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Safety Related Challenges when Designing Sustainable Cities – A Practical Example with an Underground CNG Bus Terminal

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Abstract

The transition towards sustainable city planning is challenging from many perspectives, e.g. the speed of development towards fossil free fuels and updating of regulations for controlling risk in the transport infrastructure do not manage to keep an even pace. This applies both at the detailed level regarding technical design requirements and on a more comprehensive performance level of safety objectives that can be verified to confirm compliance with society's safety objectives. This paper presents challenges, experiences and results in connection with the analysis of the risks associated with an underground bus terminal operated with gas-powered buses. A risk analysis approach used in an ongoing project in the final stage of the planning process, which makes it possible to discuss experiences and difficulties based on work in practice. Two main types of injury are studied; fire and explosion, where people can be exposed to both high temperatures, toxic smoke, radiation, pressure waves and impact by flying debris. Fire, may occur with ignition of combustible gas mixture (in air). It can be noted that an underground bus terminal operated by gas-powered buses constitutes a complex facility from a risk perspective and that the risk level without special consideration for additional safety measures is expected to be high. Therefore, a safety concept is required that is balanced between different types of measures, such as supervision, control and safety enhancing installations as well as inherent passive protection.

Keywords: compressed natural gas, risk analysis, explosion, jet-flame, shockwave, biogas, fossil free

1. Introduction

The transition towards sustainable city planning is challenging from many perspectives. Earlier we were heavily relying on transportation using fossil fuels but a trend is that quite rapidly renewable fuels, for example compressed natural gas (CNG), are introduced in a large scale, e.g. in bus fleets. Risks associated with some types of renewable fuels differ quite substantially compared to traditional fuels, which must be taken into account both in city planning and design work, and appropriate risk reducing measures applied. This does not only concern the busses themselves, especially not since a trend is to place transport infrastructure in underground facilities to avoid creating barriers in society and reducing environmental impact such as noise. This adds additional complexity and this changed risk picture needs to be considered when safety concepts are developed for facilities, such as underground bus terminals to ensure compliance with society's safety ambitions (Gehandler et al. 2016). To emphasise this a number of fires in gas-powered buses have occurred and been reported on, which provides a limited empirical evidence that the risks associated with them need to be taken seriously and that the potential for major damage is available (Swedish Accident Investigation Authority, 2013; Dutch Safety Board, 2012).

Another challenge is that the speed of development towards fossil free fuels and the authorities' ability updating regulations for controlling risk in the transport infrastructure do not manage to keep an even pace. This applies both at the detailed level regarding technical design requirements and on a more comprehensive performance level of safety objectives that can be verified to confirm compliance with society's safety objectives. Since such national explicit objectives are lacking, explicit safety targets need to be formulated within each specific construction project, then using qualitative and/or quantitative methods to verify that the goals are met in an iterative process. However, both guidelines and underlying research is limited, since the combination of application, underground facilities and fossil free fuels are relatively new. Therefore, the risk assessment itself poses a project risk which can be significant.

In practical terms, this has consequences. Either we may refrain from allowing new types of facilities that go hand in hand with development of sustainable urban development, or further steps needs to be taken to derive safety concepts based on risk analysis in a credibly and satisfactorily way. The question therefore needs to be addressed if it is suitable and possible to use an engineering approach to design such a facility and how to address the challenges it entails when knowledge, research and guidance in the field is highly limited. A direct effect of this is that the need for research and development in connection with the project work becomes necessary and comprehensive. Since uncertainties are large, it also calls for extensive uncertainty analysis.

In the bus terminal used as a real case example there is a departure hall occupied by about 2000 persons at high traffic hours. The risk analysis is the basis for the design of the safety concept, as detailed requirements on safety measures directed towards risks associated with the use of CNG are lacking. The risk image is complex to analyse and evaluate by multiple scenarios characterized by potentially large consequences but with very low probabilities, such as jet flame, Unconfined Vapor Cloud Explosion (UCVE), pressure vessel explosion and domino effects. These scenarios are of a type that is not traditionally encountered in the current type of facility, and there is no way to lean against practices or regulations to develop appropriate risk mitigation measures. The prerequisites and risk exposure in some respects correspond to the design of a hazmat industry or a tunnel where transport of dangerous goods occur. However, a big difference is that in a bus terminal a large number of people is in close vicinity to the busses, which poses challenges on the safety concept and questions about the appropriateness of the facility.

2. Purpose and Objectives

The purpose of this paper is to present challenges, experiences and results in connection with the analysis of risks associated with an underground bus terminal operated with CNG-powered buses.

The objective of the paper is to present how qualitative and/or quantitative methods can be used to verify that the safety targets are met in an iterative process and how research and development in connection with the project work becomes necessary and comprehensive.

3. Terminal Description

3.1 Overview

A new bus terminal is planned in the central parts of Stockholm. The bus terminal will be located underground in Katarinaberget. Included in the terminal are large waiting areas, bus areas, boarding areas and a combined single tube exit and entrance road tunnel. The terminal is connected to the Stockholm metro and a large shopping mall area through a mutual arrival hall. The terminal and the complexity of the facility and its surroundings is presented in Figure 1.

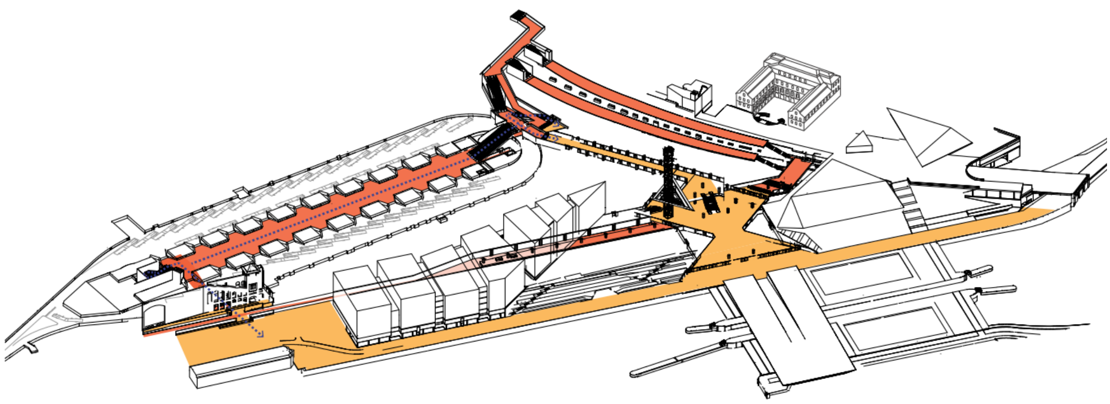

Figure 1. Site plan showing location of terminal and surroundings.

The bus terminal is about 280 metres long, 80 metres wide and is divided into three main valves; two valves for buses and one large departure hall in the middle. The terminal is located -4 m below sea level. Figure 2 and Figure 3 illustrates; (A) Northern bus area, (B) Departure hall, (C) Southern bus area, (D) West entrance connected to the shopping mall and the Stockholm metro, (E) East entrance, (F) road tunnel including an emergency exit.

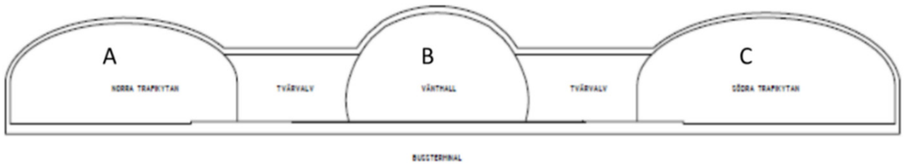

Figure 2. Cross section of bus terminal.

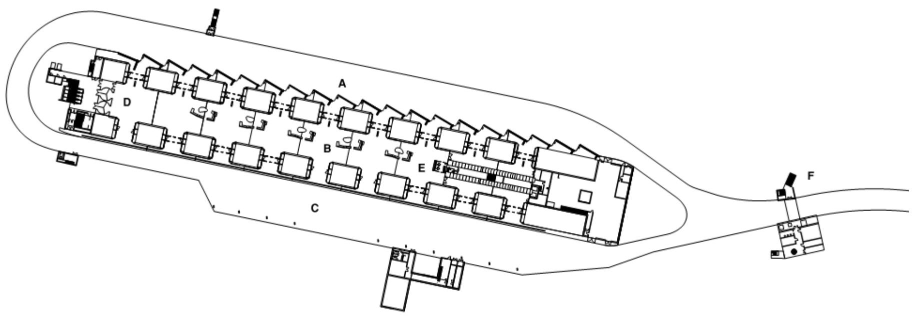

Figure 3. Horizontal view of bus terminal.

Either before departure or after arrival all travelers are passing through the departure hall. It is located between the two bus areas and can be reach from two different entrances. The hall is about 3000 m^2 and the height of the valve is 8.6 m. The hall is a separate fire compartment.

The entrance hall is connected to a number of different occupancies, i.e. commuter train terminal to Saltsjöbanan, the Stockholm metro and a shopping mall. The entrance hall is a three-level fire compartment fire separated from the different occupancies.

Buses arrive to the terminal through a road tunnel and stop on the south side of the departure hall. After travelers are disembarked, the buses may either temporarily park in a bus waiting area or drive to the other side of the departure hall to be boarded. The bus area is about 15 000 m^2 and the height of the northern valve is 8.0 m and the height of the southern valve is 8.5 m.

The width of the road tunnel where the buses enter the terminal is 9 m and the length is 100 m. The construction material of the road tunnel is a mix of rock and concrete. The gradient of the road tunnel is 3.8%.

The construction material in the bus area is mainly of solid rock, spray concrete with steel fibers and pp-fibers, reinforced concrete and parts with lightweight structures.

3.2. Capacity and loads

Performed traffic demand analyses verify that the bus traffic differs a lot during the day. In the morning a large number of travelers will arrive and in the afternoon a lot of travelers will departure. The number of arriving buses and departing buses at the busiest hour (in the afternoon and in the morning) are described in Table 1.

Table 1. Number of buses to and from bus terminal in 2030.

	Arrivals	**Departures**
Morning peak hour	227	80
Afternoon peak hour	90	204

Translated to number of people the maximum occupant load is 11 000 in the morning. Where about 8000 travellers, from 227 buses, are assumed to arrive to the bus terminal during one hour. 84% of them is assumed to transfer to the Metro. About 3000 travellers, 80 buses, are assumed to departure from the bus terminal during the same hour. 84% of them are transferred from the Metro and the remaining 16 % are transferred from connecting trains, busses or arriving by foot.

The maximum occupant load is 9 000 in the afternoon. Where about 7000 travellers, using 204 buses, are assumed to depart from the bus terminal during one hour. During the same hour about 3000 travellers, in 90 buses, are assumed to arrive. 84% of them is assumed to transfer to the metro. The remaining 16 % is transferred to connecting trains, local busses or departing by foot.

In the risk analysis a maximum occupant load in the departure hall of 5000 persons is assumed.

4. CNG Buses

4.1 Identification and Description of Hazards

The following hazards have been identified in a fuel system in a gas driven bus, see also Figure 4.

F (Bottles)	=	Fuel tank (gas bottles)
H (High Pressure)	=	Piping and associated armature (high pressure)
S (Safety Equipment)	=	Safety equipment (malfunctioning pressure release valve located on high pressure side or activated fuse due to bus fire)
L (Low pressure)	=	Piping and associated armature (low pressure, after pressure reduction)

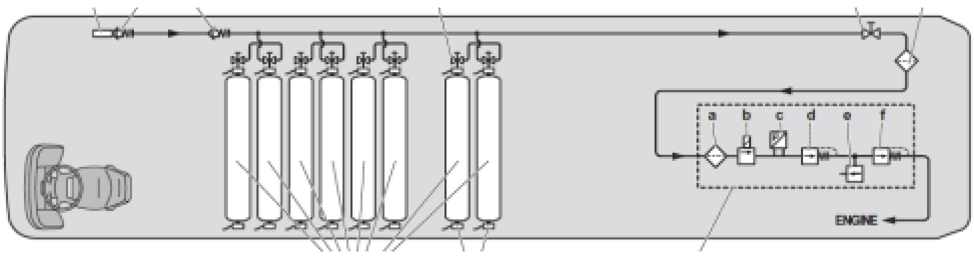

Figure 4. Schematic overview of bottles, valves and pipes on gas bus. The figure is collected from Volvos vehicle manual for buses but is also representative for other vehicles.

4.2 Hazardous Events

Hazardous events can occur from a number of different causes and result in different outcomes, i.e. scenarios. How severe an emission of fuel gas becomes is dependent on several factors e.g. what initiates the emission, what part of the fuel system that the emission is initiated in, the spread of the emission, if the emission is ignited or not and the effect of the emission on humans within the bus and the surroundings.

Two sources resulting in emission of fuel gas are bus fire (where the fire initiates from another reason than due to emission of fuel gas) and malfunctioning equipment in the fuel system.

Figure 5 and Figure 6 shows examples of buses being exposed to fire (Linköping 2005-01-28).

Figure 5. Internal ceiling in fire exposed bus. Soot on the cylinder-shaped fuel tanks can be seen through the holes in the ceiling.

Figure 6. Fuel tanks in fire exposed gas bus seen from above (roof of bus) with the cover removed.

Figure 7 shows an example of safety equipment (fuse) in a fuel system in a gas bus. The fuse activates at a temperature of 110-130°C and stays open after being activated. The fuses' purpose is to depressurize high temperature gas bottles in order to avoid high pressure within the bottles and decrease the risk of explosion.

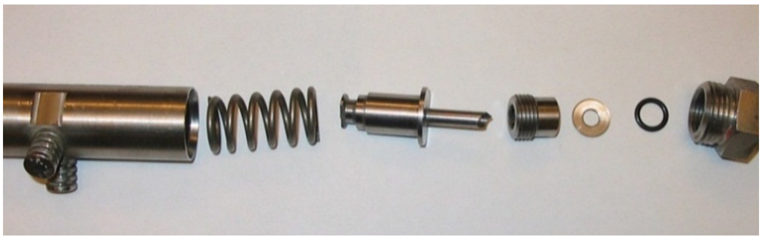

Figure 7. Example of safety equipment (pressure release device).

4.3 Hazards

In this analysis the following hazards are evaluated:

Fire, can occur through ignition of flammable fuel gases within air. Fire can occur as jet-flame depending on the nature of the emission, the extent of the emission and the conditions of the ignition. The spread of the jet-flame and radiation emitted from the jet-flame is evaluated within the analysis. The flame and the radiation from the flame can cause fire spread to other buses and affect people within the terminal.

Explosion**,** can occur as deflagration when combustion of fuel gases within air. Such an explosion in a contained space can create a pressure wave. Sudden release of chemical energy in the fuel tanks of a gas bus can create a pressure wave. In addition to the pressure wave itself an explosion can spread fragment and fire within its surroundings and increase the damage.

Pressure vessel explosion**,** see further in section "Example consequences of extreme accident".

4.4 Dispersion Calculations

The refuel-pressure within gas buses in Sweden is limited to 200 bar at a temperature of 15 ºC. Fuel tanks (gas bottles) in referred buses have a capacity to store around 400 Nm^3 (IEC, 1995).

The size of an emission from the high-pressure parts of the fuel system is dependent on how filled the tanks are, the area of the point of emission and the geometry of the emission point. If the buses are refuelled with around 200 Nm^3 every 24 hours the medium filling capacity is around 75 % (300 Nm^3) which results in a medium pressure within the high-pressure parts of the fuel system being 150 bar. Usually, a gas bottle has a volume of 200 litres which equals 30 m^3 gas within a bottle. This results in 20 kg methane.

The size of an emission from the low-pressure parts of the fuel system is in the same way dependent on how filled the tanks are, the area of the point of emission and the geometry of the emission point. The pressure within the low-pressure parts of the fuel system is dependent on bus manufacturer and the type of motor. The pressure can reach 15 bar when pressure is high on the gas engine and is around 5 bar when idle speeding. When operating the terminal, the pressure on the engine will be low. The pressure within the low-pressure parts of the fuel system will probably be around 5-10 bar.

The diameter of the fuel lines will slightly vary between the different bus manufacturers but is usually around 6 mm. The filling lines are usually within the range of 10-12 mm.

4.5 Properties of CNG

Compressed natural gas (CNG) can be both biogas and natural gas (fossil fuel). In both cases the main component is methane. The CNG that is used within commuter buses in Stockholm usually consist of a mixture of biogas and natural gases where most part of the molecules are biogas. Table 2 and Table 3 shows the usual composition of biogas and the physical and chemical properties for biogas (ISO, 2002).

Table 2. Normal composition for biogas

Component	Fraction
Methane (CH_4)	> 97 %
Carbon dioxide	< 2,0 %
Nitrogen	< 0,8 %

Oxygen	< 0,2 %
Hydrogen sulfide	< 0,00005 %
Tetrahydrothiophene	< 0,0010 %

Table 3. Typical physical and chemical properties for compressed natural gas (CNG).

Physical condition at 20°C	Compressed gas
Color	No color
Smell	Distinct and unpleasant if odourised, otherwise odourless. Odourised by Tetrehydrothiophene (THT)
Relative density (air=1)	Lighter than air <1
Water solubility [mg/l]	Not known but considered low
Limit of flammability [vol% in air]	5-15 %
Self ignition temperature [°C]	> 600 °C in normal pressure
Minimum ignition energy (MIE)	0,3 mJ

5. Risk Analysis

From the start of the project it has been discussed whether CNG powered buses are safe to operate in an underground terminal environment. Consequently, the project group conducted a holistic risk identification analysis, where a number of risks where identified, ranging from serious to low consequences. Additionally, low probability scenarios with high consequence where also studied, since these risks could not be dismissed as negligible. Special attention was also placed on bus related accidents, which could lead to a greater risk contribution, hence to the fact that the terminal is located underground compared to a more traditional above ground terminal. CNG-powered buses have been operating for several years in the public transport system. However, during this period, little emphasis has been placed on the fire protection design for these types of terminals related to the inherited risks in using CNG as fuel.

At an early stage, the identified risks were deemed difficult to handle, considering that the risks involved accident scenarios with jet flame, gas cloud explosion and pressure vessel explosion. In addition to these risks, other risks were also identified, such as fire in bus with diesel fuel, etc., but these risks are not included in this paper. The identified accident scenarios combined with high traffic flows of buses (about 8 buses / minutes in peak traffic), high commuter rate (about 2000 people simultaneously in the facility), proximity to other facilities and intersections (subway, commercial galleries, various types infrastructures and buildings) and that the entire facility is located below ground, results in a complex risk analysis.

For this reason, a preliminary safety concept was presented. The basis for the safety concept is to be comprehensive with a combination of administrative measures, a management function, and that the facility is provided with both passive and active systems for dealing with accidents. This is to create a good robustness for the facility, hence that no system malfunction or insufficient reliability could compromise the safety. Furthermore, the operator requested a high demand on the availability and reliability for the facility, as terminal represent an important focal point in public transport in Stockholm. With the safeguards imposed on the safety concept as a basis, a quantitative risk analysis was conducted based on an event-tree analysis. During the analysis, the safety concept has been adjusted and adapted to optimize the protection measures. After that, the risk calculations have been completed.

In Sweden, there are no guidelines for how a risk analysis for these types of underground facilities should be conducted. However, there is a prevailing practice when designing road tunnels or when physical planning is carried out. The methodology includes; risk analysis consisting of a quantitative risk analysis and event tree methodology. In this project, which has some similarities with tunnels with high complexity, such as road tunnels with dangerous goods transport, the risk assessment methodology was considered very suitable, since the methodology includes; systematically and transparently implementing, managing and reporting the risks. The method is able to handle many different types of safety barriers and system failures, etc. Nevertheless, the great disadvantage is that the analysis becomes very complex and usually resulting in uncertainties that needs further in- depth analysis. This approach is based on the fact that the calculated risk can be estimated in some way to determine whether the risk level is acceptable or if additional risk mitigation measures are necessary. There is no national safety target for acceptable risk in for these types of facilities. Therefore, an important part of the project has been to elaborate a project-specific safety target that could be used in risk evaluation to perform the risk assessment. The development of such a safety target for the bus terminal is presented in more detail in (Lundin, 2019).

5.1 Method Description and Event Tree

The conducted risk analysis is based on literature studies, computer simulations, hand calculations, experience assessments, statistical evidence, expertise and event-tree methodology. The analysis is thus both qualitative and quantitative by nature.

The event tree methodology provides tools that systematically bring forth and describes the evolution of accidents with its relation to implemented protection barriers and how they work. The barriers can consist of technical and administrative measures, fixed and manual extinguishing systems and fire walls. Event tree gives an illustrative picture of possible accident developments that may arise after an initial event. In the current case, the vehicle gas involved in accidents where the initial events consist of traffic accidents, arson, technical errors or material defects.

The main features of the analysis follow below overall elements:

- Literature study, collection of statistics, basis for consequences etc.
- Qualitative analysis of the object and its conditions.
- Development of safety concepts.
- Selection of initial events as well as relevant and representative accident scenarios.
- Analyze events and build event trees with its various barriers. Adjusted and adapted to optimize the protection measures.
- Quantitative estimation of frequencies for different initial events occurs in different ways depending on the available data and its applicability.
- Estimate of the consequences of the various accident scenarios. The calculations are based on scenario specific quantitative studies of fire and explosion processes in combination with evacuation possibilities in these processes as well as the various traffic conditions in the facility (high-speed, low-traffic and night traffic).

In order to nuance the risk image, comparisons were also made with a bus terminal that is located above ground. When conducting a literature-study the following accidents with buses which were powered by CNG have been identified. In all studied cases the buses have ignited which has led to jet-flames being generated from the fuel system. In all cases the fuses in the fuel system have work as designated.

1. The bus fire at Strandbadsvägen in Helsingborg, Sweden.
2. The bus fire at Ättekullagatan in Helsingborg, Sweden.
3. The bus fire at Tornavägen in Lund, Sweden.
4. The bus fire at Wittenburgerweg, Holland.
5. The bus fire at Gnistängtunneln, Göteborg, Sweden.

For the bus fire at Ättekullavägen in Helsingborg The Swedish Accident Investigation Authority (2013) conducted a detailed investigation of the accident. The summary and recommendations of the investigation do not touch upon the CNG system for the buses or the design of the facilities in which such the vehicles are being used.

The investigation consolidates that accidents with biogas as a fuel can lead to fast development and potentially severe damage. Several scenarios with such development have been studied in this report and the mapping of such scenarios are part of the risk identification being conducted. The result of the calculations of these scenarios are similar as in the real cases. The fire development is very rapid and there is a potential for fatalities.

In the conducted analysis, severe accidents related to vehicles with CNG fuel systems which results in jet flames, gas cloud explosion as well as pressure vessel explosion are identified. However, when the risk analysis was conducted there was no documented accidents resulting in gas cloud explosion or pressure vessel explosion in tunnels in Sweden. In recent years there has been a few accidents with pressure vessel explosion, for example in the Gnistängtunnel (Gehandler et al., 2016). Internationally these types of occurrences have been documented, such as the CNG propelled bus explosion in South Korea. Although the circumstances surrounding the accident are not clear, but documented on film. The conclusion is that the consequences modelled in the risk analysis reflects the potential severe damaged that can occur during unfortunate circumstances exemplified by the real case accidents, for example if an accident occurs adjacent to a bus terminal.

5.2 Description of Scenarios

Since the problems which are analysed are complex, inherently the analysis models also become complex. This section outlines the structure of the event-tree model. In order to create transparency of the calculation process the chapter also includes used conditions and assumptions. Due to the fact, that the event-tree model is extensive, it cannot be subsequently fully reported in an easy-to-understand manner. For that reason, the section will instead describe the principles for building the event-tree. For detailed information of the event tree model, please review the original project report (Hellsten & Nygren, 2016).

The event-tree model consists simply of a number of small event-trees that are inter linked in a network of different event-trees. The in-depth parameters for the event-tree model are described based on the following basic classification:

- Event-tree for fire in a CNG fueled bus.
- Event-tree for technical failure of equipment in a CNG fuel system.

In the following sections, the above-mentioned event-trees are described in more detail. However, the event-trees only pertains to a fire on a CNG fuelled bus, other fuel systems are not included.

5.3 Event-Tree for Fire in a CNG Powered Bus

The event tree assumes that a CNG powered bus starts to burn. The origin of the fire may be due to collision, technical fault, self-ignition or arson. With these fire origins as a starting point, the event tree is built based on the parameters (branches) shown below. Note that some parameters only constitute a specification of other individual parameters, i.e. there are parameters that are only relevant to certain event development and or scenarios.

- Traffic situation (High traffic/Low traffic/Night traffic)
- Accident scene (Entrance to a tunnel/Disembark/Boarding/Crank/Standby)
- Fire event origin (Engine/tire/bus coupé)
- Does the engine sprinklers system work (Yes/No)
- The fire is manually extinguished, at an early stage (Yes/No)
- Fire detection system works (Yes/No)
- The facility sprinkler system works (Yes/No)
- Affected equipment part, (failing pressure release device gives pressure vessel explosion) (Bottle/Pressure release device/None)
- Ignition occurs (Yes/No)
- Type of ignition (Delayed/Direct)
- Direction Jet Flame (Up/Sideways)
- Spreading to adjacent located bus (Yes/No)

As shown above, the event-trees uses a large number of parameters, which results to an extensive number of outcome combinations, where the risk impact consists of multiple scenarios linked to various sources of fire, different conditions and protective measures that do not work as intended.

5.4 Statistical Input

According to Swedish and Norwegian statistics (Petzäll, 2010) 1-2 buses out of a 100 begins to burn each year. The statistics applies to buses regardless of fuel type and it also known that fire in buses evolve rapidly. Specific statistics relating to fire in CNG powered busses could not be located during the literature studies. Below pie chart depicts the origin or cause of a fire in busses according to available statistics, see Figure 8 (Petzäll, 2010).

It has been assumed that the above statistics are well represented for commuter busses. Although, the proportion of arson might be slightly higher for the Stockholm commuter busses (SL) than buses which are chartered. The fire cause has a crucial role in how quickly an accident evolves, hence the accident development has been weighed into the assumptions in the analysis.

When identifying potential sources of emissions, four different sources of emissions were identified. These are; high-pressure pipes, low-pressure pipes, CNG containers and pressure release device. There are also other components in the fuel system that could be the source of a CNG leak. However, these components are considered to be included in the above-mentioned emission sources.

There are very little statistics for failure rates on equipment for CNG vehicles. Therefore, relevant statistics was used from other types of gas systems as a base-line. For example, failure rate statistics for pressure release devices are rare to find, hence statistics for safety valves was used.

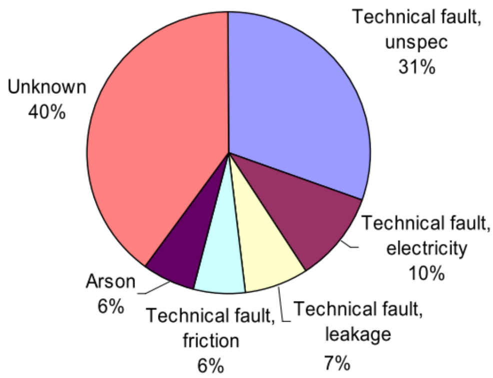

Figure 8. The origin of fires in busses.

For natural gas pipelines there are some statistics for leakage, while more general statistics are available for pressurized containers. This, of course, adds further uncertainty to the analysis, but the uncertainties are well within the framework of how risk analysis are carried out in other areas. All uncertainties are managed in an in-depth uncertainty analysis only briefly reported on to illustrate how the results are affected. The failure rate for pressurized containers and safety valves occur 5E-7 and 2E-5 annually (Committee for the prevention of disasters, 1992). It is assumed that each bus is equipped with ten containers, where each container is equipped with an individual pressure release device. However, within the normal operational environment of the underground bus terminal, other fuel system designs on commuter busses could be operated. In conclusion, this means that the initial failure rate for technical systems is 2.15E-3 annually per bus.

The failure rate calculation for the underground bus terminal is calculated, in the same fashion as for commuter busses. Hence the following calculation argument; the total failure rate for commuter busses in the terminal, is calculated by adding the number of buses moving in the bus terminal per hour and the number of hours each bus is present in the bus terminal. For high traffic there are 216 buses per hour, for 7 h. In a low traffic environment, there are 65 buses per hour for 9 h and for night traffic, there are 12 buses per hour for 8 h. During weekends it is assumed that half of the day in comprised by low-traffic, while the other half is comprised by night traffic. In total the calculation results to an initial frequency of 2.05E-2 annually, which can be converted to roughly one fuel system failure in every 49 years. The expected frequency of a fire on bus in underground terminal has been calculated to 7.48E-02 annually, i.e. recalculated to a frequency of about one fire for every 13.4 years.

5.5 Consequence Calculations

The impact assessments have investigated the radiation levels that arise from different sizes of jet flames and the pressure levels that occur at different sizes of emissions. The calculations then form the basis to the estimation of expected number of deaths, similar to the traditional ASET-RSET analysis, i.e. number of people that are thought to be killed if exposed to critical conditions. How critical conditions propagate, are modeled differently for the different scenarios, which is then compared to the evacuation evolution of the accident in the corresponding scenarios.

The calculations have been carried out partly as hand calculations and in other cases through computer simulations. The following scenarios have been calculated:

1. Extreme accident (pressure vessel explosion)
2. Large hole (6 mm) on high pressure line and explosion
3. Large hole (6 mm) on high pressure line and jet flame
4. Medium hole (1.9 mm) on high pressure line and explosion
5. Medium hole (1.9 mm) on high pressure line and jet flame
6. Small hole (0.75 mm) on high pressure line and explosion
7. Small hole (0.75 mm) on high pressure line and jet flame
8. Large hole (6 mm) on low pressure line and explosion

9. Large hole (6 mm) on low pressure line and jet flame
10. Medium hole (1.9 mm) on low pressure line and explosion
11. Medium hole (1.9 mm) on low pressure line and jet flame
12. Small hole (0.75 mm) on low pressure line and explosion
13. Small hole (0.75 mm) on low pressure line and jet flame
14. Emission pressure release device and explosion
15. Emission pressure release device and jet flame

5.6 Examples of Scenario Types

Within the risk analysis for the underground bus terminal, the following failure scenarios have been used, selection of examples, short version. In the risk analysis these types of scenarios are elaborated based on specific conditions combined together into an extensive event tree.

5.7 Example Consequences of Extreme Accident (Pressure Vessel Explosion)

If a CNG container with compressed gas bursts or if a larger hole is created on the container, the following consequences will emerge:

1. Emissions of combustible gas. Gas emissions can result in secondary effects such as a so-called fireball, where all gas is burned within a few seconds, accompanying with high heat radiation levels for onto objects located near the fireball.
2. The CNG container bursts, which can result that fragments are shot out. Parts of the gas's compressive energy are transferred to motion energy on to the fragments, creating projectiles that can be transported long ways, hence create significant damage all objects the fragments encounter.
3. The origin of a shock wave, overpressure, due to gas expansion. Parts of the compression energy pass into motion energy of the released gas and cause a shockwave that can destroy or propel objects away.

Usually there are two reasons why a CNG vessel may rapture, either due to overpressure exceeds the design pressure of the container or because the strength of the container has deteriorated, for example due to fatigue.

The most common reason for overriding the design pressure of the vessel is overfilling or because thermal heating causes failure in the pressure release device or malfunction of the pressure regulator.

The most common reason for the strength deterioration is that the bottle is oxidized, rusted, material defect, wear due to vibration or collision with other objects (vehicle collision).

5.8 Example Shockwave Consequence

As the container breaks a part, the gas expands resulting in a shock wave. The strength of the shockwave path at different distances, x, from the center of the explosion, is appreciated by using the TNT method. The pressure has been calculated to 10 kPa at a distance of 12 to 13 meters.

The calculations are made by adopting the TNT equivalent calculation works for the particular case. The calculations are judged very conservative, as no consideration is given to the damping effect of the pressure wave caused by the roof cover on top of the containers.

5.9 Example over Pressure Consequence

Two explosion calculations have been carried out with the CFD-program FLACS (Gexcon, 2019), one corresponding to the released amount of gas simulated on a large hole approximately 100 g gas, which corresponds to a gas cloud of about 1 m^3. The other explosion used a gas cloud of 10 kg gas which corresponds to a gas cloud at 175 m^3 (7x5x5 m). The results of the calculations show that the cloud of 100 g of gas produces very small pressure increases without any significant environmental impact, less than 0.5 kPa (5 mbar).

The larger CNG container with 10 kg of gas gives a maximum pressure of about 13 kPa in the zone of combustion, i.e. in the vicinity of buses. Outside this zone, the pressure decreases to 8-10 kPa with an impulse of about 250 ms and is constant throughout the underground terminal's environment.

There are currently no research and data from conducted trials on vehicle gas leakage and ignition of gas clouds, which leads to uncertainties about the size of the gas cloud. Calculations and assessment shows that combustible mix that can lead to explosion cannot be ruled out. Further, in calculations, conservative assumptions have been made regarding the combustible amount of gas that may participate in an explosion based on the precautionary principle and the lack of input.

5.10 Example Jet-Flame Consequence

Given that an ignition takes place is considered to happen in two different ways, delayed or directly. In the more common occurring scenarios fire starts in some parts of the bus and then spread to the fuel tanks. The pressure vessel explosion is affected and a jet-flame occurs, the pressure vessel explosion has low probability to fail. In the scenarios, if this is not the scenario, an explosion can occur when the gas bottle explodes. This, however, after relatively late into the scenario, which means that commuters have had time to evacuate.

The initial length of the jet flame length has been calculated to range from 10 to 12 meters. After approximately 2 minutes, the jet flame length has been reduced to about 7.5 meters and then continues to decrease as pressure drops.

The flames from natural gas do not become optically thick (the emission factor becomes significantly less than 1, which results in the radiation transfer to the environment being less than for heavier hydrocarbons. This is reflected in the fraction of power output emitting natural gas flares, F, being less than for heavier hydrocarbons. Radiation calculations have been performed with an emissivity of 0.2. The distance to the ignition level at which the radiation intensity of a flame will be able to ignite materials such as wood, plastic or rubber (12.5 kW / m^2 for about 10 minutes) is initially only a few meters around the flame (2-4 meters).

The distance to the level when the radiation intensity from a flame may affect people critically (risk of second degree burns has been afflicted to 4 kW/m^2) is initially up to 18 meters (after 2 minutes up to approximately 10 meters).

A major prerequisite for limiting the consequences of the jet flame is that the pressure release device is facing upwards, which causes the jet flame to hit the ceiling and the radiation levels around the flame evolve as described above. In the above scenario, the bus is already on fire, which means that there are already high radiation levels around the bus.

6. The Safety Concept

The preliminary safety concept of the bus terminal is a prerequisite for this analysis (Nygren & Östlund, 2016). The preliminary safety concept is a description of the safety measures that the facility is assumed to be equipped with as a starting point based on a qualitative risk analysis. The safety concept is based on robustness and have a holistic perspective in which different types of risk mitigation measures, but might need to be complemented after the quantitative risk evaluation.

The bus terminal is designed with the following safety measures, see Figure 9:

1. The evacuation of the facility is designed to ensure satisfactory evacuation. This is based on sufficient capacity in evacuation routes, evacuation routes location, etc.
2. The facility is equipped with fire ventilation, which is automatically started by the automatic fire alarm, but can also be controlled by the emergency service from the fire alarm control unit and by the management function.
3. The entire facility is equipped with automatic extinguishing system. The bus carriageway is equipped with a fixed firefighting system called deluge system with high water flow. A deluge system means that the entire or several sections of sprinkler heads are activated upon detection.
4. The structural system in the bus carriageway area is designed in accordance with the regulations for tunnels. Carrying construction, frame completions and separations, i.e. lightweight construction in the bus carriageway is dimensioned to cope with increased pressure build-up due to a delayed ignition of a vehicle gas. Design value for pressure is calculated in this analysis.
5. The facility is divided into different fire cells to ensure the satisfactory evacuation and to limit the consequences of a possible fire. When dimensioning of the fire separations between bus carriageway and waiting halls, particular consideration is given to the origin of jet flame in buses with vehicle gases and emission of vehicle gases. The bus terminal is equipped with indoor fire hydrants and fire hydrant risers.
6. The facility is provided by a safety management function. The management function has the task of monitoring and controlling the functions in case of fire or other undesired events of the facility. The management function is able to manually control various functions in the bus terminal.
7. The ventilation system in the bus carriageway, as well as the installation vault / roof of the bus carriageway and entrance tunnel are designed with the EX classifications (ATEX).
8. Evacuation routes are provided with systems for pressurizing the compartments in order to prevent spreading of fire gases in to the area.

9. The entire facility is equipped with an automatic fire alarm with full monitoring. Bus carriageway including entrance tunnel is equipped with two different types of fire detection system and a system for detecting vehicle gases.
10. The whole facility is equipped with an evacuation alarm with spoken announcements.
11. The facility is equipped with traffic control systems.
12. The facility is equipped with CCTV.
13. The entire plant is equipped with emergency power and UPS to manage redundancy on safety technology systems and to be self-sufficient. The emergency power lasts 24 hours.
14. The safety valves should be oriented vertically to avoid the risk of extensive fire spread and domino effects.

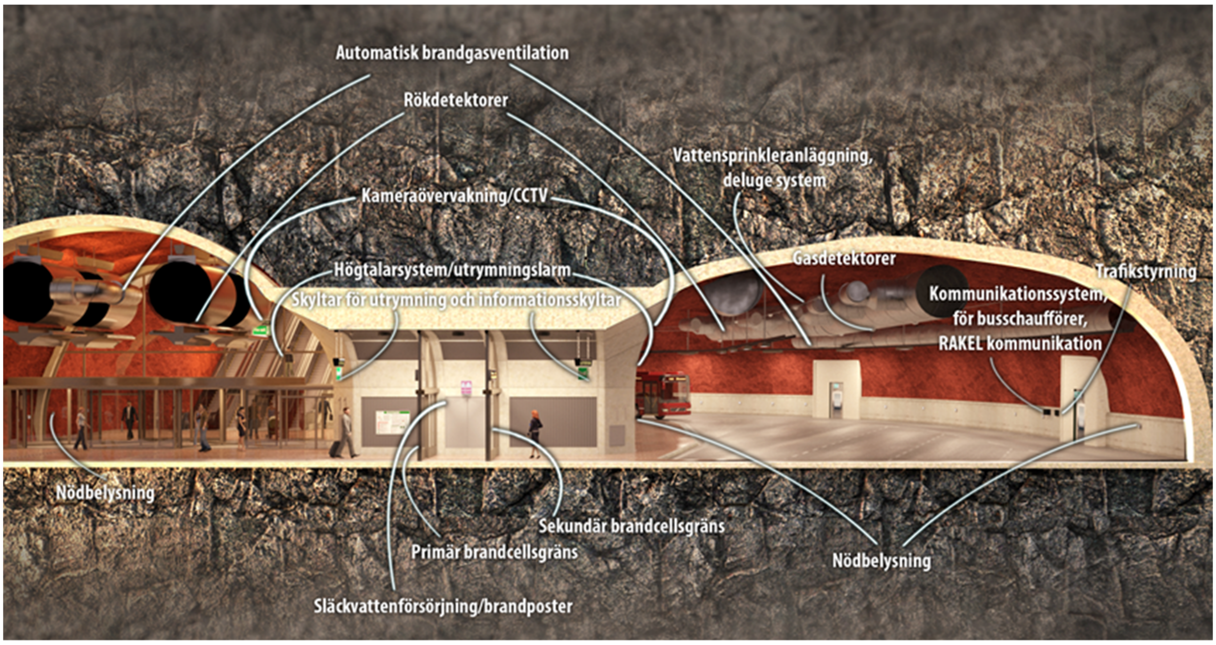

Figure 9. Parts of the safety concept of the bus terminal.

7. Uncertainty Analysis

The uncertainties in this quantitative risk analysis have been analyzed and attributed to two fundamental categories; stochastic uncertainties (non-reducible) or knowledge-based uncertainties (reducible). Both categories are represented in this analysis. The following classification of uncertainties is more useful in practice:

- Model uncertainties.
- Completeness uncertainties.
- Parameter uncertainties.

The three classifications are reviewed, motivated and described for the analysis. When considering the results and presenting the conclusions, it should be taken into account that quantitative risk analyzes are to a large extent based on assessments and rough estimates.

8. Calculated Risk Level

The calculated risk for the facility is presented in the form of societal risk with F/N curve (F = frequency, N = number of fatalities).

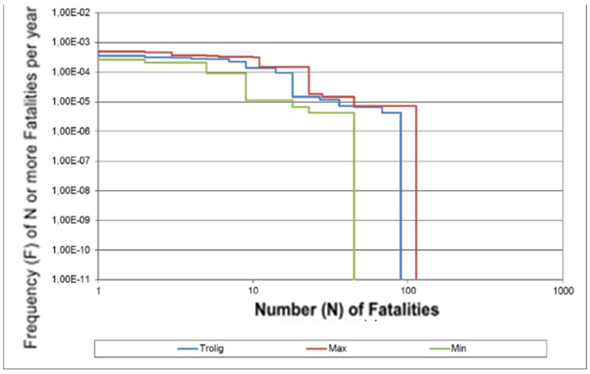

Figure 10. The societal risk, F/N-curve. Please note that it refers only to accidents with gas-powered buses.

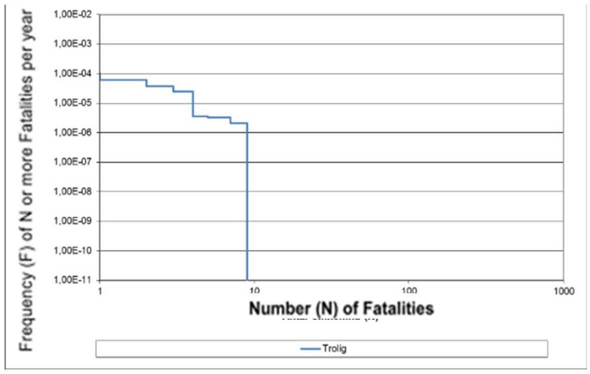

Figure 11. The additional risk contribution from accidents that are estimated to occur only because the facility is located underground.

The presented risk level for the bus terminal for gas-powered buses, includes accident risks within a wide range of accidents with varying degrees of severity where some have potentially major consequences see Figure 10.

These consequences are largely due to the consequences that are created momentarily when parts of the fuel system's components for various reasons fails/malfunction, e.g. so-called pressurized vessel explosion. The severity of the consequences is not due entirely to the fact that the facility is underground. Corresponding accidents can also occur in the facilities above ground and outdoors, and have substantial consequences.

Figure 10 shows the risk contribution from the consequences that are estimated to occur only because the facility is located underground, i.e. this can be seen as a comparison to a bus terminal on the ground (Figure 11). Note that no risk analysis has been conducted for a bus terminal on the ground, so the comparison is just a rough estimation. It can be seen from the figure that mainly scenarios with fewer number of affected persons that can be related to the terminal being placed underground.

9. Sensitivity Analysis

The analysis shows clearly that uncertainties regarding the expected number of technical failures on the fuel systems of vehicle gas-powered buses, make a significant contribution to the societal risk, while the uncertainty in other parameters is estimated to have a relatively low impact on the results. The reason that technical failures that lead to gas emissions affect the result greatly, is that this type of accidents does not give people a warning, but results in an explosion or a jet flame instantaneously.

The parameters that have been identified as relevant for the sensitivity analysis and give the greatest impact on the results are presented below.

Frequency of failures on cylinders, according to Committee for the prevention of disasters (1992) pressure vessels have a defect rate of 5.0E-07 per bottle per year. This gives the current facility a probability regarding the part of equipment that is affected with respect to bottles of 0.1%. This parameter significantly affects the results. This is illustrated in Figure 12 and Figure 13 below where the frequency of 30 or more deaths is one-tenth lower if the likelihood of pressurized vessel explosion is 0.01% instead of 0.1%.

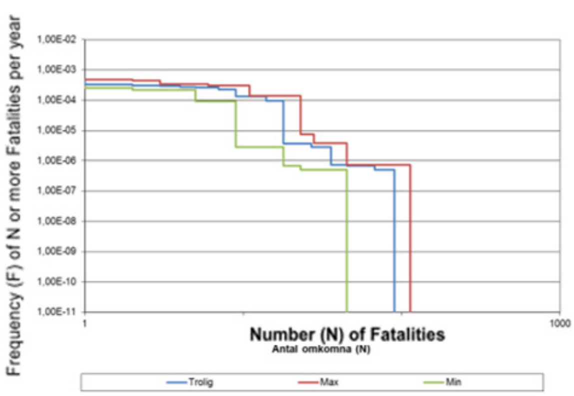

Figure 12. The societal risk with 0,01 % likelihood for pressurized vessel explosion.

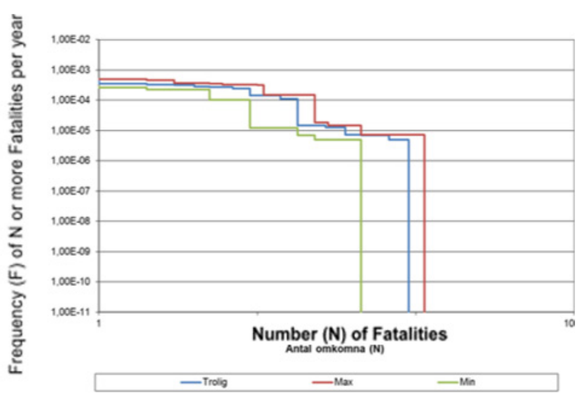

Figure 13. The societal risk with 0,1 % likelihood for pressurized vessel explosion.

The number of vehicles powered by gas in the operation phase is assumed to be 100% in these analyses.

10. Examples of Further Challenges

10.1 Separating Walls

Protecting people in the waiting hall and meeting architectural requirements at the same time has been a challenge. There is a desire to have transparency between bus carriageway and waiting hall. The bus terminal architecture should be more like an airport architecture, which places high demands on how technical solutions are designed. In order to meet the requirements, special solutions have been needed to resolve the requirements for separations to handle fire and pressure build-up and to solve evacuations between the areas. A dividing glass wall that have fire resistance cannot be designed durable against dynamic pressure. This has resulted in constructing two different separations. The designed pressure against the separating walls between the bus carriageway and the waiting hall is dimensioned for an explosion that makes a pressure of 10 kPa with an impulse of 250 ms. The fire separations walls is designed to EI90. It was also necessary to install two doors in order to make evacuation between the two areas possible in some places. One door is intended for evacuation in one direction and the other one for the opposite direction. The doors used for everyday use will also consist of sliding doors whereupon the complexity of control is increased etc.

10.2 Direction of Safety Valves on the Buses' Fuel System

The conducted risk analysis shows that a side-facing (horizontal) safety valve will create a jet flame that result in high risks of fire spread between buses and fire compartments. This even if the deluge sprinkler system is also activated. Since the jet flame probably occurs after evacuation has been completed, consequences apply mainly to the facility but can also affect the safety for evacuating people. Large domino effects in the form of rapid fire spread between buses as well as a fire that is not expected to be managed by the rescue service, threaten the bus terminal. However, it can be difficult to ensure that all buses that operate in the facility in the future will have an upward safety valve, this makes a major challenge for the operator of the bus terminal.

11. Conclusions

The challenge to evaluate risk in a bus terminal where buses are gas-powered is substantial but possible. The risk analysis shows that buses that are gas-powered contribute to high level of risk and different types of risk mitigation systems are necessary. The uncertainties in the area, with a bus terminal underground, are large but can be managed, by adding different risk mitigation measures and make a robust safety concept. The sensitivity and uncertainty analysis shows that the safety concept that are introduced is robust and gives the bus terminal good possibilities to handle accidents with gas-powered buses.

The selected methodology with fault- and event tree gives a good overview over the risk analysis and where different risk mitigation measures are needed. Event tree methodology is a tool to systematically develop and illustrate an accident possible course depending on what barriers and conditions there are and how they work. These barriers may consist of both technical and administrative measures. Fixed firefighting system, smoke control system, well placed escape routes are examples of protective barriers.

The systems and the restriction are showing a significant reduction of the risk level in bus terminal. The analysis also shows that huge demands are set on the mitigation systems that are deployed. Among other things, this need creates customized systems and detailed designs and tests of them. This applies, for example, to separations that will handle dynamic pressures and directions of safety valves etc.

In complex projects of this type, it is necessary to take a holistic approach to the safety of the object and find a robust solution based on several risk mitigation systems and safety barriers. With the method used by WSP in the current project, this is achieved in a transparent way which is a key issue to resolve the current project risk that sustainable development can introduce in infrastructure projects.

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