analysis D: Multistory car park at Johan på Gårdas gata

The car park in this analysis is placed between E6 and Gårda 18:25. In the analysis for Gårda 18:25 it was said that a barrier was needed. When the car park is built closer to the road than 30 m, the barrier suggested in that analysis cannot be used. In analysis for the multistory car park one suggestion for reducing the risk for explosion is to build a stiff railing that prevents trucks and cars from driving of the road. Together with the parking house the railing will have the same effect as the first suggested barrier. Except from this suggestion about the railing, nothing else is mentioned about what type of explosion that should be considered or what risk level that the building have.

6.5.5 Analysis E: Gårda 18:23

The risk analysis evaluated what difference a change in the zoning for Gårda 18:23 will result in concerning risks. In earlier made risk analyses the result has been that the two most important risks to consider were connected to flammable gases and liquids. Why, is because this is what was transported the most, the probability for accidents of this type were the highest and the consequence in case of an accident was large. What might happen in case of accidents with flammable liquids or gases are described in the analysis.

In the analysis some risk reducing actions that were suggested in analysis B and D were mentioned. These are now built and will contribute to a safer environment. It is considered that fires are the risk that will have the largest influence on the risk level. Therefore, it is suggested that windows are changed to class EI30 on the floors in the building where offices are changed into centrum activities.

6.5.6 Analysis F: Gårda 2:12 etc.

Explosives, flammable gases and oxidizing substances are three out of the five most important risk sources according to this analysis. When looking at what type of actions that should be done to reduce the risk level it has been considered what type of accidents that is contributing to a risk level above what is tolerable. Thereafter, suggestions of risk reducing actions have been given to prevent these accidents or reduce the consequence if they occur. One risk reducing action that is suggested is that the buildings should be built to prevent progressive collapse and destroyed windows in case of an explosion.

The type of explosion that is most probable to occur is from gas. Massive explosions from explosives are less probable and they will not have a large impact on the risk level. When looking at the consequence 16 ton TNT has been considered for explosions from explosives. The way the explosive load, to be used for the design of the building, are well explained in an appendix to the risk analysis.

6.5.7 Analysis G: Eken, Cedern and Lejonet

It is described that explosions from explosives, gas and oxidizing substances is possible to happen and therefore they should be included in the risk analysis. However, when the risk reducing actions are presented nothing that is said to treat risk of explosions is suggested.

It is argued that due to strict regulations for how explosives of class 1.1 are allowed to be transported and the small number of transported explosives, the probability for such an accident is so low that this class could be neglected in the analysis. Despite this, the risk is further analyzed because of the small distance of 3-5 meter between the road and the building. When doing this, the transports of explosives are divided, and an assumption is made that 2% of the transports are filled with 16 ton TNT while the rest of the transports are filled with 20 kg TNT. The consequence and the probability are calculated for several events that could have large impact on the building.

6.5.8 Analysis H: Ullevigatan

In the risk analysis for Ullevigatan some of the most important risks to consider are from explosives, flammable gas and oxidizing substances which all can result in explosions. A risk reducing action is that buildings should withstand gas explosions at the size of 10 kg liquefied petroleum gas. To withstand means that progressive collapse should be prevented.

In the analysis the risk level curve is above the recommended level according to GÖP for accidents with many deaths. What is critical in this case is the consequence BLEVE, a large fire ball which can occur in case of an accident with flammable gas. However, since the risk level is below the limit of what can be tolerable according to DNV´s criteria it has been concluded that risk reducing actions to reduce the risk of a BLEVE is not economically reasonable. This due to the large pressure that the BLEVE will result in, which is much higher than the pressure of 10 kg liquefied petroleum gas which is the design value chosen for a gas explosion.

6.6 Comparison of result

As described in Section 2.2.3 one can evaluate the individual risk level and the risk for the society. The individual risk level has only been evaluated in the four analyses that were quantitative analyses. And from that the result was that the risk level was acceptable at a distance between 65-100 meters from the road E6. In Table 6.4 the distance for when the individual risk is considered to be tolerable and acceptable is presented.

Table 6.4 Distances for tolerable and acceptable individual risk level for risk analyses in Gårda.

Analysis	Name	Tolerable distance	Acceptable distance
C	Gårda 3:3, 3:11, 3:13	Presented in a map	-
F	Gårda 2:12	0 m	40 m
G	Eken, Cedern and Lejonet	0 m	110 m
H	Ullevigatan	Outside 25-50 m Inside 0-25 m	Outside 50-100 m Inside 25-50 m

The risk for the society were evaluated for the same four projects as the individual risk level. All analyses except Analysis G gets the result that without any risk reducing actions the society risk level will be too high to be tolerable. The risk analysis concerning Analysis G has not yet been accepted by the county administration board. Critique has also been presented by the emergency services that the result may be wrong and that the risk may be larger than what has been presented in the risk analysis. As one can see in Figure 6.1 this project is located in the red area closest to the road and the risk level may therefore probably be higher than for the other projects located at a larger distance from the road.

The results for the society risk level are presented in curves and compared to DNV´s criteria and in some cases also the criteria from GÖP, see Figure 6.2 to Figure 6.5. In all the risk analyses the criteria has been recalculated to fit the size of the area in the analysis. Because of this a comparison cannot easily be made be just looking at the figures.

Since the distance from the road to the building varies for the four projects it is reasonable that the risk level varies a bit. The shortest distance between the road and the buildings are presented in Table 6.5. If just taking the distance into consideration it would be reasonable to think that the building closest to the road would have the highest risk level. On the other hand, there might be existing structures in between the road and the buildings that reduces the risk level.

Table 6.5 Shortest distance between road and building.

	Name	Distance
C	Gårda 3:3, 3:11, 3:13	16 m
F	Gårda 2:12 etc.	23 m
G	Eken, Cedern and Lejonet	3 m
H	Ullevigatan	45 m

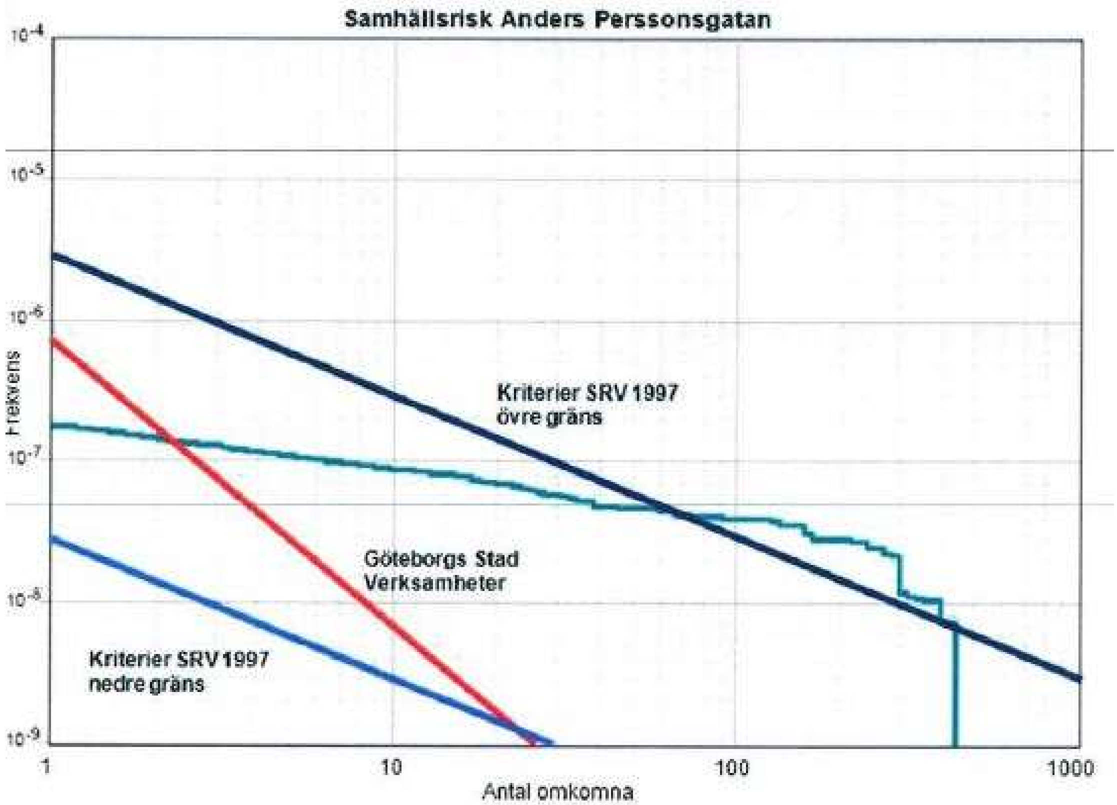


Figure 6.2 Society risk level for analysis C. The risk levels are recalculated to a distance of 60 m with buildings on one side of the road. The dark blue line represents DNV´s tolerable level, the light blue line DNV´s acceptable level, the red line the criteria from Gothenburg city and the blue-green line is the calculated risk level. From Norconsult (2009).

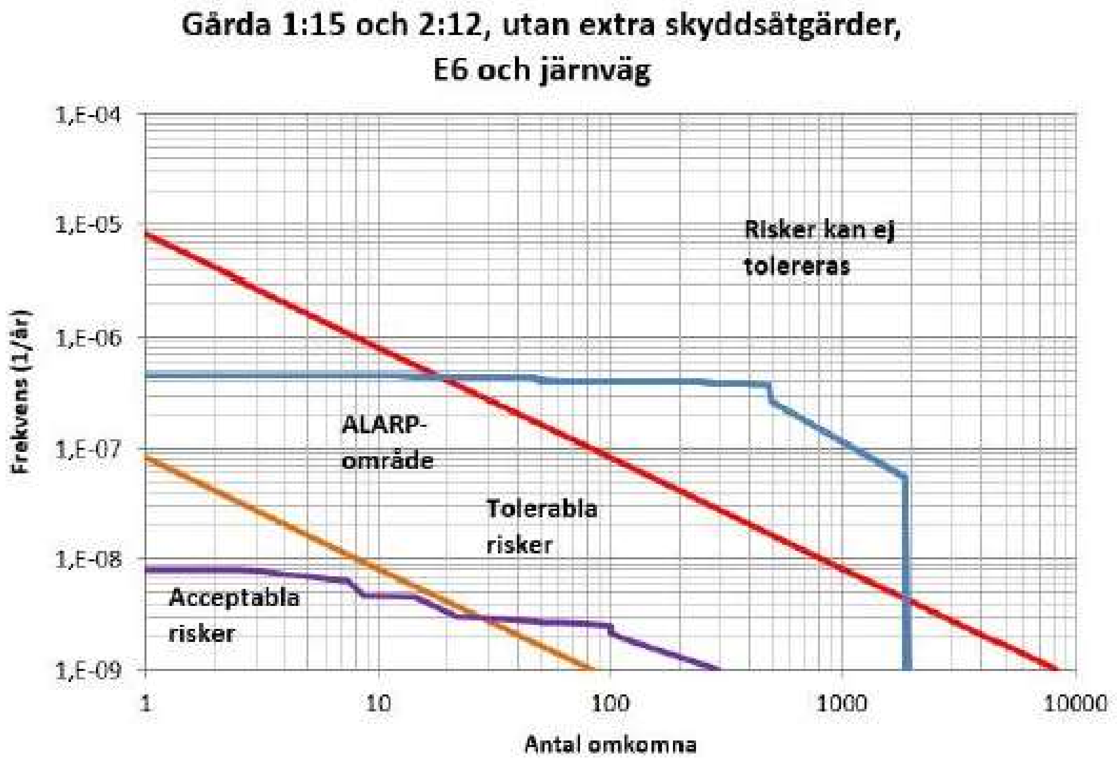


Figure 6.3 Society risk level for analysis F. The risk levels are recalculated to a distance of 165 m and one side of the road. The blue line represents the risks from E6 and the purple represent the risks from the railway. The red line represents DNV´s tolerable level and the orange line DNV´s acceptable level. From Norconsult (2017c).

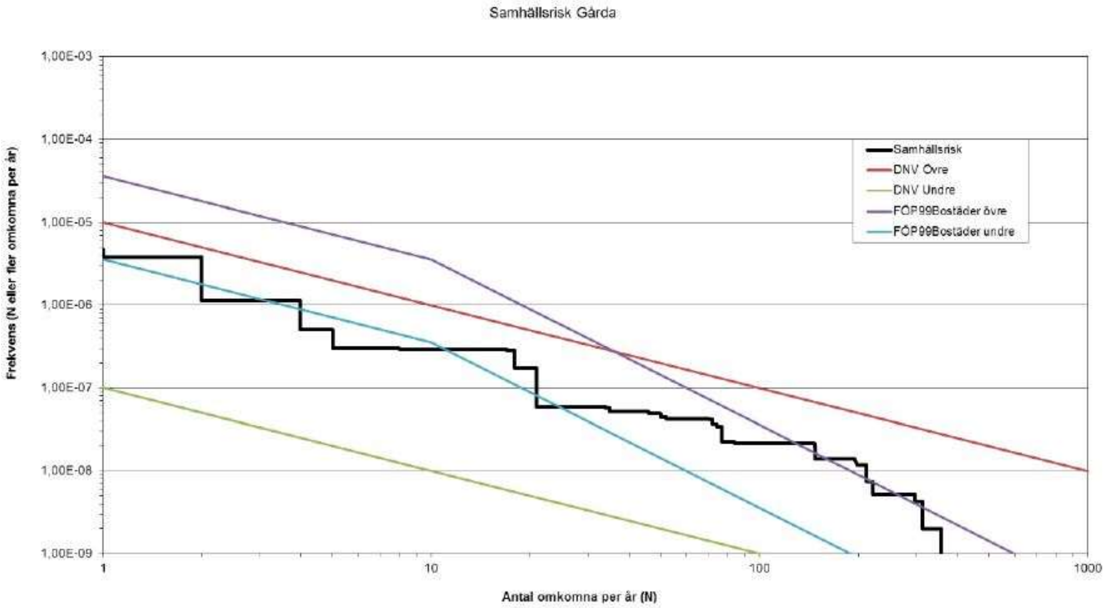


Figure 6.4 Society risk level for analysis G. Here the criteria have been changed so that it will correspond to the criteria for 200 m and for one side of the road. The red line represents DNV's tolerable level, the green line DNV's acceptable level, the purple and blue lines the criteria from Gothenburg city for offices and apartments and the black line is the calculated risk level. From ÅF Infrastructure AB (2016).

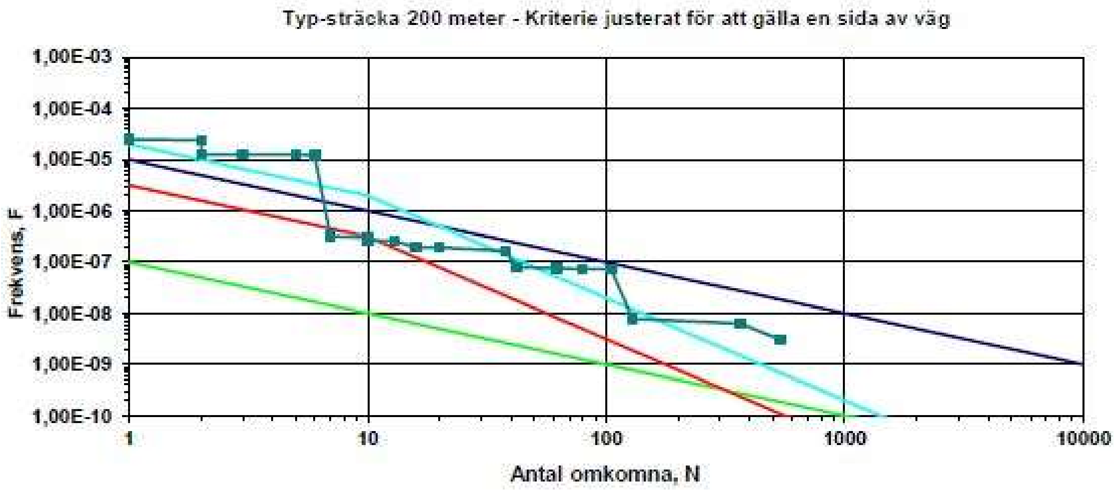


Figure 6.5 Society risk level for analysis H. Here the criteria have been changed so that it will correspond to the criteria for 200 m and for one side of the road. The dark blue line represents DNV's tolerable level, the green line DNV's acceptable level, the light blue and the red lines the criteria from Gothenburg city for offices and apartments and the blue-green line is the calculated risk level. From COWI (2017a).

6.7 Discussion

Acceptable risk criteria

Some years ago, two different risk criteria were available for Gothenburg. This may have caused some uncertainty about what should be used. It is possible that the criteria that was less strict was used because then it was easier to fulfil the criteria. Since both the county administration board and Norconsult had comments about the use of double criteria there was a need for making a decision for what criteria should be used. This has according to Heijmans now been done, see Section 8.2. Now it is decided that DNV´s criteria could be used in all parts of Sweden. This decision will hopefully make it easier for the risk analysts to know what criteria to follow.

Used statistics for transports

In Table 6.3 it was clearly visible that the statistics for the number of transports that passed Gårda was different. Although, the same source for statistics were used the assumed number of transports were different. In one analysis it was mentioned that no statistics was available for the part of E6 that passes the projects in Gårda. It was the same situation regarding the statistics for all the analyses although they did not mention it. Because of this all the risk analyses have made their own assumptions. Some has taken into consideration that there are some restrictions of what is allowed to be transported through Tingstadstunneln north of Gårda and on some other surrounding roads. It is reasonable that the number of transports that passes Gårda is a bit fewer than what passes south of Gothenburg, where statistics are available for the traffic.

In one of the analyses the difference in traffic during day and night-time has been considered which also contribute to a different result compared to the other analyses. If restrictions on surrounding roads as well as day and night traffic are considered it might have large effects on and reducing the calculated risk level in the end.

It is also worth mentioning that in most cases only one source for statistics was used. It is even mentioned by Räddningsverket (2006), which created the statistics, that it is a bad idea to use only one source. It might be a good idea to make a new investigation of the number of transports with dangerous goods in Sweden. The investigation should then be done during a longer period to get more reliable data. It would also be a good idea to include the part of E6 that passes through the centre of Gothenburg. It is argued for that Gårda is an area with large needs of expansion and densification and in order to avoid bad estimations of number of transports a new investigation could be recommended.

The county administration board and emergency services comments

Both the county administration board and the emergency services had some comments about risk reducing actions. To have more knowledge about how much the suggested risk reducing actions would reduce the risks would probably be a very good idea. It is possible that risk analysts do not have enough knowledge to specify any numbers of the reduction. If the reduction should be specified in the risk analyses, which sounds reasonable, there might be need of some kind of document helping the risk analysts with this.

To have a good knowledge of the effect of the risk reducing actions will be of large importance when the risk level is above that of what can be tolerable. Here, it is important that the assumption made are not too uncertain. Even though an uncertainty analysis in most cases are done at the end of the analysis, taking such things into consideration a bit more knowledge in the area would not be bad.

The emergency services commented on the possibility for them to have rescue service operations in the area. From what has been described in Chapter 2 nothing has been mentioned that this types of parameter should be considered in a risk analysis. To consider how well rescue service operations could be performed in the area is of course an important thing. A better communication with the rescue services in the city and the risk analysts would probably contribute to better performed risk analyses. To include a part concerning this in a document giving recommendations for how a risk analysis should be performed could also be something preferable.

Handling of explosions in risk analyses
When summarizing how explosions have been treated in the risk analyses, one can see that explosions from explosives are not considered to have a very large impact on the risk level. In some analyses the massive explosions are not even included due to the fact that the probability for them to occur is so low.

The risk analyses do agree that it is the risks with flammable gases and liquids that make up the largest risks. If it is specified which event will give the largest effect, BLEVE is pointed out. Is it reasonable to assume this to be the largest risk? One need to look at the probability for it as well.

In analysis B it was mentioned that the building should resist a large explosion and a higher pressure than normally. What is meant is that the building needs to resist a larger load than if it would have been placed at the recommended distance. However, the way it is expressed in the risk analysis, one might get the impression that there exists a standard explosion which buildings are designed for. However, this is not the case.

When it comes to the recommended risk reducing actions the same suggestions are given for things that will reduce the explosion risk. The façade and the windows should have a good resistance to pressure and heat. It is common to recommend windows of class EI30. Further suggestions are to say that the building should prevent progressive collapse and that a protective wall should be built in front of the building.

Individual and society risk
When looking at the risk level for individuals it has nothing to do with the assumed number of persons that will be in the building. The individual risk level is only a value for how probable it is for a person to die at a certain distance from the risk object, which in this case is the road E6. Since the risk source is the same for all projects it is reasonable to believe that the individual risk level also should be approximately the same, for the risk level outside the building. However, as one can see from the few analyses which presents distances for when the individual risk level is acceptable and tolerable the calculated distances are not the same.

The individual risk level could vary due to existing risk reducing actions or what the building looks like. If the building is robust, which prevents progressive collapse the risk for the person inside is lower than if the building could not prevent progressive collapse. Therefore, some differences in the individual risk level are not very strange.

However, the reason for the differences in the results is difficult to know. Differences in what's intended to be built is one thing, but it could also be differences in the traffic that is assumed to pass the area or different assumptions of how well filled the transports are.

When comparing the result of the risk analyses, analysis C and F gets a result where the tolerable limit according to DNV is exceeded somewhere in-between 20 – 90 deaths for the society risk level. As the distance to the road is 16 m for analysis C and 23 m for analysis F the result should be somewhat similar, which they are. Noticeable is that the building closer to the road has a lower risk level.

Another factor that will have a large impact on the result on the society risk level is the number of people that will be inside the building. It might be the case that this factor has larger impact on the result than the distance to the road. This makes it even more difficult to make a comparison. To get a good comparison it is not enough to just look at if there is plans of building offices, hotels or apartments there are also other parameters that is included when making the assumption of the number of people in the area.

Even though it is difficult to make a complete comparison it is worth mentioning that the only risk analysis that gets a risk level that is lower than the tolerable level, according to DNV, is analysis G with buildings at a distance of 3 m from the road. According to the risk analysis the buildings might include both hotels, offices and apartments. The county administration board did have a lot of comments on this risk analysis, but it is possible that the risk level is calculated as too low.

The risk level at Ullevigatan, Analysis H, is too high for risks that results in accidents with 1 to 7 deaths. Why it in this analysis is risks with consequences leading to less than ten dead that is critical while it in two other analysis are risks with approximately 50 – 1000 deaths that is critical is interesting.

7 Response of a wall subjected to explosion load

7.1 Orientation

To understand dynamic loads such as explosion loads, can be complicated. To better illustrate the influence of various type of explosion loads this chapter present a simple example of a wall subjected to such loads. This illustration has been made in order to make it easier to understand what different choices of explosion loads in a risk analysis will result in and how different types of structures respond to explosion loads of different magnitudes. It is investigated what distance to the explosion centre that is necessary for the wall to withstand the explosion studied.

The wall which is used to illustrate the effects of explosions is assumed to be placed close to a road where dangerous goods is transported. The wall is described in Figure 7.1. The height of the wall is 3 m and a 1 m wide strip of it is studied. The wall is simply supported and does not carry any load vertically; i.e. the wall is only exposed to the load from the explosion. In the base case the wall is 200 mm thick and has a density of 2500 kg/m^3. The response of the concrete is plastic. However, these parameters will be changed to see what influence it will have on the response. For further description of the model used in the calculations see Appendix B.

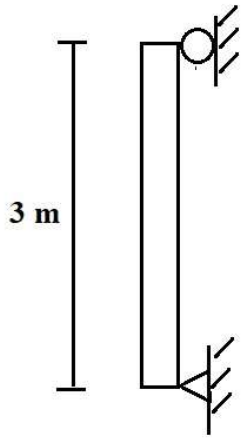


Figure 7.1 Description of wall used in calculations

The wall will be modified in order to describe how different characteristics will influence the structural response. The thickness of the wall will be changed from the original value of 200 mm to 150 mm and 300 mm. Also, the density of the concrete will be modified to 500 kg/m^3 to visualize how a lightweight structure respond. Furthermore, plastic and elastic behaviour will be compared. All modifications of the wall will be compared to the basic case described above. The reason for changing the input parameters like this is to show how other structures than reinforced concrete would respond. However, the stiffness and load capacity are calculated as for concrete. The idea of the modifications is not to symbolise a specific material but to visualize the principals and phenomena.

For the analysis of TNT explosions different amount of reinforcement will be compared, 0.2 %, 0.4 % and 0.8 %. The concrete cover c' was 40 mm; giving the distance to the concrete level, d=160 mm, see Equation (7.1). When it comes to the gas explosions only 0.2 % reinforcement has been analysed due to the smaller magnitude of the explosions.

$$d = h - c' = 200 - 40 = 160\ mm \tag{7.1}$$

The loads that are used in the calculations are explosions from TNT and from gas. This is because this is the kind of explosions which could occur on a road. Explosions from explosives are normally described as an amount of TNT while the gas explosion may be described as a volume of the gas cloud and a strength factor, see Section 3.4 for TNT explosions and Section 3.5 for gas explosions. The size of the explosions used in this chapter are chosen to visualize how different sizes of explosions would affect the response of the wall.

7.2 Description of calculation method

The method used for structural response in the calculations behind the presented figures is a numerical method which is based on the single degree of freedom method and the central difference method. For the central difference method see Johansson, (2012c) and for single degree of freedom method, see Johansson (2015). This method is also somewhat described in Section 4.2 where the single degree of freedom method is described and equations for deformations are presented.

For calculations of the load the methods described in Chapter 3 are used. For empirical relations for TNT explosions see Section 3.4 and for gas Section 3.5. A calculation template was used to find the load values for TNT and gas explosions.

To find the distances where the capacity of the wall was used to 100 %, different distances were tested and the load capacity were controlled. For elastic response the maximum deformation capacity was controlled. The distances presented below is the shortest possible distance between the wall and the centre of the explosion.

Furthermore, concerning TNT explosions a reflection factor of 1.8 is used in the calculation. This is because the explosion is assumed to occur close to the ground. Further explanation of this effect is found in Section 3.3.2.

7.3 The explosion loads

7.3.1 TNT explosions

Firstly, the load is described as a pressure at different distances from the centre of the explosion, see Figure 7.2. As one can see the pressure close to the explosion becomes large. But with an increased distance the pressure decreases quickly. From Figure 7.2 one can realize that depending on how far from the explosion centre a building is placed it will resist the explosion load different. Due to the fact that the largest pressures are so high this is not shown in Figure 7.2. In Figure 7.3 the pressure variations are presented with a logarithmic scale. Here the pressure level at a short distance from an explosion are visible also for large explosions with 1000 kg TNT.

What is also needed to express the explosion load is to describe the impulse intensity. It is described as pressure multiplied by second and it varies by distance similarly as the pressure. Figure 7.2 describes the impulse at different distances from the explosion for different sizes of TNT explosions and Figure 7.3 describes the same but with a logarithmic scale. These values are also given in Table B.5.

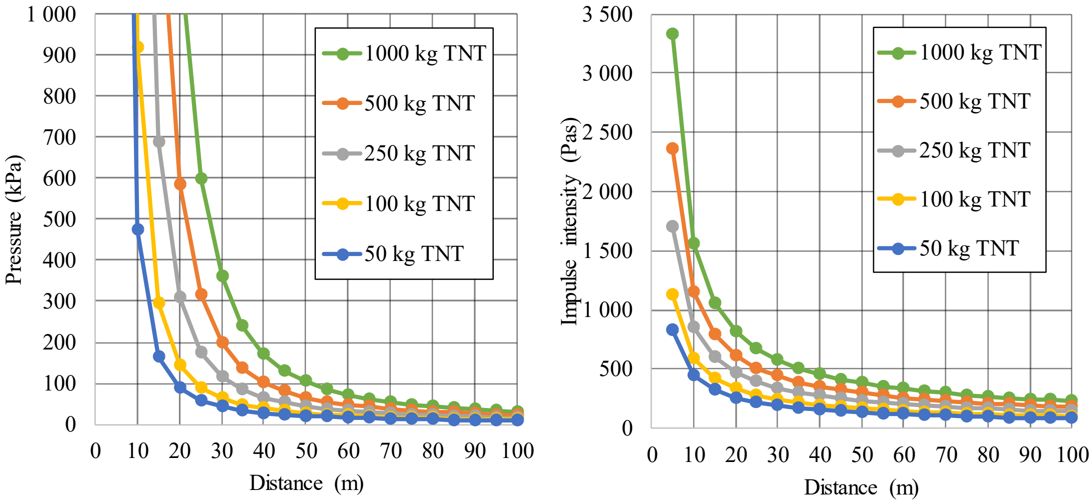


Figure 7.2 Pressure at different distances from TNT explosions of different sizes (left) and impulse load at different distances from TNT explosions of different sizes (right).

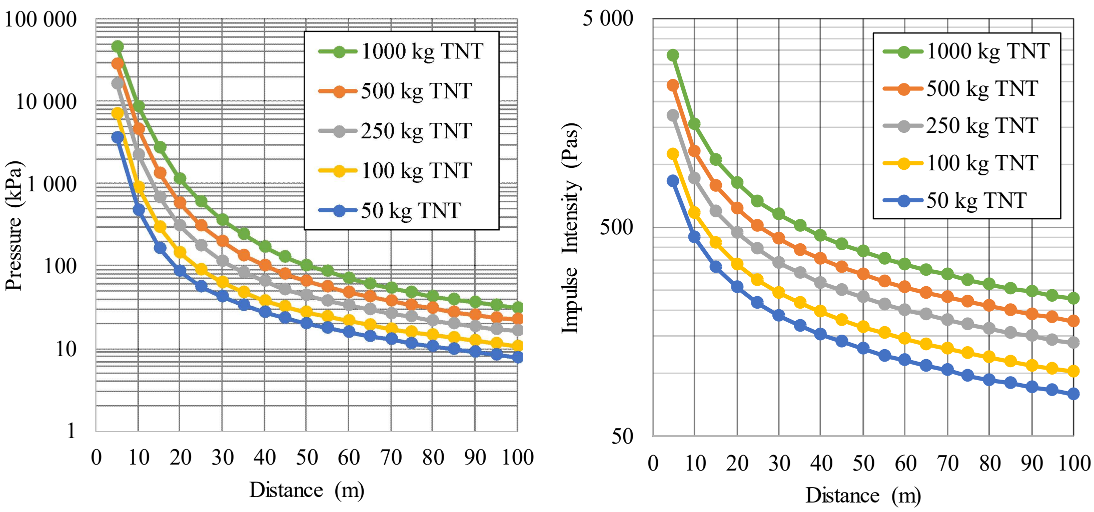


Figure 7.3 Pressure at different distances from TNT explosions of different sizes, logarithmic scale (left) and impulse load at different distances from TNT explosions of different sizes, logarithmic scale (right).

7.3.2 Gas explosions

The load from a gas explosion can be described by the pressure and the impulse at different distances. This is shown in Figure 7.4. In Figure 7.5 the pressure and impulse are shown with a logarithmic scale. What can be seen is that the pressure level and impulse become high at a short distance from the centre of the explosion and it decreases quickly with an increased distance. In Figure 7.4 and Figure 7.5 two gas explosions with 100 m^3 volume with strength factors 5 and 7 are compared to an explosion of 50 kg TNT. This is also described in Table B.6. The pressure of the TNT explosion is higher than for the gas explosions. However, the impulse the gas explosion with strength factor 7 results in the largest impulse.

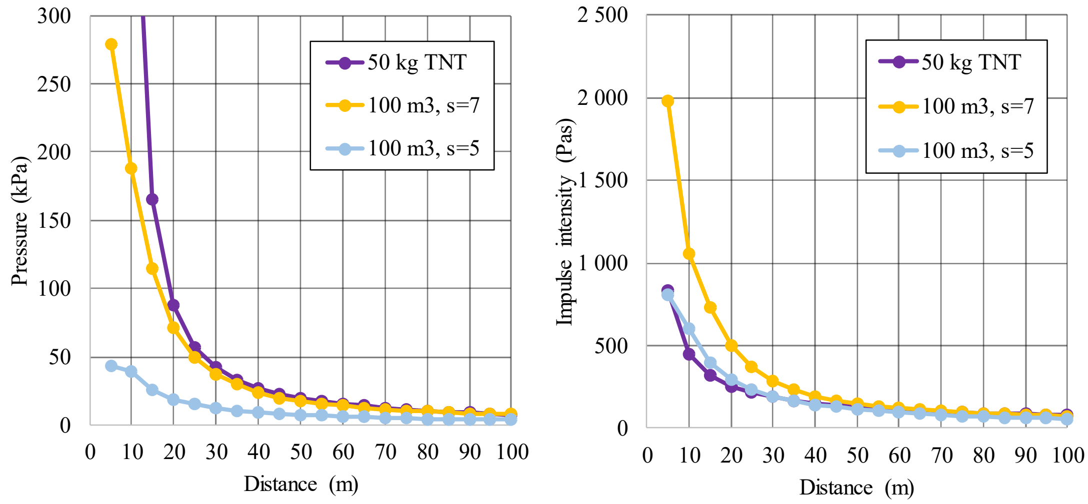


Figure 7.4 Pressure at different distances from gas explosions of different sizes (left) and impulse load at different distances from gas explosions of different sizes (right). This compared with pressure and impulse of a TNT explosion of 50 kg.

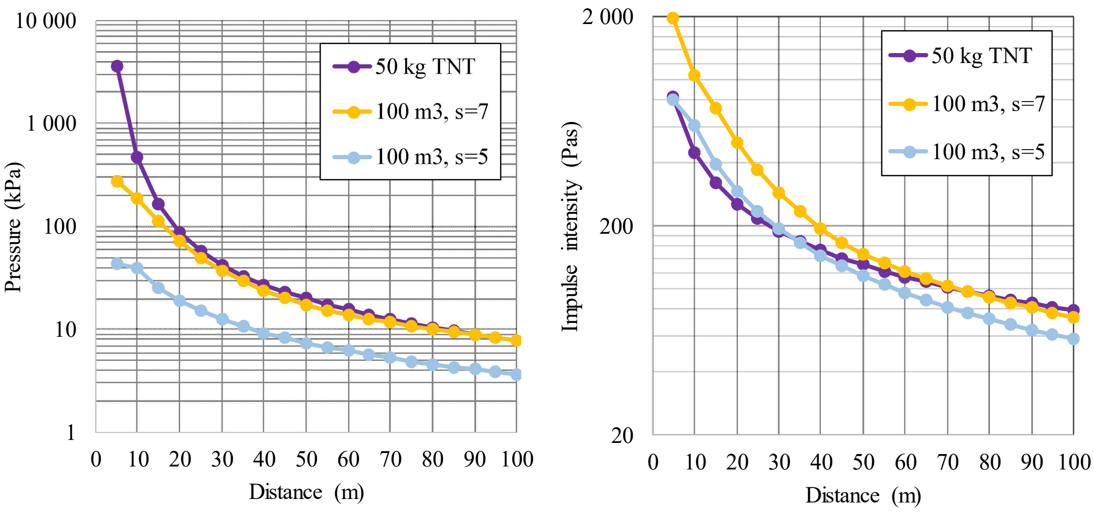


Figure 7.5 Pressure at different distances from gas explosions of different sizes, logarithmic scale (left) and impulse load at different distances from gas explosions of different sizes, logarithmic scale (right). This compared with pressure and impulse of a TNT explosion of 50 kg.

7.4 Structural response

7.4.1 TNT explosions

Comparison of concrete with different amount of reinforcement

The amount of reinforcement is something that can vary in a structure and therefore it is of interest to show what influence different reinforcement amounts will have on the resistance to an explosion load. In Figure 7.6 the reinforcement amount varies between 0.2 %, 0.4 % and 0.8 %. The reason why these values are chosen is because 0.2 % reinforcement is close to what should be used as minimum amount of reinforcement while constructions with more than 0.8 % reinforcement is uncommon. The figure shows at what distance a wall can be positioned if it should resist an explosion with different amount of TNT. In this figure the load varies from 50 kg TNT to 1000 kg TNT. What can be seen in this figure is that with more reinforcement the wall can stand closer to the explosion than it could with a lower amount of reinforcement. As an example of this Figure 7.6 shows that for 500 kg TNT a wall with 0.8 % reinforcement can stand at 21 meters distance while a wall with 0.2 % reinforcement needs 36 meters without being damaged.

The case shown in Figure 7.6 is what will be the base case in this chapter. Here the thickness of the wall is 200 mm, the density of the concrete is normal at 2500 kg/m^3 and the behaviour of the concrete is plastic. In all future comparisons there will be three different amounts of reinforcement, 0.2 %, 0.4 % and 0.8 %. The red line will always represent 0.2 % of reinforcement, the blue line 0.4 % reinforcement and the green line 0.8 % reinforcement. The solid lines will represent the base case and different variations of dashed or dotted lines represents that a change has been made.

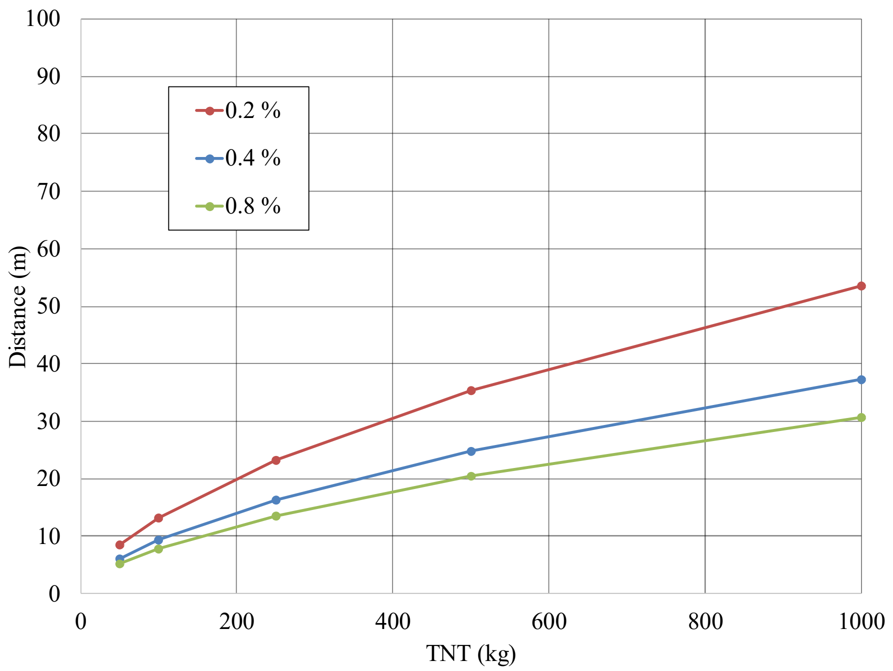


Figure 7.6 The base case. 200 mm concrete. 2500 kg/m^3. Plastic behavior. The percentage represent the amount of reinforcement.

Comparison of concrete with different thickness

As described in Section 4.2.1 the mass of the structure is one of the parameters that will it's the response. In this section the influence of thickness is presented. In figure Figure 7.7 the behaviour of a concrete wall with 150 mm thickness is compared to the wall with 200 mm thickness. Figure 7.8 compares the behaviour of a concrete wall with 300 mm thickness with a wall with 200 mm thickness. Comparing the different thicknesses with each other, one can see that a thicker wall will have better resistance to explosions than a thin wall. This is due to the larger mass that needs to be moved. See Chapter 4 for explanation of the structural response.

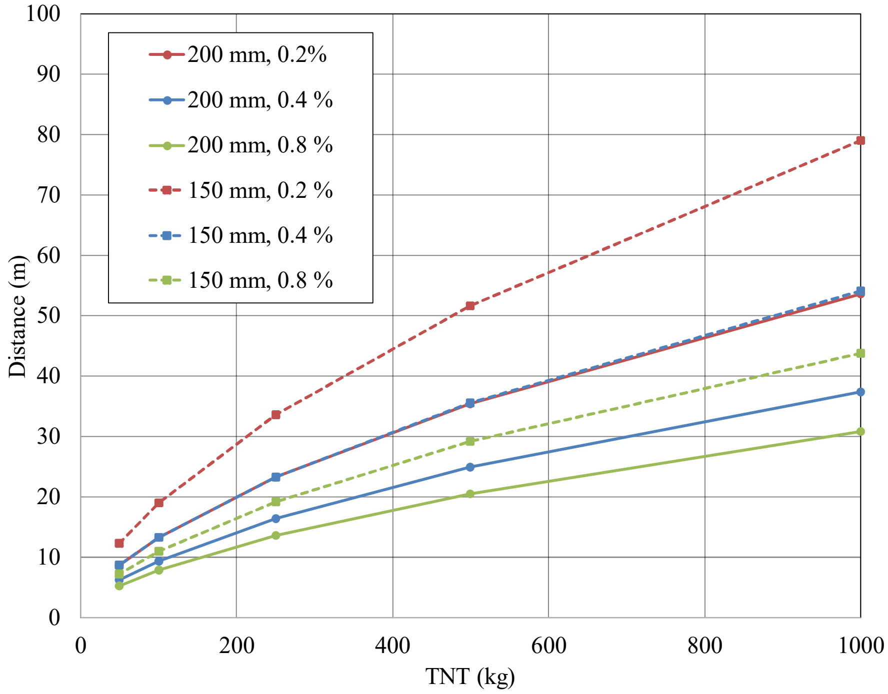


Figure 7.7 *Comparison with a wall with thickness of 150 mm (dotted lines). Both walls have concrete density of 2500 kg/m^3 and plastic behavior. The percentage represent the amount of reinforcement.*

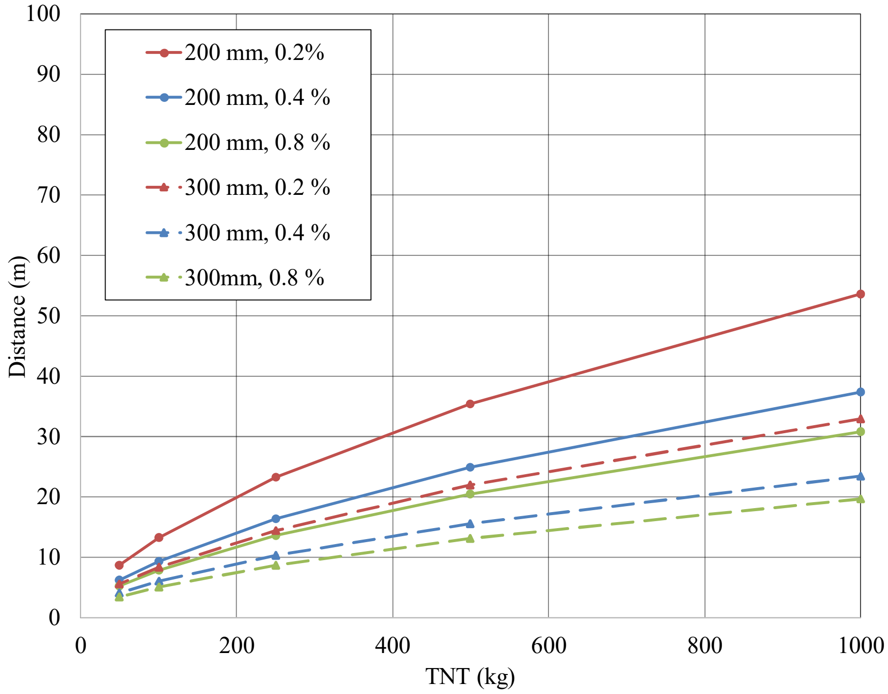


Figure 7.8 *Comparison with a wall with thickness of 300 mm (dashed lines). Both walls have concrete density of 2500 kg/m^3 and plastic behavior. The percentage represent the amount of reinforcement.*

Comparison of concrete with different densities

The density of the wall is another parameter which will have influence on the mass of the structure. Here the density of the concrete will vary while the thickness remains at 200 mm. This is done to visualize how a light-weight construction would have responded to an explosion. In Figure 7.9 a comparison of concrete with a density of 2500 kg/m^3 (solid lines) and concrete with density of 500 kg/m^3 (dotted lines) is made. What can be seen from the comparison is that a larger mass will resist an explosion better.

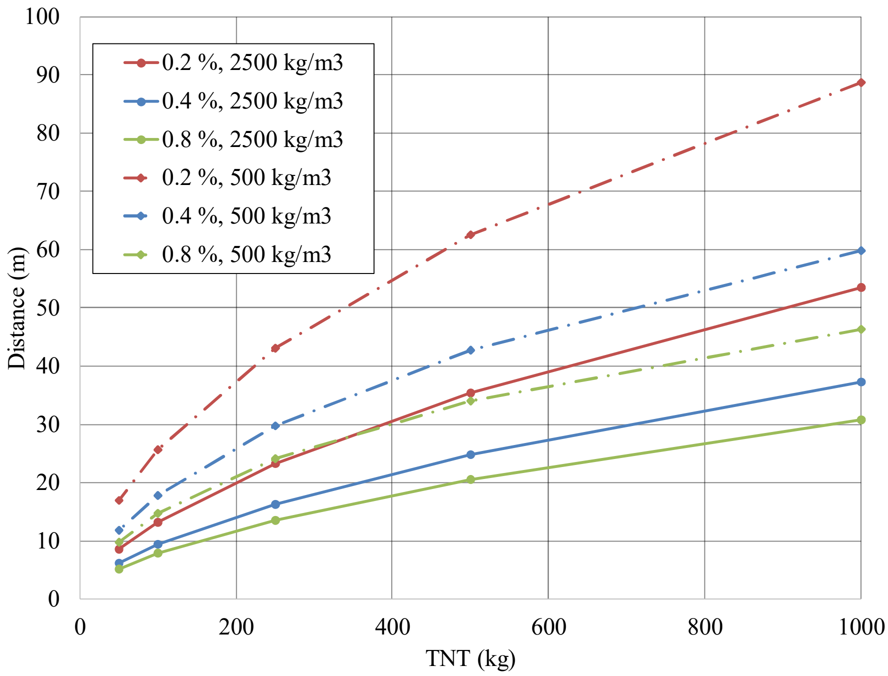


Figure 7.9 A comparison of concrete with different densities 2500kg/m^3 (solid lines) and 500 kg/m^3(dotted lines). 200 mm concrete. Plastic behavior. The percentage represent the amount of reinforcement.

Comparison of concrete with elastic and plastic behaviour

In this section the base case is compared to a concrete were plastic behaviour is not allowed. With this comparison the preferable effects of a plastic response are presented. An example of when plastic response is not allowed is when reinforcement of class A is used. When comparing the elastic and the plastic case in Figure 7.10 one can see that with a plastic behaviour the wall can stand closer to an explosion without being damaged.

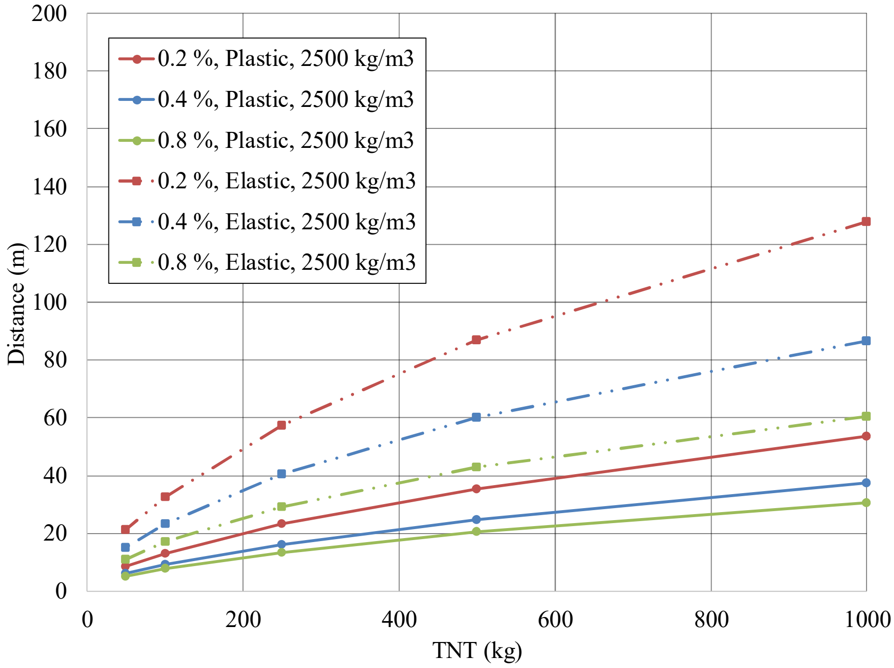


Figure 7.10 *A comparison of elastic behavior (dashed lines) and plastic behavior (solid lines). 200 mm concrete. 2500 kg/m^3. The percentage represent the amount of reinforcement.*

Comparison with decreased mass and with elastic behaviour

If both changing to a lower density of concrete and to an elastic behaviour one will get a construction a bit similar to a timber structure. The behaviour of such a construction is shown in Figure 7.11. This construction is compared to a concrete construction with a normal density of 2500 kg/m^3 and with plastic behaviour. What can be seen from the comparison is that with both an elastic behaviour and a low density the ability to resist an explosion becomes lower.

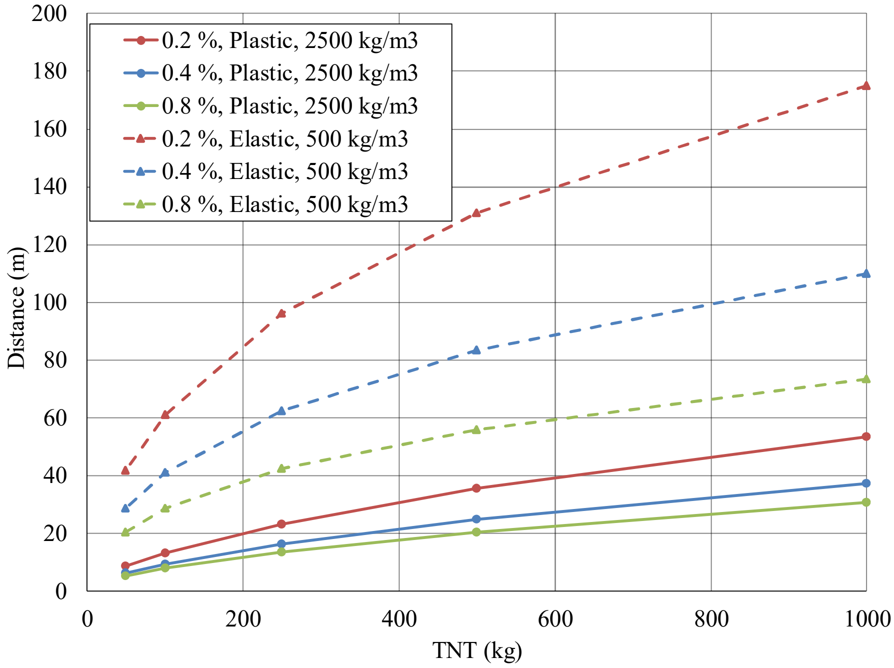


Figure 7.11 A comparison between plastic behavior with 2500 kg/m^3 and elastic behavior with 500 kg/m^3. 200 mm concrete. The percentage represent the amount of reinforcement.

7.4.2 Gas explosions

In this Section the walls resistance to gas explosions are analysed. Here it has been analysed the difference between plastic and elastic behaviour of concrete and the difference between normal and low density. See Figure 7.12. As one can see the wall resists the explosions much better with a plastic behaviour than with elastic behaviour. With an increased density the resistance is higher than it is for the lower density. The different colours represent different sizes of explosions. Two gas explosions with 100 m^3 gas cloud and with strength factor 7 and 5 are compared to a 50 kg TNT explosion.

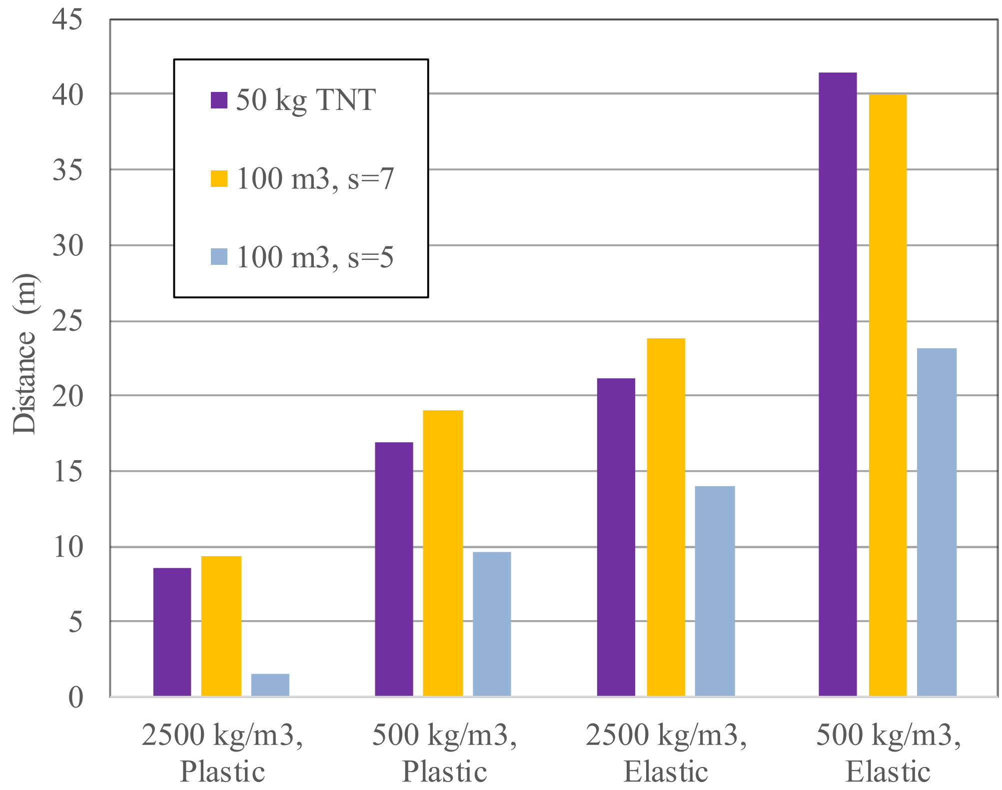


Figure 7.12 Comparison of plastic and elastic behavior and different densities for resistance to gas explosions of different sizes. 200 mm concrete with 0.2% reinforcement. Also, a comparison with a 50 kg TNT explosion.

7.5 Discussion

What can be concluded from these comparisons is that both reinforcement amount, density, thickness and type of response will have a large impact on how well a wall can resist an explosion. See Section B.3 for a compilation of the result from all cases. When planning for a building close to a road it could be good to have that in mind. In the analysis the wall was made of concrete without any openings for windows. If placing windows in the façade the capacity of the wall becomes smaller.

It can also be concluded that depending on what load that the building should be able to resist the building needs to be designed in different ways to resist the loads. As an example, one could compare a TNT explosion of 1000 kg and 500 kg. 30 meters is a distance which use to be recommended as the smallest distance between a building and a road. If a building at 30 meters distance should be able to resist 500 kg TNT 0.4 % reinforcement is possible but for 1000 kg TNT 0.8 % reinforcement is almost not enough. This is for when the thickness is 200 mm, the density 2500 kg/m^3 and the concrete has plastic behaviour, see Figure 7.6. This is also for a wall without openings or windows. However, if keeping 0.4 % reinforcement but changing to a thinner construction as in Figure 7.7 or a lighter construction as in Figure 7.9 or a construction with elastic response as in Figure 7.10 the construction will not be able to resist explosions with 500 kg TNT.

When it comes to gas explosions one can see that with a normal construction, like the one described as the base case, there will no problem to resist a gas explosion. It is only where both the density is decreased and we have elastic behaviour it is need of placing the wall at a larger distance than 30 m.

8 Interviews

8.1 Orientation

This chapter includes interviews with people in the building sector which has a connection to explosion loads in their work. Most people interviewed are people which has a connection to Norconsult in some way through for example common projects. The interviews reflect different perspectives and they highlight possible solutions for how the work with explosions can be improved.

The arrangement of the interviews was to discuss around the following topics:

- In what way do you handle explosions in your work?
- Do you believe there is a need for increased knowledge about explosions?
- How is the explosion risk treated?
- Do you believe that the handling of explosions is inadequate?
- What is needed to improve the handling of explosions?
- What do you think about the handling of explosions in risk analyses?
- Is there a need of improved statistics?
- Is there a need of better communication between companies and authorities?

These questions were the base for the interviews. Further questions that was more specified for the person interviewed had these questions in mind. These questions were also based on the literature study and questions that came up by reading documents connected to explosion risk, explosion load and structural response. The questions were also somewhat formed by the previous made interviews. If a problem was brought up in one analyse which could be of interest in another interview this was included.

The interviewees are from several different authorities and companies and are briefly presented in Table 8.1.

Table 8.1 The interviewees.

Name	Company	Title	Date for interview
Herman Heijmans	Norconsult	Risk analyst	2019-04-09
Erik Egardt	MSB	Fire engineer	2019-04-24
Henric Modig	Trafikverket	Fire engineer	2019-04-25
Ulf Lundström	Trafikverket	Tunnel security coordinator	2019-04-25 2019-04-29
Maria Nilsson	Trafikverket	Tunnel safety expert	2019-04-29
Rebecka Thorwaldsdotter	Länsstyrelsen	Risk engineer	2019-05-07
Patrik Jansson	Länsstyrelsen	Risk engineer	2019-05-07
Mathias Lööf	Projektstaben	Risk engineer	2019-05-07
Marie Sjölander	Spetsprojektledning	Project management	2019-05-16

8.2 Herman Heijmans

About the interviewee
Herman Heijmans works at Norconsult as a risk analyst. A risk analyst plays an important role in how explosions will be handled in the building process. The risk analyst will decide if explosion is a risk worth taking into consideration, decide about how large explosion that is probable and suggest risk reducing actions to prevent the explosion risk. Heijmans will give the risk analyst perspective on how explosions are handled in the risk analyses.

How risk analysts handle explosions
As a risk analyst Heijmans calculates and evaluates the probability as well as the consequence for explosions as well as other risk sources. This Heijmans does based on modified Dutch methods for risk calculations, see Section 2.4.3. The result from the calculations is predictions for how many that will die in case of an accident with explosions and a prediction of how probable it is that explosions will occur. The risk is mostly presented in probability for number of deaths. Heijmans explains that they never treat people that get injured since this measurement is not very specific. However, Heijmans says that the number of injured will be reflected by the number of deaths according to what he describes as the pyramid of injury.

Need for increased knowledge about explosions
Heijmans believes that there is a need of increased knowledge about explosions. He describes that the Dutch method that he partly uses may be a bit too conservative. He describes the method as very general and that the consequences in many cases can be excessive.

Heijmans believes that there is a need for knowing more of exactly what will happen in case of an explosion. To get a detailed model one need to look at many special situations. In some cases, this can be needed. As it is today, general models are used too to get an overall picture of the risk.

Treatment of explosion risks
Heijmans explains that there is no generally accepted way in Sweden of handling explosions. Therefore, there are often differences between different consultants. The evaluation of the risk and the calculation of how many that will die may be done in several different ways and then the result also becomes different. He highlights that it might be small variations in assumptions that has large effects on the final result.

Heijmans brings up an example of a situation where one consultant got the result that a jet flame probable would be 30 meters long while Heijmans predicted a 60 meters long flame. The reason for the difference was an assumption of at what level in the tank the hole occurred. An assumption that it happened over the liquid level gave 30 meters while an assumption of that both gas and liquid was included in the emission gave 60 meters as result. What is most reasonable to assume is difficult to say according to Heijmans. What can be concluded from this is that risk analyses are done differently and that the result hence also can differ considerably.

Heijmans, though, has however never received any critique from customers that risk analyses have been done differently. Often the task to make a risk analysis is only handed out to one consultant. Comparisons can be done with projects in the surrounding area, but since not all assumptions are presented in the risk analysis a complete comparison cannot usually be made.

How to improve the handling of explosions

Heijmans says that in order to increase the safety regarding explosions one also need to look at existing buildings which have been built without todays requirements of safety. When it comes to new buildings clearer requirements are needed.

As an example of what type of requirements that are needed, Heijmans brings up guidelines for risk reducing actions. If there is a need of decreasing the risk because the risk level is above what can be tolerable, he explains that it is a difficult for the risk analyst to decide about the risk reducing actions since the knowledge of the effect is unclear or insufficient.

Heijmans thinks there is a need of national methods for risk analyses similar to those in the Netherlands. However, the Dutch method is not perfect either. This is because risks of categories 1 and 5.1 are not included since these substances are not transported in large amounts in the Netherlands (see Table 5.1 for description of the categories). Anyway, if a national method was available this would result in that more time could be spent on treating details that would increase the quality of the risk analysis.

In addition, the statistics used in the analyses could be updated to get better risk analyses. Furthermore, the relevant statistics, e.g. traffic with dangerous goods and probabilities for different events to happen in an accident, needs to be easier available for the risk analysts. Heijmans explains that some of the statistics he uses are used only due to contacts at the authorities which could provide him with the information. He wishes that all statistics that have been produced also should be possible to be used by all risk analysts. He also makes a guess for why this is not the case today. Since the statistics are not very reliable MSB, which has access to the full statistics, will only hand out approximate data and not the exact measured values. If exact values are handed out, they may be seen as the true values, which they are not.

Heijmans also gives a suggestion for how the statistics risk analysts use in the risk analyses could be improved. Using existing techniques, e.g. cameras on the roads used to register transports with signs which indicated dangerous goods transports as well as the category of the goods, the statistics could be improved. They would also be more easily updated. It is also possible to connect the sign with the registration number to be able to follow the rout for the transport. This technique has been tried out in Gothenburg and then worked rather well (Strand, 2015). Heijmans also mentiones an investigation made by TRAFA where it was analysed if better statistics could be produced out of the data that was gathered during 2006 by SRV. The conclusion was that it was not possible if not any new statistics were gathered. This investigation is further presented in Section A.2.

When it comes to railway traffic Heijmans has some suggestions for improvement as well. Today, the statistics for railway traffic are available, however it is not reachable by everyone. The information for what is transported on railways are much more detailed than on roads. The amount in kg for each category of dangerous goods as well as the number of train carts is information that is collected. Heijmans was not sure about what rules that regulated how this information could be shared. If there were risks with letting the information be available for anyone a system where risk analysts had a password to reach it would perhaps be a possible solution.

As suggestions for improvement, Heijmans again brings up that there is need for a national method of how to perform a risk analysis. There is still uncertainty about how mass explosions should be treated and due to that, many assumptions are made. What is even more unclear is explosions from oxidizing substances, category 5.1. Here the knowledge needs are large.

One more suggestion is that the risk reducing actions should have more information available. There are documents available for information about what risk reducing action is suitable for different events. However, there are no values given for what effect the risk reducing action may have. Heijmans believes that a standard which help the risk analyst to determine such values, would be very helpful. Such a document should also include information about the probability for that the risk reducing actions will work as intended. If these types of documents were available, the risk analysts would have to make fewer assumptions in areas where they do not have enough knowledge and make fewer decisions which they are uncomfortable with. Another alternative is, according to Heijmans, to set descriptions of what function the risk reducing actions should have. If this is done, more events can be considered and the effect of the risk reducing actions will be analyzed also in a later stage of the project.

Explosions and risk analyses
Heijmans gives two examples of guidelines that he uses, guidelines from Räddningstjänsten Storgöteborg and Storstädernas riskpolicy, see Räddningstjänsten Storgöteborg, 2004 and Länsstyrelserna, 2006. Heijmans also describes that some county administration boards give their own guidelines. These guidelines often provide information about what safety distances is needed and when risks from a road or an industry needs to be considered. Heijmans brought up that it is odd that the guidelines should be different for different locations in Sweden. But Heijmans still believes that there might be some advantages with these divisions since one then also can consider local differences.

Concerning risk criteria Heijmans thinks that the risk criteria that he uses, which are the ones from DNV, are easy to use. See Räddningsverket, 1997 for the criteria. The criteria are given for 1 km road and for both sides of the road. The criteria can easily be regulated to fit the size of the analyzed area and the risk level can also be calculated for the size of the analyzed area. This makes a comparison of the risk level and the risk criteria easy.

Whether the criteria are at a reasonable level Heijmans did not have an opinion about. He explains that no authorities actually have accepted these criteria officially. On the other hand, the county administration board are the ones accepting the risk analyses and they use to accept risk analyses when the risk level is below the tolerable level according to DNV.

What could be seen in the reviewed risk analyses in Chapter 5 and 6 was that both criteria from Gothenburg and national criteria from DNV had been used. However, according to Heijmans this is not done anymore. Today only DNV's criteria are being used.

When it comes to decide about what explosion load should be considered according to Heijmans the maximum allowed load to transport is often chosen. This in order to be conservative and on the safe side when no statistics are available. Even though this assumption may be far from the truth about what is actually transported this could be okay if the risk level in the end is below what can be tolerable. If the risk level is found to be too high, though there is reason to reconsider the assumptions.

For the task of the risk analysis there is no need of exact values of the explosion load. The main purpose of the risk analysis is to find out if the risk is acceptable, if one must make actions to decrease the risk or if risk reducing actions are recommended. To make this type of assessment, values of the load calculated with several decimals is not needed. However, when the risk analysis should be the base for when the structural engineer shall design the resistance of the building such vague assumptions are not enough. However the risk analyst, like Heijmans, cannot make the decision for what load the building should be able to resist because the risk analyst does not have sufficient knowledge about the structural response of the building or about the explosion load. According to Heijmans there is need for better communication, a working team or a person which can connect the work from the risk analyst with the engineer's design calculations.

Furthermore, assumptions of where on the road the explosion load should be placed are made. This may differ between different companies but Heijmans assumes that the load is placed at the edge of the road closest to the analyzed building. For the risk analysis this assumption may not have a very large impact, depending on the specific project. Uncertainties on other parts could have larger effects than the position of the load. However, for the structural engineer the position of the load will make a large difference for the design of the building. A discussion about what is a reasonable assumption for the load position may be needed.

Sometimes it would be good to make more detailed investigations of how many people that are inside a building. As an example of this Heijmans talks about that it seldom is 100% of the people working somewhere that are at the office. An estimation of 70% may be more correct and this would decrease the society risk level a lot. Connected to this it is important that the correct information is given from the one that wants to build, and that this stakeholder is aware of the consequences these numbers have on the risk analysis result.

In many cases the owner wants to have the ability to change the plans for the building at a later stage. In this case the risk analyst will assume the worst possible case for the number of people that will be in the building which usually leads to an increased risk level. More detailed plans for what should be built would contribute to more detailed risk analyses as well.

An alternative way of looking at the society risk level is to divide the analysed area into several regions where the number of persons may be different. This however is normally not done. Instead it is common that the assumed number of persons is just smeared out over the analysed area. In most cases Heijmans believe that this assumption is good enough but if the risk level is too high it could be a good idea to make this part more detailed. Heijmans also explains that this change will be done in Norconsult's new calculation method that is currently being developed.

To get better risk analyses there is also need for increased knowledge in some areas. When it comes to accidents with trains there is uncertainty about how derailment should be treated and how the society risk should be evaluated. The explosion risk is another area where there is need for increased knowledge.

There is need for a better method for how a risk analysis should be performed. To take help from the methods used in for example the Netherlands could be a good idea. With standardized methods more time could be spent on other parts which would increase the quality of the risk analysis. It is also valuable to get a method for interactions between different risks, for example a combination of risks from roads and railways. A handbook for this would according to Heijmans be very helpful.

Lastly, there is also need for documents which would help the risk analyst with what effect the risk reducing actions will have. As it is today the effect of the risk reducing actions are mostly guesses and predictions which could vary a lot depending on who makes the risk analysis and what experience that person has. A national document which could be followed for the risk reducing actions and which also comes with numbers of the effect, would according to Heijmans therefore be very helpful.

Need for improved statistics
The statistics for transports on roads need to get improved. The investigation that was made during 2006 by SRV has some limitations and it should not be used as the only source pf statistics. Together with statistics from SIKA, about the overall transports in Sweden, and the estimation of 4.6% transports of dangerous goods, an approximation of the number of transports can be made. In addition, there are no information available for how well loaded the transports are. Assumptions are needed to be made and an assumption of fully loaded cars may be a huge overestimation. It is possible that an assumption like this has only small effects on the risk analysis result but when it comes to the design of the building these general assumptions may have a huge impact. There might be need for a national standard regarding what load should be used for the design of buildings with regard to such events.

Collaboration and communication
Heijmans thinks that a better connection with other parts of the building sector would be good. According to him there are only a few companies which works with risk analyses only. However, even those does not produce perfect risk analyses. Support from fire engineers would be helpful in the step to connect the risk analysis with structural engineers' design work.

There are also other groups which could be preferable to have better connections with. Heijmans mentions e.g. architects, contractors, the investor and anyone that has knowledge about the costs for the risk reducing actions. If the risk is between the two lines of what is considered tolerable and acceptable, risk reducing actions should be evaluated with regard to the cost of it. However, this is something that the risk analysts usually do not have sufficient knowledge to do. This evaluation is often up to the investor to carry out which in many cases have not enough knowledge about the risks. Here the municipality plays an important role. The municipality regulates the zoning of the municipality and what could be built or not. They are the step in between the risk analyst and the investor, and they are making the important decisions.

The risk analyses are always reviewed by the county administration board. Heijmans believes that the knowledge to do this review is enough but there may be lack of time that results in that this review is not made very detailed. The municipality does also have something to say about the risk analyses. Often the emergency services are there to help them with these decisions. According to Heijmans, it is common that the emergency services suggests even more risk reducing actions than what the risk analyst suggested. The competences from the emergency services may also vary a lot depending on what background the persons working there have.

8.3 Erik Egardt

About the interviewee

Erik Egardt works at MSB, Swedish Civil Contingencies Agency. He works as a fire engineer and has experience of working with flammable and explosive substances. Egardt is therefore an experienced fire engineer regarding explosions. The reason why Egardt is being interviewed is because of his employment at MSB, his experience of working with explosion loads and risks. He has also worked a lot in collaboration with emergency services and will therefore contribute with interesting and important inputs in the discussion about what can and what needs to be improved in order to treat explosion loads in a better way.

Limitations

This thesis focusses on explosions and their effect on buildings. During the interview Egardt discusses a lot about what should be improved in order to make the work for the rescue services safer regarding explosion risks. In this thesis these parts have to a large extent not been included.

How MSB handle explosions

Egardt describes that MSB as authority works with explosions in many ways. He explains that MSB:

- are the authority which has the responsibility for rules concerning transports of dangerous goods
- have responsibility for the rules concerning flammable and explosives substances
- work in collaboration with rescue services
- build and takes care of civil defence shelters and conducts research connected to these
- performs test on explosives which they also manufacture.

Need for increased knowledge about explosions

Egardt believes that there is need for increased knowledge about explosions of several reasons. There are a lot of sequences of events possible for explosions and the source of the explosion can also vary. There is a need of being able to estimate the risk and asses what will happen. There are types of explosions which there is need for more knowledge about. As it is today Egardt explains that the knowledge about the shock wave that will occur due to an explosion is good but when it comes to debris from an explosion there is need for more knowledge. He also describes that debris are a more probable reason for injuring that the shock wave will be. Therefore, there is need for increased knowledge in this area.

Treatment of explosion risks
Egardt brings up two examples of where the handling of the explosion risk has been inadequate. There have been cases both in Gothenburg and Stockholm of where gas buses have exploded. For more information see Jusufi, (2019) and Möller Berg, (2019). There are also cases where garbage trucks have exploded. For more information see Myndigheten för samhällsskydd och beredskap, 2017. According to Egardt, the safety in these vehicles has not been good enough. Even though all the vehicles did follow the laws Egardt explains that they could have been designed a lot better. Egardt also mentions that it is a large problem that the companies producing gas vehicles don't want to accept the fact that there is a risk of explosion. By making their vehicles safer they accept that their vehicles are unsafe concerning explosions and that is something that they don't want to agree with.

How to improve the handling of explosions
To increase the safety regarding explosions Egardt specially points at the need for increased safety in tunnels. Egardt explains that today the tunnels are not designed to resist an explosion. In many cases tunnels are built with two parallel tubes for traffic in different directions. The wall and the doors in between the tubes are not able to resist a shock wave. If an explosion occurs inside one tunnel tube the second tube will not be safe to use as an emergency escape as it will be filled with gases from the fire leaking in from the first tunnel. Egardt means that the tunnel safety needs to be improved so that it is safe with regard to explosions.

As mentioned above, the design of gas vehicles, such as buses and garbage trucks, are not good enough according to Egardt. Therefore, he wants to improve their design. Accidents with gas vehicles has happened and therefore Egardt thinks that the municipalities should set higher requirements on the safety of the vehicles they order. This would be a much cheaper alternative than designing buildings close to the roads where gas buses drives. There is also a need for to improve the methods used to take into account that such gas explosion can occur. To forbid gas buses from traveling through tunnels where the safety regarding explosions is low and the rescue actions are limited is according to Egardt a good idea.

Egardt want to learn more about some types of explosion events where there is lack of knowledge today. As an example, he wants to look at gas vehicles that is used today and make tests on them to get information about how such explosions will develop. The distribution of debris from such explosions is something that he wants to analyse during such tests. Egardt tells us that this type of information would be valuable to emergency services because they will know from what direction they can approach the vehicle in the safest way without being hit by a jet flame or debris from an explosion. To make similar tests on other vehicles than gas vehicles would also be valuable according to Egardt.

Explosions and risk analyses
Generally, Egardt believes that there are good methods available for making risk and consequence analyses. As an example of a good method he brings up the method used in the Netherlands, see Section 2.4.3. However, he also mentions that by using these methods there are risk for expensive solutions. There are both pros and cons by using the same methods as they do in the Netherlands. Positive is that the analysis becomes objective and quantitative. However, according to Egardt the need for such evaluation methods are larger in the Netherlands. In Sweden he believes that it would be better to use the area that we have and place dangerous objects at a larger distance from what we want to protect.

Furthermore, Egardt discusses the fact that risk analyses only evaluate how many that will die in case of an accident. According to Egardt there is also a need to include other things as well. What would be the consequence for the society if there is an explosion in a tunnel on an important transport route for thousands of people and the tunnel becomes out of use during several months? Egardt thinks that questions like this is important to evaluate as well.

Egardt discusses the way that risk reducing actions are evaluated. He describes that an action reducing the risk for something, for example a protective wall in between a road and a building, might result in a decreased risk for the building but an increased risk somewhere else, due to reflections of the explosion or decreased possibilities for evacuation from a road. Therefore, these types of evaluations need to be improved according to Egardt. It is a problem that there might be lack of people capable of making these types of evaluations. Egardt suggests that a handbook could be produced to help risk analysts with evaluation of explosion risks. A handbook could also give suggestions for risk reducing actions and what effect they will have. This handbook could help overarch the lack of knowledge in between the risk analyst and the structural engineer designing the building.

Additionally, Egardt explains that it is a problem that risk analysts only considers the shock wave from an explosion and not the debris which he claims to be more dangerous. In order for the risk analysts to do this the knowledge about debris needs to be increased.

Need for improved statistics
Egardt believes that improved statistics of transports would be good in order to increase the quality of risk analyses. He also explains that this is a question that has been discussed a lot at MSB. According to Egardt the problem is not how the information should be collected in the easiest way. The actual problem is the fact that companies do not want to share this type of information due to safety reasons. There is also a discussion about the risks with having this type of information collected. If someone with antagonistic motives gets the information, it may be dangerous. If this threat was not a problem Egardt gives as example that speed limit cameras could be used to collect information about the dangerous goods transports. When collecting the statistics that is used today in risk analyses, the statistics from Räddningsverket 2006 described in Appendix A, the threat connected to collection of statistics was not regarded as problem.

Collaboration and communication
Egardt believes that MSB has a pretty good collaboration with many authorities. The national defence, the police and the National Board of health and Welfare are some authorities that MSB has good collaboration with at the place of an accident. As MSB wants to do research and tests instead of making guesses of what could happen at an explosion it is important for them to have a good collaboration with the ones that will later use this information.

8.4 Henric Modig

About the interviewee
Henric Modig works at Trafikverket as a fire and risk engineer. Modig is much involved in large tunnel projects where he focus on installations and the tunnel safety. Because of the knowledge about how safety questions are handled in tunnel projects Modig is an interesting person to discuss explosion risks with.

How fire and risk engineers handle explosions
A question that Modig, as a fire and risk engineer, has worked with is how to evaluate the explosion load when buildings are placed on top of a tunnel. The easiest solution would be to always have a certain distance between a tunnel and nearby buildings. However, this is not always possible in urban environments. It is especially difficult at the places where the tunnel reaches ground level at its entrance and exit. Another problematic situation, according to Modig, is when tunnels with different traffic types cross each other. How to evaluate the risk in this type of situations is difficult.

Needs for increased knowledge about explosions
According to Modig the knowledge about explosions needs to be increased in all areas. It is too few people with sufficient knowledge about explosions in Sweden.

Extinguishing system for fires in tunnels is an example of another area where Modig wants to increase the knowledge. Modig argues that there is need for a better understanding of the probabilities of what will happen in case of an accident. In how many cases will a fire lead to an explosion of the truck? What forces is needed to cause an explosion after a crash? Is it possible to eliminate the explosion risk because of fire by using extinguishing systems inside the tunnel?

One more question that was discussed during the interview was how tunnels are designed to resist explosions. What explosion should the wall between two tubes be able to resist? And what about the doors between the two tubes. If there is a large explosion which the inside walls cannot resist, how much people will survive the explosion so that they are in need of using the other tube for evacuation? These types of reflections are something that Modig wants to have more discussions about.

Treatment of explosion risks
Modig argues that the way explosions are handled needs to be done more consequent. He does not believe that the risk of explosions is underestimated or that the risk is not considered enough. However, he believes that it is possible that the way that explosions are evaluated leads to unnecessarily expensive solutions that maybe is not needed. Modig also explains that the focus on explosions has increased in road and

tunnel projects. It has been a change from mostly considering gas emissions and fires to including explosion risks to a larger extent.

How to improve the handling of explosions
Modig wants to have standards for how explosions should be handled. He also analyses the difficulties with such standards. Standards could lead to recommended distances and for the cases where there is a need of placing a building closer than that there will still be a need of making advanced risk analyses. With better standards, though, the knowledge needed by the risk analyst could be decreased.

In some cases, Modig believes that to use a standard explosion load for the design of e.g. tunnels would be useful. This could then be used in cases where there are people in the surrounding outside the tunnel that could be affected by an explosion. However, Modig believes that it would be difficult to make authorities agree on such things like a standard explosion load, and from a security perspective it might not be wise to do so.

Modig believes that instead of putting more resources on increased reinforcement and concrete one should try to increase the knowledge about what will happen during different accident events. Modig think that this information can be found by advanced modelling. This could be done in collaboration with for example RISE and MSB. To do full scale tests for these types of things would not be possible according to Modig. Full scale tests for fires could be done but it is difficult. To do it with explosions is not possible, though. But Modig believes that a lot of information can be found from doing numerical modelling.

Explosions and risk analyses
The way that large explosion loads are handled in risk analyses is according to Modig a bit strange. According to Modig risk analyst sometimes forget the probability reasoning in tunnel projects and therefore try to design the tunnel for loads that is impossible to have as design criterium. In his experience people in the building sector are talking about explosions of several ton TNT as it was common to happen, but it is not. Even if the probability is calculated to be very low, the focus is on what could be the consequence if there was an explosion of that size.

Modig explains that Trafikverket are having a mindset where they try to avoid catastrophes and where they look on what can be done in order to decrease the risks. They are working towards the principles called plausibility principles, proportions principles, distribution principles and principles for avoidance of catastrophes.

Modig comments that risk analyses for tunnels are made also for tunnels through rock with buildings above. To calculate what risk that an explosion inside the tunnel will result in outside the tunnel is according to Modig a complicated task. It would simplify their work if there was a limit for when there is enough distance to not consider the risk on the surface. However, Modig believes that to find this distance would be complicated or maybe even impossible due to the fact that the quality of the rock may vary significantly.

In addition, Modig comments on the suggested risk reducing actions. In his opinion there might be a lot of guesses of what effect the risk reducing actions will have.

Furthermore, the suggested actions in the risk analysis has a bit of a difficulty to be transferred through the whole project. If for example a protective screen has been suggested in an early stage, it might be difficult to know what the screen should be able to resist when it is finally designed. According to Modig it is easier to have a good communication to overcome these projects when working in larger projects. In smaller projects however, it might be more difficult due to the lack of resources.

Modig expects from the risk analysts that they have enough knowledge about what the risk reducing actions they suggest in risk analyses have as effect. However, he understands that it might be problematic to give good solutions for risk reducing actions in an early stage when many things in the project have not yet been decided.

Need for improved statistics
Modig explains that there is a need of knowing how many transports of different sizes that actually passes the tunnel in order to know what the tunnel should be designed to resist. Other statistics that Modig believes would be very useful is statistics of what is needed to cause an explosion from for example a fire or a crash. To improve these statistics would result in much better risk analyses according to Modig. In addition, statistics for what effects e.g. sprinkler systems will have on reducing the risk of explosion due to fire would be interesting to produce according to Modig.

Collaboration and communication
Modig wants to have more discussions with other authorities and professions about the need of an increased knowledge level, concerning explosions. He has also reflected about that many authorities and companies do not have the resources to spend enough time on questions regarding explosion. One reason may be the lack of people with enough knowledge in the explosion area.

Modig believes that there is a large need of spreading the knowledge about explosion to more people. It is also a large problem that even if there are people who have the knowledge about explosions the one who is in need of such a person does not know who has the knowledge.

Modig also mentions an ongoing collaboration where Transportstyrelsen and Trafikverket works on risk acceptance criteria, like the one DNV presents, but for the safety of people inside a tunnel. This is to make it easier for them to evaluate if they have a safety inside the tunnel which can be considered as good enough. However, today the safety for people outside the tunnel, which can be affected in case of an accident inside a tunnel, is not included.

8.5 Ulf Lundström

About the interviewee
Ulf Lundström works at Trafikverket with tunnel safety on a national level. He is often called in to help when someone has plans of building an over-decking over a road or a railway. Lundström also has earlier experiences of working at Länsstyrelsen. Therefore, he can look at explosion risks from two perspectives. Lundström was interviewed due to his interest in how explosions are handled when densifying the environment and due to his experience in tunnel safety where explosions are discussed a lot.

Need for increased knowledge about explosions

According to Lundström there is a need of increasing the knowledge about explosions. He explains that a lot of guesses are made for example in risk analyses. Lundström perceives it as if something is written in a risk analysis more than five times it is true. However, this truth could be a bad guess which may be far from true. When it comes to consequences in case of an accident Lundström says that many assumptions and guesses are made.

Lundström believes that due to the lack of knowledge it is a large risk that structures are designed to resist unnecessary large loads. Lundström believes that too many things that almost never happens or never has happen are taken into consideration even though this might not be needed. This may lead to that projects becomes unnecessarily expensive or that they cannot be built. Lundström is afraid that lack of knowledge inhibits the urban development. However, Lundström admits that it is a difficult task to decide what is a reasonable level to design for.

Treatment of explosion risks

Lundström explains that explosion risks are taken into consideration when tunnels are built in Sweden today. The focus on explosion risks is especially high when something is going to be built on top of the tunnel and when it is less than 20 m of rock between the tunnel and the surface. Often large explosions are taken into consideration in tunnels. Sometimes the load may even be larger than the load that is considered outside the tunnel. According to Lundström this reasoning is a bit strange. He argues that a tunnel or an over decking may result in an increased safety for the buildings in the surrounding area. If an explosion occurs inside the tunnel it might result in less damage than if it happened on ground level. In some tunnels the risk of explosions has been considered to be too high and then transports with large loads of explosives have been forbidden to use the tunnel. According to Lundström there is a need of analysing the alternative roads that the transports will use instead; i.e. it may be possible that it is safer to use the tunnel instead of the roads on the ground.

Lundström explains that for small explosion loads there are guidelines of how it should be handled in a tunnel. However, when it comes to explosions from ADR transports, see classes in Table 5.5, which is much larger, no guidelines are given. One large problem that Lundström discusses is the difficulty of knowing when an explosion inside the tunnel will affect the people outside of it.

Lundström explains that there has been an increased focus on tunnel safety since year 2000. The emergency services, the county administration board and some risk consultants were according to Lundström the ones leading the discussion towards a situation where large explosion loads where considered. The project Hagastaden in Stockholm has according to Lundström become the guide in Sweden of how explosions should be handled in tunnel projects. However, according to Lundström, too large explosion loads have been considered in this project. Before Hagastaden, the focus was on the risks which were most probable to happen. Today even risks which have so low probability that they have never happened is considered. Lundström believes that it is strange that these large explosions are considered in Sweden when it is not considered in any other countries. Lundström believes that there is need for a nationally accepted method which all authorities and companies can agree on.

When too large explosions are taken into consideration the tunnel becomes much more expensive, partly due to the needed risk reducing actions needed. It is possible that other actions, like adding sprinkler systems in the buildings above, would result in a reduced total risk level. According to Lundström it is possible that the economic resources are not optimally used to reduce the risks.

How to improve the handling of explosions

Lundström believe that common and approved knowledge is needed to decrease the number of guesses. Additionally, it is brought up how risk reducing actions inside tunnels will affect the risk. Lundström believes that the knowledge about what effect the risk reducing actions will have are enough. However, decision-takers need to listen to the information available and use it. According to Lundström the decision-takers may sometimes have too low knowledge in the risk area to make reasonable decisions.

Additional things that Lundström believes would be good is to have more knowledge about how a building on top of an over decking could be designed in order to better withstand an explosion within the over-decking. Furthermore, Lundström mentions that it would be interesting to analyse what effect sprinkle systems could have on a burning truck loaded with explosives. Is it possible to reduce the risk of explosions completely, due to fire, by using sprinkler systems? Furthermore, he wants to analyse what forces that is needed to cause an explosion in a truck. Lundström also mentions that it is of interest to have better knowledge of how rescue services handle a truck with explosion risk. This would be useful to know when designing the tunnel.

Explosions and risk analyses

According to Lundström, the risk analysis can have a large effect on a project; it can even be the risk analysis that decides whether the project can be realized or not. It could also result in expensive actions that is needed to reduce the risk level.

According to Lundström there is need for a discussion of what it is worth for the society to decrease the risks for the people near the tunnel. Could the money be used in a better way where they would have been more effective to reduce the total risks in the society? Lundström gives an example of instead of designing tunnels to resist large explosions it is possible that increased traffic safety could have decreased the number of deaths in the city even more.

Another reflection Lundström presents is that tunnels are designed to resist explosions that are less probable than it is for an airplane to crash into a building. Buildings are not designed to withstand a crashing airplane, but there are tunnels that are designed to withstand large explosions. This is why Lundström believes that money is used on wrong risk reducing actions. Lundström argues that more focus needs to be on the probability. As it is today there is too much focus on the consequences and avoidance of catastrophes that are very unlikely to happen.

Lundström also questions if the risk analysts have enough knowledge about what effects the suggested risk reducing actions will have. One thing that Lundström has discovered is that additional railway tracks inside the primary tracks are suggested for many high-speed railways, even though this will not have any effect on decreasing the risk of derailment for speeds over 100 km/h. According to Lundström risk analysts often suggests the same risk reducing actions without being fully aware of the effects they will have.

Need for improved statistics
Lundström argues that it is unsafe to improve the statistics of explosive goods transports. The statistics is something that varies over time. To use the statistics as true values may be dangerous since there might be much more dangerous goods than what the statistics tells. To collect statistics of explosives is according to Lundström a large risk due to threat from antagonists. However, Lundström explains that it would be interesting to have statistics of transports of explosives if the amount of transports were zero. If it was, then this risk could be excluded in the risk analysis.

Tests have been made for how cameras could be used to get statistics of dangerous goods in tunnels, an example is given in Strand (2015). According to Lundström the cameras did not detect all transports that it should be able to and because of that the statistics from the cameras was not useful.

Lundström believes that it could be a good idea to improve the statistics for all categories except from explosives. It is statistics of explosives that would be the largest risk to collect, due to antagonistic threats. To have statistics of the other categories would be useful for risk analysts.

Collaboration and communication
Lundström wants to have a better collaboration with the companies producing, transporting and handling explosives. According to Lundström they are seldom included in the discussions of explosion risks on roads and in tunnels.

To have a better communication with risk analysts could also be a good idea. According to Lundström it can be long time periods between when the risk analysis is made and when the tunnel is designed. Decisions taken in an early stage can be difficult to withhold during the entire project.

According to Lundström structural engineers are seldom included in the project in an early stage. Therefore, it is a large gap between the risk analyst and the structural engineers. If the structural engineers could be involved in an earlier stage this would be beneficial according to Lundström.

8.6 Maria Nilsson

About the interviewee
Nilsson works at Trafikverket as a tunnel safety specialist. She works with questions regarding rescue work and evacuation and she supports the planning of roads and railways. Today Nilsson works with Västlänken, Gothenburg, where she ensures that the requirements for the tunnel safety regarding evacuation and rescue is fulfilled throughout the project. Nilsson also has a background as a risk engineer at FB Engineering/Cowi where she made risk analyses concerning dangerous goods transports and industries. Nilsson is interviewed for this thesis because of her experience of handling explosion risks both as a risk analyst and in large projects as Västlänken.

How a tunnel safety specialist handle explosions

Nilsson works with explosion risks at Västlänken. No dangerous goods transports will be transported in Västlänken according to Nilsson. However, explosion risks from antagonistic events is something that needs to be considered in for example the station platforms. Further, when Västlänken is built, tracks where dangerous goods are transported close to Olskroken are moved closer to existing buildings and Nilsson explains that because of this the risk from dangerous goods including explosion risk for nearby buildings also needs to be evaluated.

Need for increased knowledge about explosions

According to Nilsson Trafikverket wants to investigate what is a reasonable handling of the design explosion load for buildings close to new production of roads and railways with dangerous goods transports. According to Nilsson the design explosion load may vary depending on which company makes the risk analysis. This may be due to some variations in the methods that is used, which input data that is used and what assumptions that is made. However, the overall method for the risk analysis is mostly the same according to Nilsson.

Nilsson explains that Trafikverket also wants to know what design explosion load that is reasonable to use depending on the number of transports and what number of explosives that the vehicle is carrying. According to Nilsson the considered explosion load has never been too low; either a reasonable explosion load has been considered or it has been too large. The reason for why this type of investigation is needed is that if a too large design explosion load is used the project will become unnecessary expensive.

Nilsson thinks that there is need for improved guidelines for how explosion loads should be handled. Trafikverket has some own guidelines for tunnels where an explosion load is assigned. However, there is need for guidelines for explosion loads on railways and roads above ground and for stations.

How to improve the handling of explosions

Nilsson believes that a study of where the resources would have the largest effects on reducing the risks would be good. She wants to know if it is better to use the resources on risks that are more probable to occur instead of risk with a low probability and a large consequence. However, Nilsson has not experienced that too large resources has been used to reduce the explosion risk.

One thing that Nilsson believes more effort should be put into is the statistics. One need to start with analysing the statistics in order to know what things needs to be prioritised and what the available resources should be used for. There is both need for statistics of the number of transports and the probabilities for different events to occur.

Explosions and risk analyses

Nilsson explains that a risk analysis may result in expensive risk reducing actions. The risk analysis result is not allowed to affect what type of traffic can be allowed on the railway. It is only in a few cases that dangerous goods traffic has not been allowed in a tunnel. In these cases, there have been other better alternative routes available for the dangerous goods traffic.

Need for improved statistics
In order to improve the handling of explosions there is need for improved statistics of transports according to Nilsson. There is need for good statistics for what is transported to be able to make good predictions also for the future traffic. What kind of dangerous goods transports that passes on a road or a railway will have large influence on the risk level and therefore there is a need of improving this statistics. However, there might be some risks with producing the statistics of dangerous goods traffic according to Nilsson.

Collaboration and communication
Nilsson says that a better collaboration with MSB would be to prefer. According to Nilsson the time and the resources at MSB has not been enough for them to be involved in Trafikverkets projects at a level that Trafikverket would have wanted.

According to Nilsson the collaboration with risk analysts is good. Due to the small sector it is easy to know who has the knowledge of making risk analyses.

Nilsson also believes that the county administration boards has enough knowledge to make good evaluations and decisions regarding explosion risks. It is possible that the knowledge in Stockholm and Gothenburg are higher than in smaller cities. However, the knowledge is not needed to the same extent where it is not the same need for building roads close to urban areas.

For the structural engineers Nilsson think that every structural engineer has not enough knowledge in the area. Sometimes specialists are needed for the task. However, in the end Nilsson believes that explosion loads are handled in a good way, even though it might take some time to find the person with the right knowledge.

8.7 Mathias Lööf

About the interviewee
Lööf works as a fire and risk engineer at Projektstaben in Stockholm. He works with risk analyses from the client's side and with coordination of fire and risk questions when it comes to civil engineering and infrastructure projects. Lööf mostly works with risk analyses in the zoning plan stage of planning a city. However, he also helps interpret the requirements set on the zoning plan when someone wants to build something within it. This since the requirements are not easily interpreted and it could be difficult to know exactly what is needed in order to fulfil them. Lööf has also experience of working with over-decking projects, which he says is where he mostly treats questions with explosion risks.

Need for increased knowledge about explosions
Lööf believes that an increased knowledge about explosions is needed. He explains that there is need for knowing more about probabilities for explosions to occur and what consequences to expect from such an event. in Lööf experience, the probability reasoning has been a bit forgotten. Even if the risk analyst would consider the probability, in a to them reasonable way, they may often be criticized by the ones who

reviews the risk analyses. Because of this there is need for more research connected to the probability for events to happen.

Treatment of explosion risks
According to Lööf explosions are well treated in risk analysis. Even though the probability for an explosion to happen is low it is still considered in the risk analyses. However, it is possible that the loads that are considered in the risk analyses are higher than what is actually necessary to consider. Lööf explains that there is no agreement, in between different risk analysts, what explosion charge should be considered. There is also a need of taking the prerequisites for the specific location into consideration.

According to Lööf the explosion source considered in tunnels are often higher than what is taken into consideration outside tunnels. He believes that people are looking too much on how explosions were considered in the project Hagastaden[1] where large explosion loads were designed for. However, in Hagastaden the prerequisites were special. According to Lööf there is need to regard explosions more from a risk perspective, in which higher focus is put on probabilities and not, as often is the case today, so much on the possible consequences.

Lööf also points on the positive effects of building a tunnel or over-deckingand letting the dangerous goods traffic go through the tunnel instead of on ground level. For many accidental events the tunnel will protect the buildings close to it better thanwhat had been the case without a tunnel. Lööf also says that one should look at the alternative transport routs that the dangerous goods traffic needs to take if it is forbidden to use the tunnel. When this was done for Hagastaden the consequence for an explosion in the tunnel or outside was almost the same. However, in most cases the alternative route will both be longer and have lower traffic safety. In the tunnel one could also use extinguishing methods reducing the risk of an explosion due to fire.

Lööf also explains that today one considers explosives as amount of TNT, something that Lööf thinks is a bit strange. According to him it is only the military who transports and uses TNT. To use TNT in risk analyses is also a conservative way of treating the risk of explosions. It may be the case that this assumption is way too conservative.

How to improve the handling of explosions
According to Lööf, the information about how probable it is to get an explosion when there is a fire in a truck transporting something explosive or to get an explosion from a crash needs to be improved. He explains that today the statistics used are from normal trucks. However, the trucks transporting dangerous goods are specially designed to protect the cargo at an accident. The cargo is also placed in a container which is a separate fire cell. This leads to significant reduced risks. Despite this such improvements are not considered in the risk analyses and this might according to Lööf lead to a huge overestimation of the risk.

[1] Hagastaden is a project in Stockholm where an over-decking is going to be built over Essingeleden. On top of the over-decking buildings will be placed. In this project the explosion risk has been discussed a lot.

In addition, Lööf believes that it is difficult to evaluate what consequence an explosion will have. To make an estimation about how many will die due to different types of accidents is a difficult estimation to make. For example is it extremely difficult for the risk analysts to evaluate how many people would have time to evacuate from the area before the fire lead to an explosion. It is also very difficult to estimate the behaviour of humans; will people stand close to the windows where they are exposed to large risks looking at the accident or will they evacuate the building. Today the risk analysts assume a momentaneous explosion, even though it often is an extended sequence of events before an explosion can occur.

Lööf believes that a standard for how such consequence calculations should be performed would be beneficial. On the other hand, Lööf comments on that too detailed standards for how to handle explosion risks also could be dangerous. If there are too detailed standards there is risk that the risk analyses will not follow the development of the society and that the specific prerequisites are not taken into consideration well enough.

Lööf also discusses how risk evaluation criteria are used. According to him the DNV criteria was initially used to help deciding where to locate new roads and to evaluate what location of the road would result in the lowest risk. Today the criteria are used when building new buildings in an area already containing existing buildings. It might be the case that the old buildings already contribute with a large risk level so that even though new buildings would be designed to resist the risks much better it could not be built since the existing risk level already is too high. Even when using a good design, a new building would inevitably contribute to an increased risk level. Lööf believes that this type of reasoning is a bit strange. According to him there is need for more discussions about how the risk criteria should be used in areas with existing buildings. Currently, there is no consensus of how this should be done.

Lööf also points out the fact that risks are evaluated differently in different situations. For example, in different industries risks are considered to be small enough to not take into consideration when the probability is under a specific value. However, when it comes to explosion risk in urban planning, it is still considered even though the probability is much lower than what in other cases should be events that would be ignored.

When it comes to recommended risk reducing action in risk analyses Lööf believes that it would be possible to get better predictions of how much effect a risk reducing action will have on the explosion risk. From a risk analyst perspective, it is good if the suggested action will reduce the risk with 100 %. As an example of this is to design a building so that it resists a specific load. But for other types of suggestions it could be much more difficult to know what effect it will have and in these cases a lot of guesses are usually made. To have a handbook for risk reducing actions could be a good idea according to Lööf depending on how this handbook was done. However, Lööf point on the fact that the idea with a risk analysis is in fact not to set specific numbers of how many people that will die because of an accident. Regarding risk reducing actions Lööf also points out that one need to look more on the feasibility of the suggested actions. He also believes that it would be better to set requirements of what function the risk reducing action should have instead of e.g. saying that a special type of windows is needed, which is a commonly suggested requirement.

Need for improved statistics
According to Lööf there is need of improving the statistics for how explosion events are and how large the probability for an explosion are. Lööf also explains that there is a difficulty of collecting such statistics due to the fact that these types of events seldom or never have occurred. To improve the statistics of what is transported and how many transports there are would also be good according to Lööf. Improving the statistics would, according to Lööf, increase the quality of the risk analysis. Lööf does not think that there is a risk that an improvement of the statistics would lead to an interpretation that it represents true values. According to Lööf the risk analyst always needs to consider the traffic in the future anyway. But by updating the statistics continuously the risk analyses would also become better.

In Stockholm, though, Lööf experience is that the statistics for the transports are pretty good. This is due to an investigation done by Trafikverket and Trafikkontoret in Stockholm during 2015 or 2016 for what dangerous goods that was transported. For more information see WSP (2017). Cameras were placed out at primary roads for dangerous goods transports during a period of some months. All categories except the ones with explosives of class 1 was registered by the cameras. Class 1 could not be registered due to the fact that they do not have any signs because of antagonistic risks.

Lööf explains that when updating the statistics for Stockholm it was discovered that the transports of flammable and explosive gases had been underestimated for a long time. The number of transports were approximately twice as many compared to what was assumed when using the statistics produced by MSB during 2006, see Appendix A. Because of this Lööf argues that it is important to know where the development of the society is heading and to have a good knowledge about what is transported.

To use cameras to improve the statistics for transports is one possible way according to Lööf. However, Lööf also believes that by looking at what end destination the transports will have it is possible to make a pretty good estimation of what is transported. However, in areas such as where E6/E20 passes Gårda in Gothenburg and where the transport may have destinations far from Gothenburg this method might be more difficult. Lööf argues that it is in these types of situations one could have most use of cameras for detecting the traffic of dangerous goods.

Collaboration and communication
Lööf believes that communication with various authorities throughout the process is beneficial. Lööf believes that a good way of working is to have a project group for every project, dealing with the risk of explosions. Thereby, the possibilities of discussing the problems and finding solutions together increase. Lööf wishes for improvement in the communication with the county administration board. He would like to have faster decision processes when it comes to zoning plans which the risk analysis is a part of. He believes that everyone would be happy if fast replies could be given.

8.8 Rebecka Thorwaldsdotter and Patrik Jansson

The interview

Since both Rebecka Thorwaldsdotter and Patrik Jansson work together at the county administration board (Länsstyrelsen) they were interviewed at the same time. Thorwaldsdotter was first contacted by the author of this report and Jansson was participating on the interview on initiative from the county administration board. Due to the fact that the interview was done with both of them at the same time they together discussed the questions and completed each other's answers. Therefore, the opinions from both interviewees are presented in the same Section of the report. However, it will be stated who said what during the interview.

About Rebecka Thorwaldsdotter

Thorwaldsdotter works as a risk engineer on the county administration board of Västra Götaland. She also has earlier experience from working as a risk analyst and making risk analyses. Thorwaldsdotter is being interviewed due to her employment at the county administration board. The county administration board handles explosions from another perspective than the other interviewees. It is of interest for the study to get opinions from several parts of the building sector since their opinions might be different from each other and in order to see if they claim that the same things have need for improvement.

About Patrik Jansson

Jansson works as a risk engineer at the county administration board of Västra Götaland. Jansson was interviewed because of his interest of participating in the study. He will together with Thorwaldsdotter give answers to what the county administration board experience is needed to improve in the handling of explosions and also explain how a risk engineer at the county administration board treats explosions in their daily work.

How the county administration board handle explosions

According to Thorwaldsdotter the county administration board works with explosions in the physical planning of the cities. Here they handle several types of risks where risk of explosions is one of them. Jansson explains that when the municipalities want to make a new zoning plan or make changes in an existing zoning plan close to a road where dangerous goods are transported a risk analysis is made. When the municipality has made a suggestion for a zoning plan this is sent to the county administration board for inspection. This is called the inspection stage. Thorwaldsdotter says that it is in this stage the zoning plan is sent to the risk engineers on the county administration board for inspection. The county administration board then give comments of what is needed to be changed. According to Thorwaldsdotter they will both give suggestions for improvement but also point out requirements. Thereafter the municipality have time to make changes in the zoning plan according to the suggestions from the county administration board. According to Jansson the municipality are obliged to send the zoning plan to the county administration board for inspection. When the changes have been made the zoning plan is sent to the county administration board again for a second review. Now, the county administration board present what should be changed in order for them to not take it in for further inspection after the municipality has accepted the plan. After the zoning plan is accepted by the municipality it is sent to the county administration board for a third review. Jansson explains that the county administration board now have three weeks to decide whether the zoning plan needs further inspections. Jansson describes that if the county administration board decides that the zoning plan does not fulfil their requirements the county administration board have unlimited time to inspect it further and they can then decide to not allow the zoning plan. For more information about the plan process, see Boverket (2016). It is in this process the county administration board treats the risk of explosions both from gas and explosives.

Need of increased knowledge about explosions
According to Thorwaldsdotter the county administration board cannot be experts in all areas. In order for them to be able to make a good review of the zoning plan and the risk analysis with it, a detailed investigation where assumptions is well described are needed.

Treatment of explosion risks
According to Thorwaldsdotter the quality of risk analyses for the zoning plan, regarding explosions can vary a lot. Some risk analysts do not even realize that explosion risks are something that they should take into consideration.

When the risks are considered and suggestions of risk reducing actions are given it is important that the actions become a part of the zoning plan. Jansson explains that the zoning plan has some limitations and that it is not always possible to include all risk reducing actions in it. When this is the case Jansson explains that it could be included in contracts. This method is however not to prefer. Jansson claims that what could be regulated by the zoning should be. Regarding those things that can not be regulated, Jansson argues that these could be included in the calculations of what effect the risk reducing actions will have on the risk level. However, because of uncertainty about if they will be made or not, one need to take this uncertainty into consideration in the calculations. Thorwaldsdotter adds that in some cases it is possible to make references to a given page in a document and that it could be a way to add things which normally could not be treated in the zoning plan. However, she explains that there are shared opinions about if this could be accepted.

How to improve the handling of explosions
Jansson believes that it might be good to have national guidelines for how to treat explosions in the building sector. However, he believes that Boverket might be critical to such things as they want location specific evaluations which, according to Jansson, could be difficult with national standards. Thorwaldsdotter believes that standards on a general level could be used but that standards like the ones used in the Netherlands are not going to be produced. For information about the standards used in the Netherlands see Section 2.4.3.

A way to improve the handling of explosions is according to Thorwaldsdotter to include explosion experts early in the process. This could help to ensure that the zoning plan becomes feasible. In Thorwaldsdotters experience it happens that suggested risk reducing actions does not work in practice. In her opinion the way that the requirements of risk reducing actions are described can also be problematic. What Thorwaldsdotter claims is important is that when a risk analyst works in a later stage, suggestions for risk reducing actions must be feasible. To give standard solutions, Thorwaldsdotter claims, is not always enough in the cases where there is an increased risk level.

Explosions and risk analyses

Thorwaldsdotter believes that the way that a risk analysis is carried out often is similar for most risk analyses. One thing that Thorwaldsdotter thinks has need of improvement regarding risk analyses is the suggested risk reducing actions. It is common that standard solutions are given. According to Thorwaldsdotter, there is need to increase the focus at the specific location and what can be done as risk reducing actions at that place. In Thorwaldsdotters opinion it is not enough to come up with some standard solutions in the cases where buildings are going to be placed at a small distance from a road. Here one need to look at what more could be done. It is also important that the risk analysts ensure that the suggested risk reducing actions is possible for that specific project and the specific location. From what Thorwaldsdotter experiences the risk analysts have different pictures of what a risk analyst should do. In some cases, the risk analyses and the risk reducing actions are well treated and in others vague suggestions for what could reduce the risk is given. Furthermore, Thorwaldsdotter comments that it is good if questions about risks are raised in an early stage in the process. Jansson explains that he believes that the municipalities need to be better of asking the right questions. They may be more specific on what they want to get help with from the risk analysts. Jansson says that if the municipality are too unspecific in their questions, they will get unspecific suggestions of risk reducing actions but no requirements of what is needed.

Need for improved statistics

Jansson believes that the statistics of dangerous goods transports that are used today are insufficient and in need of improvement. This is since the statistics are the core of the risk analysis. Jansson claims that one of the largest problems is that there is no company or authority responsible for producing such statistics. When the question was raised if there might be a risk with collecting this type of information Jansson agrees that it could be dangerous if the statistics comes into wrong hands. Thorwaldsdotter also adds that it can be dangerous if the statistics is used as true values. Jansson explains that it is important that the risk analyses also consider future traffic.

Jansson brings up an example of where cameras were used in Gnistängstunneln, Gothenburg, to collect information about dangerous goods traffic. The result was 85-90 % safe; meaning that 85-90% of the transports the cameras should have registered was registered. However, Jansson believes that to use this method for collecting statistics may be both expensive and complicated. For more information about the collection of statistics of dangerous goods traffic in Gnistängstunneln, see Strand (2015).

The county administration board think that it is a problem with the division of the transported load into a number of vehicles. According to Jansson it may not be a very good assumption that there is one transport with 16 ton TNT. Thorwaldsdotter agrees on this and explains that the design scenario might instead be more transports with less load in each. According to Thorwaldsdotter the county administration board use to comment on when 16 ton TNT transports are assumed since they believe that such transport most likely not represent the transports that generally made in a correct way.

Collaboration and communication
Concerning collaborations with other authorities Jansson explains that Länsstyrelsen mostly are in contact with the municipalities when it comes to explosion handling. In some cases, the risk analyst who did the risk analysis on command from the municipality are included in the discussions as well. Thorwaldsdotter believes that the county administration board has, in general, good contact with both the risk analysts and rescue services. The rescue services acts as a support to the municipalities in risk questions. According to Thorwaldsdotter they often have very similar views on things. However, Jansson points out that this is from their perspective working in a larger city and that it might look different in other parts of Sweden.

8.9 Marie Sjölander

About the interviewee
Sjölander has her own company Spets Projektledning Marie Sjölander AB in which she works with project management and helps developers with for example handling questions regarding authorities, quality and environment. Sjölander does not directly handle explosion risks but she often comes in contact with such questions through the risk analyses affecting the project which she is involved in. Sjölander will contribute to the study because she represents the developers view on how explosions are treated. Further, she has good knowledge about what effect the assumptions made in the risk analysis will have on the building.

Need for increased knowledge about explosions
Sjölander believes that there is a need for increasing the knowledge about explosions and that it especially is a need for having national standards for how the explosion risk should be evaluated and handled. This is something that she experiences is missing today. Sjölander brings up that Sweden has need for a national standard for how risks should be treated. This could be a method a bit similar to the ones used in the Netherlands, but adjusted to Sweden´s conditions. Sjölander also expresses a need for having a discussion about when the probability is high enough to take a risk into consideration. Here it might be a conflict between different interests where human lives are evaluated versus economy. Today, it is up to the risk analyst to make this judgement. However, Sjölander believes that this evaluation is something that should be done by the county administration board.

another reason Sjölander believes there is a need for increased knowledge about explosions is because of the fact that explosion risks may be evaluated rather differently in various projects even though they are located close to each other, next to the same road. She also believes that it is a bit strange that this could happen since Länsstyrelsen has evaluated the risk analyses for both projects.

Treatment of explosion risks
Sjölander explains that there has been a change in how the explosion risk is treated. Twenty years ago, the question about explosion risks were not evaluated in the same way as it is today. She also explains that this might have to do with the fact that it today is more common to place buildings at locations where they are more exposed to risks such as explosions.

One way that the explosion risk is treated today, Sjölander says, is by constructing buildings close to transport routes for dangerous goods. These buildings usually consist of e.g. car parks and offices, which are designed to act as a protective barrier to the buildings behind. Hence, the idea is to protect the residential areas built behind. However, Sjölander explains that the purpose for building closer to the roads are double. There is both a need for protecting the buildings behind and to make use of the protecting area when densifying cities. Residential houses could not be placed close to the roads due to requirements for sound and emissions. However, the requirements are a bit lower for offices and parking and the duration people are in these type of buildings are shorter than for residential houses.

Sjölander believes that there is a gap between the risk analyst and the zoning plan. She says that when too much things are regulated by the zoning plan by technical requirements this might be a problem. There could be a large time span between when the risk analysis is made until the building is constructed. If the suggestions for risk reducing actions are described as technical requirements this might be problematic since a lot may happen in e.g. technical development during the years from the risk analysis is made until the construction starts. She also believes that there might be changes in how things are evaluated.

How to improve the handling of explosions

In risk analyses Sjölander explains that the requirements that the risk analysts suggest often are technical requirements instead of requirements on the function of the building. From the developer's point of view, it would have been better to provide function requirements. Technical descriptions as requirements might result in that one gets locked up by solutions which otherwise could have been solved in a much better way. However, Sjölander believes that the authorities have other opinions about this. They might believe that it is easier to follow up the requirements if they are not expressed as function requirements. Sjölander believes that function requirements will not make any difference in the follow up. In fact, the only document handed in to get the building permission is the architect's drawings, which does not say anything about the technical solutions. In her opinion Länsstyrelsen would achieve more control if these questions were handled at the technical consultation before starting the construction work at the building site.

Another suggestion of improvement by Sjölander is to not set up requirements on the building in the zoning plan. According to her it would be much better to handle this discussion during the technical consultation which always needs to take place before the construction start. If these questions were brought up here it would also be easier to take the design of the building into consideration.

In addition to this Sjölander suggests that more seminars should be held in order to increase the knowledge about explosions and risks. Risk analysts could have discussions about how risks should be treated and how requirements for risk reducing actions should be expressed. Maybe they could agree on that they only should make use of function requirements. According to Sjölander this would be preferable. Seminars for developers could also be beneficial. Their knowledge about explosions and other risks are generally low and if their knowledge was increased, Sjölander believes that the projects would become even better.

Sjölander also points out that there are no guidelines for how to act in case of an accident outside a building. BBR (Boverkets building rules) is based on risks inside a building and does not include any threats from the outside. For further information see Boverket (2018). Depending on the situation it could be best for people to stay inside or to evacuate the building. A suggestion to solve this may be using control systems which could evaluate what kind of risk there is on the road outside the building and make a plan for how to act.

Explosions and risk analyses
Sjölander believes that the suggested risk reducing actions generally are customized to the specific project. However, Sjölander has difficulties of evaluating if the explosion load considered are adjusted to the traffic close to the building. Anyway, Sjölander has not experienced that the developer believes that the considered explosion load is too high. She also explains that the developers trust the evaluation which is done by the risk analyst.

Need for improved statistics
Sjölander is very positive to improving the statistics of what is transported. In fact, she says that there was a discussion for a project in Gårda in Gothenburg if the project should make its own investigation for what was transported on the road nearby. When the idea of using cameras to detect dangerous goods transports was brought up Sjölander believed that this suggestion could be really good. As our society becomes more and more complex Sjölander believes that the need of improving the statistics increases. She argues that in order to make correct evaluations of the risk there is need for updated statistics.

Concerning statistics for what could happen during an accident Sjölander also believes that this needs to be improved. She says that if this was better modelled it would also increase the understanding about why the risk reducing actions were needed and what effect they would have.

Collaboration and communication
Concerning collaborations Sjölander suggests that a better communication between the developer, the risk analyst and the emergency services would be good. With an improved discussion between them, combinations of risk reducing actions could be discussed. It would also be possible to find an economic solution that fits the project well and which still fulfils the function requirements for the building.

8.10Compilation of the result of the interviews

All the interviewees agree that there is a need for increased knowledge about explosions. The reason for why they think that the knowledge is insufficient varies depending on in what way they are handling explosions in their work. In Heijmans perspective as a risk analyst, there is need of more knowledge about the consequences at an explosion, since today the consequences may be a bit overestimated. The three interviewees from Trafikverket, Modig, Lundström and Nilsson, agree with the risk analyst on this point. According to them there is a need of a better understanding of what the probability are for different events to happen. The reason they see this as a problem is because their projects get more expensive if they need to consider large explosion loads that probably never will happen. Lööf also expresses a need for this and explains that he thinks that the probability reasoning in the risk evaluation has been somewhat forgotten. It was also pointed out by Lundström that the lack of knowledge inhibits the urban development. He also expressed that in his experience a lot of guesses were made in the risk analyses. According to Modig another large problem was the fact that there are few people in the building sector who have sufficient knowledge about explosions. From MSB and Egardts point of view he also agrees that there are explosion types in need of increased knowledge. Thorwaldsdotter and Jansson believes there is a need of increased knowledge about the risk reducing actions handling explosions. Sjölander expresses a need for increased knowledge due to the fact that explosion risks are treated very differently in different projects today.

When it comes to solutions of how explosions are handled the interviewees came up with different suggestions. To have some type of standard or commonly accepted knowledge and methods are something that almost all interviewees expressed a need for. However, in contrast, Lööf adds that too detailed standards could be dangerous since they always need to be updated to represent the current situation. It was also found out that there is a need of knowing more about what will happen at an accident and how large probabilities it is for explosions to occur due to a fire or a crash. Further suggestions of improvement were more related to in what way the interviewee handled explosions in their work.

Risk analyst Heijmans expressed a need of more information about what effect the risk reducing actions would have. Egardt at MSB, which works a lot in collaboration with the emergency services, expressed a large need of increased safety due to explosions in e.g. tunnels. This was however something that Modig, Lundström and Nilsson had different opinions about. In their opinion more information about explosions was needed since they believed that the loads considered in tunnels today was unnecessary large. Lööf agrees that sometimes too large loads are considered in tunnels, which is not considered for the same road outside the tunnel.

Sjölander put more focus on how to take the risks into consideration inside the buildings and how to come up with customized suggestions for risk reducing actions. Jansson expresses a need that the requirements from the risk analysis becomes a part of the zoning plan. This is however not the best method in Sjölander's opinion. She would prefer if these questions instead were discussed during the technical consultation made prior to the start of construction. Both Sjölander and Lööf would prefer to set function requirements for the risk reducing actions. This is however criticized by Thorwaldsdotter and Jansson who wants technical requirements to be a part of the zooning plan. However, Thorwaldsdotter says that today there are problems with suggestions that are not adjusted to fit the specific project.

Regarding improved statistics of dangerous goods transports there are divided opinions. Heijmans, Nilsson, Thorwaldsdotter, Jansson, Lööf and Sjölander expresses that there is a large need for improved statistics. When the statistics were updated for Stockholm Lööf explains that the earlier assumptions of transports were far from the truth, approximately half of that found in an updated study. Heijmans has a need for better statistics in order to make better risk analyses. According to him bad statistics will lead to large overestimations in the risk analysis. Nilsson believes that the statistics is needed to get information about where to put focus. Jansson and Thorwaldsdotter says that there is a need for knowing more about the division of dangerous goods into trucks. To assume fully loaded trucks may not be a good assumption and it might result in a lower risk compared to if the goods instead were transported in several trucks.

Egardt and Lundström are more critical to improving the statistics of transported explosives due to the fact that it could be a large risk doing this. If someone that has antagonistic motives get hold of this information, it could be dangerous. However, if this problem could be overcome, they can also see the advantages with improved statistics. Lundström gives a suggestion that all statistics of dangerous goods traffic except the statistics of i.e. class 1.1 goods could be collected. This, since these categories will not be as dangerous if someone unauthorized gets the information. Lundström believes that such information would still be of good use for the risk analyst.

Most of the interviewees would like to have a better collaboration and communication with other companies and authorities. Risk analyst Heijmans and Lööf expressed that they would prefer to have better communication with several authorities, structural engineers, architects, investors and fire engineers. Heijmans believed that maybe a fire engineer could help overarch the gap, he experience today, between the risk analyst and the structural engineer. Sjölander has also experienced this gap and she wants to solve it with a better communication between the developer, emergency services and the risk analysts. Lundström and Thorwaldsdotter also described that it would be a good idea to include the structural engineers and experts earlier in the project and to let risk analysts be a part of the project for longer time and not only producing a risk analysis at an early stage.

The opinions about how risk analyses treat explosions are divided. Egardt highlighted that he believed that there is a need for taking more things than number of deaths into account when making a risk analysis. For example, Egardt wanted to include the effect that an accident would have on the society. According to him there was also a need for more knowledge about what effect risk reducing actions will have. A handbook treating such things was suggested. This was something that also was brought up by risk analyst Heijmans since it, according to him, was difficult to know what effect a proposed risk reducing action would have. Furthermore, it was pointed out by Heijmans that it could be a problem that the risk analyst uses approximate values for loads in their calculations when the structural engineers are in need for more exact values when designing the building.

Further, Nilsson points out that Trafikverket do not accept that the risk analysis affects the allowance of traffic going through a tunnel. Therefore, the risk analyses might instead lead to expensive risk reducing actions. Modig, Lundström and Lööf all believes that too large loads are taken into consideration in many risk analyses considering tunnels and roads covered with over deckings, and that it needs to be a larger focus on probability of the events. Sjölander also points out that the knowledge about risks are generally low by the developer and therefore they trust the risk analysts a lot in their evaluations.

9 Discussion

9.1 Risk criteria and safety distances

There are several ways to evaluate if a risk is at an acceptable level for the surrounding. One way is to set safety distances describing what distance from a risk source one is allowed to build buildings of different types. However, when cities become more densified such safety distances can lead to unused areas (Räddningsverket, 1997). Länsstyrelserna Skåne län, Stockholms län and Västra Götalands län (2006) divide the area closest to roads into zones where buildings of different types could be built. Similar was done by Gothenburg city, see Section 2.3.2. These types of recommended distances could be good to use as guidelines but sometimes there is need to build something closer to a road than these documents suggest. When this is the case another evaluation method can be used to determine if the risk level is acceptable. It is also criticized by Boverket and Räddningsverket (2006) that using recommended distances could be a bit misleading. According to them other things than a large distance to the risk source might have larger impact on the risk level.

When looking at what criteria are used by risk analysts one could see that it in most cases are the ones from DNV, see Section 2.3.2. By using DNV´s criteria, risk analyses can be made for buildings located at a shorter distance than normally recommended. Hence, more area can be used since the risk is better evaluated. If the risk level is deemed to be too large this may be solved using risk reducing actions. It was also discovered that in Gothenburg different criteria, produced by Gothenburg city, were sometimes used. However, a shift was later made from using the GÖP criteria from Gothenburg city to only using DNV´s criteria. According to Heijmans a decision was taken to only use DNV´s criteria. During 2017 a report was done by Norconsult. In this report critique towards the fact that risk analysts did not use Gothenburg's criteria were put forward by the county administration board, see Section 6.4. However, it can also be seen as strange that Gothenburg had its own criteria while all other cities explicit used DNV´s criteria. Heijmans explained that even though DNV´s criteria can be seen as a standard for the building sector, since it is so widely used, it is not criteria that are in Sweden accepted by the government. However, risk analyses that do fulfil DNV's criteria are usually not taken in for further review by the county administration board.

To have guidelines for where to place buildings in order for it to be safe could be good. It may also be good to have different recommendations for different parts of Sweden due to variations in what risk sources there might be. However, when it is not possible to follow the recommendations there is need of an acceptable risk level below which the risk can be considered acceptable. Even though there today are criteria available which can be seen as standards it may be good to have criteria which is accepted by the government. To set a price on human life, which is basically what is done when deciding about acceptable risk levels, is a difficult task which one could understand that no one wants to decide about. Therefore, there may be a need for discussing what criteria that is reasonably to use and set a standard for the entire country.

9.2 Evaluation of risk

When it comes to evaluation of the risks Räddningsverket (1997) says that one should consider probability, consequence, avoidance of catastrophes and have a cost-efficient thinking. However, to both be cost-efficient and avoid catastrophes can be difficult. What events one should consider in the risk analysis there are also different opinions about. Lundström believes that too large loads are designed for in tunnels, which leads to structures that are unnecessarily expensive. However, according to Egardt the tunnels, with a wall in between the two tubes, are usually designed for too small loads since if there is an internal explosion, people will not be able to evacuate into the other tunnel tube. In addition, Modig discusses how many people that will be able to evacuate if there is an explosion of a size which destroys the wall and the doors between two tunnel tubes. To decide where to set the limit for what should be considered in a risk analysis is philosophic questions. It has to do with how we value human lives. What resources are we willing to spend to save a life? How small does the probability need to be in order to not consider the risk for it? These are difficult questions to answer but it needs to be done in the risk analyses and by then it is good to have a shared opinion about how to reason. It was concluded by Alvarsson and Jonsson (2016) that guidelines and standards were needed for evaluation of risks and for how consequence and frequency calculations should be performed.

9.3 Risk reducing actions

In Section 5.7 it was described that it is common that the same suggestions for risk reducing actions are given. Thorwaldsdotter argues that to just give standard solutions for risk reducing actions are not enough in the cases where one has an increased risk level. Here it is important to take the specific location into consideration and to make sure that the actions will work. Lundström is also sceptical to standard solutions. In his opinion, risk analysts sometimes give suggestions that will not work at that specific place and that instead causes other problems. It may be good to have some solutions that is common since there might be similar conditions on several locations. However, it is important to consider the specific location and what the requirements from the client are.

According to Jansson all risk reducing actions cannot be described in the zoning plan. He argues that the actions which could not be described here should not be included in the calculations of how much the risk level decreases. This is also brought up by Räddningsverket (1997); e.i. that one need to make sure that the conditions assumed in the risk analysis is retained in the final solution. It is also possible to look at the problem that Jansson bring up from another perspective. Instead of not taking into consideration the positive effects that the risk reducing actions will have, since it could not be included in the zoning plan, there might be a need to develop a new type of document where this type of requirements is listed. As it is today, Lööf explains that a risk reducing action could be to use window glass of a specifies class. In Lööf's opinion it would have been better to describe what function the window should have. In this way he believes one would overcome the problem with not knowing exactly what will be build when making the risk analysis and one could more easily make solutions that works for the specific project. It can be both pros and cons with describing the function. Describing the function means to say that the wall should resist an explosion load, would be much too unspecific. However, for a window it could be good to describe that it should be able to resist a certain dynamic load and a certain temperature for a given duration. This might be a better alternative than stating a window class, since the requirement of the classification might change during time and it may be complicated to fulfil that class with regard to other criteria given.

It was discussed that there is a need to specify the effect of the risk reducing actions and to give more specific descriptions of the suggested actions. The same reasoning is brought up in Section 6.4 where the county administration board expresses that there is a need of well-presented suggestions of how to reduce the risk and that it is an uncertainty about what effect the actions will have. This was something that also was discovered in Alvarsson and Jonssons review of risk analyses, see Section 2.4.2. From the results of the interviews one could see that everyone, also the risk analysts, agrees that the effect of the risk reducing actions are not described enough. Heijmans explains that it is difficult for risk analysts to know what effect the action will have and that there is need for a document which could help the risk analysts with this evaluation. Egardt also brings up that one need to consider the effect of the action not only on the building which the risk analysis concerns but also for its surrounding. Modig also brings up that there is need of looking more at what effect the risk reducing actions would have on the probability for an accident to occur. Since the risk level needs to be below a certain level there might be need of using risk reducing actions to get there. Especially for such situations it is important to know what effect the risk reducing action will have. How much will the action reduce the risk? Is it something else that will reduce the risk that may be more cost efficient? In order to make a good evaluation of the risk reducing action these question needs to be answered.

According to Lundström it is possible that the society spend money on the wrong risk reducing actions; e.i. if the money was spent on reducing the risk for more common accidents with less consequence it would reduce the number of deaths per year more than actions that reduces the risk of e.g. a large explosion. Nilsson also want to know where the resources should be placed to have the largest effect. However, to make such an evaluation updated statistics for the different types of events are needed. There is also a need to look at the costs to reduce the risks of different events.

9.4 Statistics

In Section 5.3 it is shown that the statistics for the traffic often were based on SRV (2006). This could also be seen in Section 6.3. Even though the same statistics were used for the risk analyses in Gårda in Gothenburg different assumptions about the traffic was made since the transport statistics available did not include that part of the road. To use such old statistics may give an inaccurate picture of the reality. Predictions for the future could be made but this includes large uncertainties. The method used to find the statistics that is presented in SRV (2006) presents can also be discussed. The period that the information was collected was not very long and it is possible that this time period does not reflect the transports over a year very well. To have better use for the statistics of the transports they need to be updated continuously.

All the interviewees believe that there is a need of improving the transport statistics in order to get a higher quality of the risk analyses. This was also brought up by

Alvarsson and Jonsson (2016). However, some describes that this may not be possible since there may be a threat from antagonists to collect such type of information. Lundström believes that it is possible to collect information about all transports except the ones with class 1.1 goods. According to him it is the explosives that is the largest risk. In the risk analyses the statistics are of large importance for evaluation of the risk level. It might be that the positive effects of improved information are higher than the possible negative effects related to antagonistic threat. If updating the statistics this should probably not be a document which would be available to everyone. With a large safety for who can reach this type of information the threat could probably be decreased. One can also argue that to not collect information about what is transported goods could be a risk as well. Without the information no one will know if the predictions of the transports are overestimations or not. Lööf explains that an improvement of the statistics was made in Stockholm. When this was done it was discovered that the earlier assumptions of gas transports were far from the reality; it was almost double compared to earlier predictions. This is a physical example of where underestimations have been made during a long time.

Both Heijmans and Thorwaldsdotter says that they believe that the estimation of fully loaded cars is an unrealistic assumption. However, this assumption is common in risk analyses. Thorwaldsdotter also explains that if the assumption is made that the trucks are fully loaded this would result in less numbers of transports and this may result in a lower risk level than if the load was divided into several trucks. To make an estimation that is believed to be an overestimation when it is not is bad. To find out what is a good estimation for how filled the cars is, the statistics of this needs to be improved as well.

In Section 6.3 it is also discussed the handling of traffic by day and night. Often the number of people in the buildings are highly dependent on what time of the day it is. For e.g. an office building people will seldom be there during night-time. Hence, if one could show by statistics that most of the dangerous goods transports passes during night-time the risk level should be markable decreased.

To use cameras for improving the statistics of dangerous goods traffic could be a good alternative. It is possible that it could be somewhat expensive, but it could also be very useful for areas where there is need of locating buildings close to roads. Lööf believes that the result from collection of statistics in this way was good and had good reliability. However, he believes that in many cases it is enough for the risk analyst to look at the surrounding and see what kind of industries and other things that handles dangerous goods traffic. However, Lööf believes that for an area like Gårda, where a lot of transports may pass and where the final destination might be far from Gothenburg, cameras could be really useful and help the risk analysts a lot. By using cameras, it would be possible to get an updated picture of what is transported. This would also make it possible to make better predictions for the future traffic.

9.5 Explosion load

As described in Chapter 7 the size of an explosion will have large impact on what will happen to a nearby building. If one should design for a large explosion this will result in a thicker concrete construction with more reinforcement and larger density. A larger load will result in higher costs for the building if it still should be built on the same distance from the road. It is therefore of importance that the explosion load is evaluated correctly. If not, there is both risk that the final building has insufficient resistance or risk of using too much resources to obtain a structure that is really not needed.

The size of the explosion will both have influence on the risk level and on the design of the building. For the risk analysis there is not a need to know the exact position of the explosion centre since the idea of the risk analysis is just to evaluate if the risk level is acceptable. If the risk level is not acceptable it is possible that the first assumption of a large explosion load is reconsidered. However, for the structural engineer and the design of the building, there is need for an exact charge weight, which the building should be designed with regard. It is also need for pointing out a specific position of the explosion centre. On a road with several lanes it could make a large difference if the explosion centre is assumed to be located at the edge of the road closest to the building or if it is in the middle of the road. This could be seen by looking at Figure 7.2 to Figure 7.5 where one could see that the load level decreases quickly by distance. However, as one could see in Table 5.10 the position of the load is often not very well described in a risk analysis.

As described in Section 2.6.2 there are several events possible from an accident with explosives or with gas. However, since these types of accidents seldom happens it is difficult to know what exactly will happen in case of an accident. Heijmans described an example of where small differences in assumptions had large influence on what could happen. Based on the interviews there is also consensus that there is a need of increasing the knowledge about explosions and what could happen. Alvarsson and Jonsson (2016) also expressed a need for knowing more about the consequences. Modig explains that it would be difficult to make full scale tests which includes explosives. Anyway, he believes that useful and reliable information could be found by doing modelling of explosion events.

9.6 Communication and collaboration

It was agreed in the interviews that increased collaboration with other authorities and companies is something that would contribute to increased knowledge. Several suggestions for which disciplines that the interviewees wanted to improve the communication with was given. Marie Sjölander suggested seminars for risk analysts in order for them to get a unified view of what should be presented in a risk analysis and how it should be done. Alternative suggestions for how the communication could look like was given by Alvarsson and Jonsson (2016). They gave the suggestion to have forums where these types of questions could be further discussed.

10 Conclusions

10.1 Inference of study

Due to that buildings are being constructed closer to roads when densifying cities, it has been discovered that there is a need of increased knowledge about explosions and how the explosion risk should be handled in the early stages of a project. However, there could be different opinions about what the knowledge needs are and what areas needs more focus. The most prioritized areas, to focus further research on, has been discovered. This has been done by doing literature studies, reviews of risk analyses, calculations about a construction's response to an explosion load and interviews with stakeholders. The thesis has given a picture of how explosions are treated today, and it has discovered problematics and possible solutions and suggestions for improvement.

From the literature study it was discovered that there were guidelines available for evaluation of risk. Even though the criteria from DNV have somewhat become an industry standard it was expressed in the interviews a need for a discussion about how the evaluation of risks should be made.

Furthermore, the review of risk analyses showed that the statistics used for transports was unreliable. This was agreed to be a large problem since the quality of the risk analyses became low. Cameras could be used to collect updated information about transports.

Moreover, statistics for probabilities of different consequences are also in need of being updated. This could be done by modelling. This is needed in order to know what explosion load that is reasonable to design for. It could be seen in the calculations of structural response for an explosion load that both the amount of reinforcement, the density, the thickness and the elastic or plastic response of the structure made large difference in how well a structure withstands an explosion load. What also could be seen was that the distance required to resist the explosion increased markable with an increased size of the charge. Therefore, it is of large importance to assume a charge which is reasonable. One could also see a need for this development from stakeholders both due to the increased costs if too large charge is assumed and uncertainty that not large enough explosion loads are considered.

In addition, the risk reducing actions has been discovered to be a problematic area. Risk analysts discovers that it is complicated to know what effect the risk reducing actions will have. The effect was also discovered to seldom be described very well in risk analyses. The county administration board also express a need for better adapting the solutions to the specific location and make sure that the solutions behave as intended for that specific project. A suggested solution would be to include experts and structural engineers earlier in the process and to have a better communication and exchange of knowledge between authorities and stakeholders.

Furthermore, it has been discussed in what way the risk reducing actions should be presented. To describe the requirements as function requirements instead of technical requirements would be preferable according to risk analysts and developers. This would probably make it easier to adjust the risk reducing actions to the situation. But then challenges arise for how to control the requirements and how they should be expressed on the zoning plan. However, it can be agreed that there is need for a discussion about how to handle the risk reducing actions in order to make both the risk analysts, the county administration board, the municipalities, the emergency services and the developers satisfied. A starting point could be to have seminars treating explosion risks in order to arouse interest for further discussions, collaborations and development.

10.2 Further research

As structural engineers and contractors were not included in the interviews of this study this would be a possible way to continue the work. This thesis has had a focus on how explosions are treated in the earlier stages mostly when the risk of explosion is evaluated. However, structural engineers would probably come with other suggestions of improvement since they handle explosions in another stage of the construction process.

What could be done in further studies is to make surveys where the highlighted problems in the interviews in this study were asked questions about. By doing this one would get confirmation about what needs to put a lot more focus on.

The Netherlands is a country where more standardized methods have been composed for how risks should be treated. It could be investigated how other countries handles risk questions and especially explosion risks. Are there methods which could be used in Sweden as well, and what can be learned from their reasoning about these types of questions?

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Appendix A Statistics

A.1 Statistics for dangerous goods

At a request from the Swedish government Räddningsverket got the task to develop material for what types of dangerous goods that was transported on roads, railways, water transport routs and by airplane in the Sweden. The amount that was transported should be analysed as well as the transport routs. This was done in order to e.g. help in risk analysis work. Statistics Sweden (SCB) was thereafter given the task from Räddningsverket to map the dangerous goods transports. The result of this mapping was presented in (Räddningsverket, 2006).

The mapping was done during September 2006. Surveys were handed out to Swedish companies which transported dangerous goods. Information from data bases were also handed in from companies and authorities which had this information. The result was later summarized into maps (Räddningsverket, 2006).

What was asked for in the analysis were:

- What was transported?
- What amounts were transported?
- From where was it transported?
- To where was it transported?
- What transport rout was used?

(Räddningsverket, 2006).

The result from the analysis includes some uncertainties. Firstly, not all companies answered to the survey that was sent out. Secondly, a lot of the answers did not include which roads that was used for the transport and therefore an estimation of transport routs was done in many cases. The response frequency was 81 % for road traffic and 87% for railway traffic. However, no international companies were included in the analysis. Further, companies which produces dangerous goods but did not transport it themselves were not included either. In addition to this, the analysis was done during September in 2006. It is possible that monthly variations exist (Räddningsverket, 2006).

A.2 Investigation done by TRAFA about statistics of transports

An investigation was done by Trafikanalys (2015) if it was possible to map the transports of dangerous goods better without need for new statistics. The background to the investigation was the need for better statistics for transports of dangerous goods. As presented in Appendix A SRV made an investigation in 2006 for the dangerous goods that was transported in Sweden.

There is a need for good statistics for what is transported, if it should be possible to work preventing with risks connected to dangerous goods transports. If good risk analyses should be performed reliable statistics are also of great importance.

TRAFA did the investigation together with MSB, Transportstyrelsen, Trafikverket and Sjöfartsverket. From the investigation several things were discovered. There are deficiencies in the statistics from SRV 2006, which makes it difficult to use the old statistics to do a new and better mapping of the transports. However, the work with collecting new data would be large and also very costly. In addition, it was discovered that safety regarding what information that could be handed out was a problem. No clear rules for what information that could be handed out was available.

Appendix B Wall exposed to an explosion

B.1 Description of calculation model

In the calculations of the structural response of a concrete wall subjected to an explosion load, see Chapter 7, several modifications were made. A description of the wall is found in Figure B.1. The amount of reinforcement ρ_s is based on the reinforcement area A_s divided by the cross section of the wall. The input data used in the calculations are presented in Table B.1. The following variations of parameters were made, see Table B.2. In Table B.3 the load – deformation relation is presented and in Table B.4 the mass of the wall. The mass is calculated with Equation (B.1). The relations between load and deformation are also presented in Figure B.2.

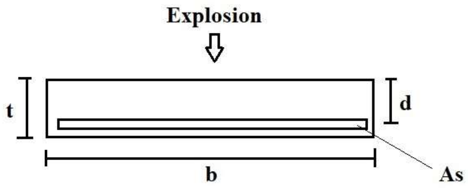

Figure B.1 Description of wall used in calculations.

Table B.1 Input data.

Height, *h*	3 m		
Width, *b*	1 m		
E_c	33 GPa		
E_s	200 GPa		
c´	40 mm		
d	*t-c´* mm		
f_{cc}	25 MPa		
f_{st}	500 MPa		
ρ_s	0.2 %	0.4 %	0.8 %
t	150 mm	200 mm	300 mm
Density	2500 kg/m^3	500 kg/m^3	

Table B.2 Modifications of input data for calculations of concrete wall.

Response	Density	t	ρ_s
	[kg/m^3]	[mm]	[%]
Elastic	500	200	0.2
Elastic	500	200	0.4
Elastic	500	200	0.8
Elastic	2500	200	0.2
Elastic	2500	200	0.4
Elastic	2500	200	0.8
Plastic	500	200	0.2
Plastic	500	200	0.4
Plastic	500	200	0.8
Plastic	2500	150	02
Plastic	2500	150	0.4
Plastic	2500	150	0.8
Plastic	2500	200	0.2
Plastic	2500	200	0.4
Plastic	2500	200	0.8
Plastic	2500	300	0.2
Plastic	2500	300	0.4
Plastic	2500	300	0.8

Table B.3 Load – deformation relations for concrete walls with different thicknesses and reinforcement amounts.

t	ρ_s	u_{el}	u_{tot}	R
[mm]	[%]	[mm]	[mm]	[kN]
150	0.2	25.6	113	32
150	0.4	27.3	129.9	62
150	0.8	29.3	109.5	119
200	0.2	17.60	90.0	67
200	0.4	18.80	103.9	131
200	0.8	20.20	86.6	252
300	0.2	10.8	67.7	177
300	0.4	11.5	78.3	346
300	0.8	12.4	64.5	664

Table B.4 Table off mass for concrete walls.

Density	t	$k_{MF,el}$	m_{el}	$k_{MF,pl}$	m_{pl}
[kg/m³]	[mm]		[kg]		[kg]
500	150	0.788	177.1	0.667	150
500	200	0.788	236.3	0.667	200
500	300	0.788	354.3	0.667	300
2500	150	0.788	885.9	0.667	750
2500	200	0.788	1181.3	0.667	1000
2500	300	0.788	1771.9	0.667	1500

$$m_{SDOF} = \kappa_{mF} \cdot \rho_{btg} \cdot b \cdot h \cdot t \quad \text{(B.1)}$$

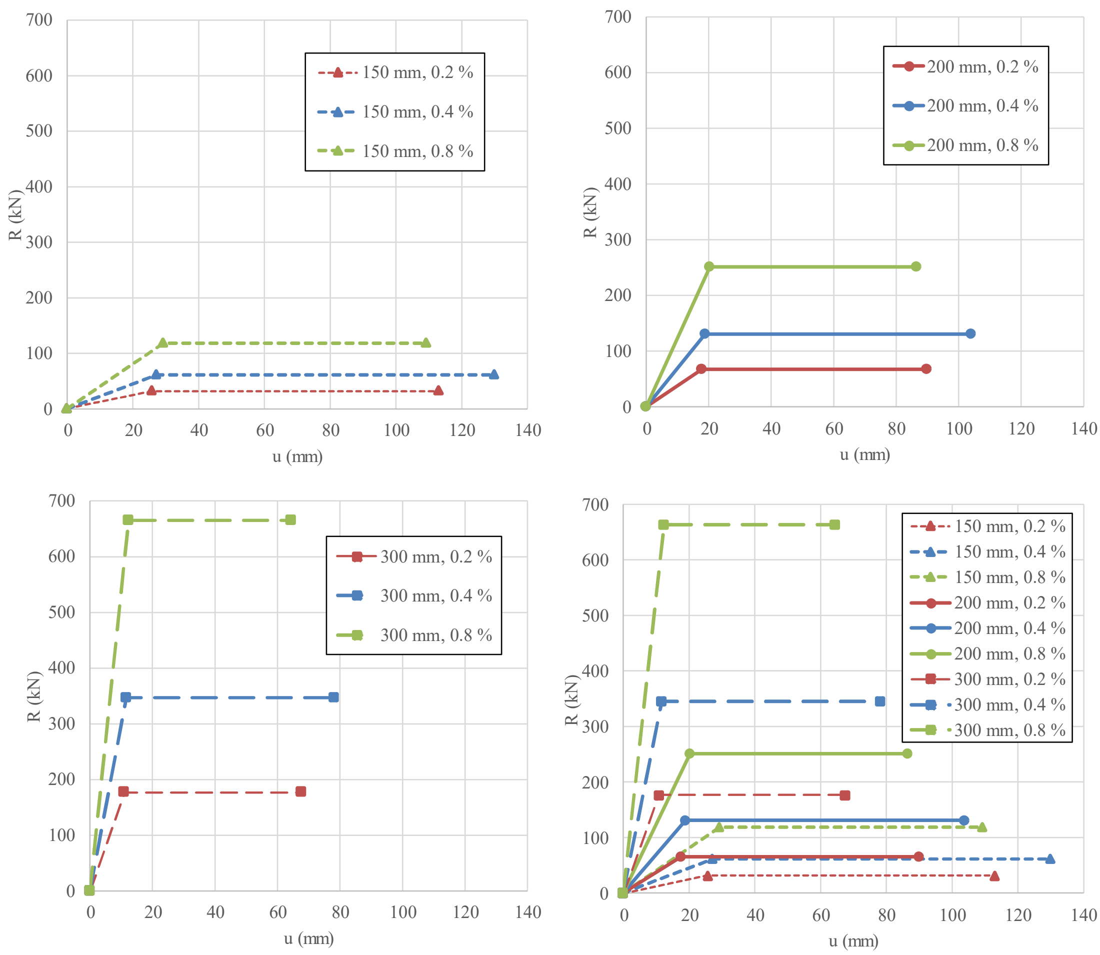

Figure B.2 Load – deformation relations for walls with different thicknesses and reinforcement amounts.

B.2 Table of explosion loads

Table B.5 Pressure and impulse intensity for TNT explosions.

Load	1000 kg TNT		500 kg TNT		250 kg TNT		100 kg TNT		50 kg TNT	
Distance	P_r^+ [kPa]	i_r^+ [Pas]	P_r^+ [kPa]	i_r^+ [Pas]	P_r^+ [kPa]	i_r^+ [Pas]	P_r^+ [kPa]	i_r^+ [Pas]	P_r^+ [kPa]	i_r^+ [Pas]
5	46 173	23 646	28 036	13 341	16 058	7 624	7 081	3 705	3 636	829
10	8 709	8 818	4 521	5 156	2 283	3 046	920	1 540	473	446
15	2 703	5 193	1 356	3 089	687	1 853	295	955	165	320
20	1 146	3 631	584	2 183	309	1 322	144	688	88	256
25	597	2 776	315	1 681	175	1 025	89	537	57	216
30	359	2 241	197	1 365	115	836	63	440	42	189
35	240	1 877	137	1 147	84	705	48	373	33	169
40	172	1 612	102	989	65	609	39	323	27	153
45	131	1 413	80	869	52	536	32	285	23	141
50	104	1 257	66	774	44	479	28	255	20	130
55	85	1 131	55	698	38	432	24	231	18	122
60	72	1 029	48	636	33	394	21	210	16	114
65	62	943	42	583	29	362	19	193	14	108
70	54	870	37	539	26	335	17	179	13	102
75	48	808	33	501	24	311	16	166	12	98
80	43	754	30	468	22	291	15	156	11	93
85	39	706	28	439	20	273	13	146	10	89
90	36	665	26	413	19	257	12	137	9	86
95	33	628	24	390	17	243	11	130	8	82
100	31	594	22	370	16	230	11	123	8	79

Table B.6 Pressure and impulse intensity for gas explosions.

Load	100 m^3 s=7		100 m^3 s=5	
Distance	P_r [kPa]	i_r [Pas]	P_r [kPa]	i_r [Pas]
5	278.58	1981	43,90	805
10	188.44	1055	39,54	603
15	114.69	729	25,75	395
20	71.39	498	19,08	295
25	49.96	374	15,15	234
30	37.54	290	12,57	194
35	29.58	235	10,73	166
40	24.10	196	9,37	145
45	20.15	168	8,31	129
50	17.37	147	7,46	116
55	15.54	133	6,78	105
60	14.05	122	6,20	96
65	12.80	112	5,72	89
70	11.75	104	5,31	82
75	10.85	97	4,95	77
80	10.07	92	4,64	72
85	9.39	86	4,36	68
90	8.79	81	4,12	64
95	8.26	77	3,90	61
100	7.79	73	3,70	58

B.3 Result of calculations for wall subjected to explosion

Table B.7 Required distances in meter for a wall to resist different sizes of explosions.

Response	Density	t	ρ_s	1000 kg TNT	500 kg TNT	250 kg TNT	100 kg TNT	50 kg TNT	100 m^3 s=7	100 m^3 s=5
	kg/m^3	mm	%							
Elastic	500	200	0.2	175.0	131.0	96.0	61.0	41.6	40.0	23.1
Elastic	500	200	0.4	110.0	83.5	62.5	41.0	28.5		
Elastic	500	200	0.8	73.5	56.0	42.3	28.5	20.3		
Elastic	2500	200	0.2	128.0	87.0	57.5	32.6	21.2	23.8	14.0
Elastic	2500	200	0.4	86.5	60.0	40.4	23.4	15.2		
Elastic	2500	200	0.8	60.5	43.0	29.1	17.0	11.1		
Plastic	500	200	0.2	88.7	62.6	43.1	25.6	16.9	19.5	9.6
Plastic	500	200	0.4	59.8	42.8	29.8	17.8	11.9		
Plastic	500	200	0.8	46.4	34.0	24.1	14.7	9.8		
Plastic	2500	150	0.2	79.0	51.6	33.6	18.9	12.3		
Plastic	2500	150	0.4	54.0	35.6	23.3	13.3	8.7		
Plastic	2500	150	0.8	43.8	29.2	19.2	11.0	7.2		
Plastic	2500	200	0.2	53.5	35.4	23.2	13.2	8.6	9.4	1.5
Plastic	2500	200	0.4	37.3	24.8	16.3	9.4	6.2		
Plastic	2500	200	0.8	30.7	20.5	13.6	7.8	5.2		
Plastic	2500	300	0.2	32.9	21.9	14.5	8.3	5.5		
Plastic	2500	300	0.4	23.4	15.6	10.4	6.0	4.0		
Plastic	2500	300	0.8	19.6	13.1	8.7	5.1	3.4		