# The Cost-effectiveness of a steel tube or a buffer zone for mitigating blast effects on a building spanning an underpass with transport of LPG

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**Abstract:** The use of space is being intensified near and above transport routes of hazardous materials. In The Netherlands, some buildings are even realized above infrastructure with transport of hazardous materials like LPG. An accident with an LPG-tank may result in a BLEVE, causing injuries and large structural damage to the spanning building and the vicinity. Fortunately, such disasters are scarce up to now. However, one should be aware of that such accidents may occur and escalation from accident to disaster should be prevented. On one hand, this paper presents the modelling and the analysis of the explosion effects and the dynamic response of the structural elements. On the other, an analysis of structural measures to control the consequences for the spanning building when the explosion occurs in the underpass is given: two mitigating measures to minimize the effects of a gas explosion or a BLEVE are analyzed, i.e. a steel tube for packing the infrastructure in which the LPG is transported or a buffer zone by adding two extra stories to the building, in which the first two lower floors are designed to be severely damaged under explosive loading forming a buffer zone between the infrastructure and the building above. Subsequently, the cost-effectiveness of these safety measures is determined.

**Keywords:** Explosion effects, BLEVE, transport of hazardous materials, multiple use of space, structural dynamics.

## 1. INTRODUCTION

As a consequence of an ever-growing population, land is becoming scarcer, especially in urban areas. This has led to the development of design and construction techniques that make intensive and multiple use of the limited space possible. In the last decade, the space available above transport infrastructure - such as roads and railway tracks - and existing buildings has been exploited at a growing rate in city centres. Because the use of space is being intensified near and above locations with potentially dangerous activities (e.g. transport routes of hazardous materials), any accident may have serious consequences. Focussing on the local project scale, it can be stated that projects using land in multiple ways (realizing buildings above infrastructure) are generally complex. The safety considerations in multiple land-use projects should not be underestimated. Usually, a large number of people and several multiple risk interactions are involved. Due to the complexity and interrelationships of such a project, a small accident, like a fire in the building or in the covered infrastructure, can easily lead to a major disaster. In The Netherlands, some of these buildings are even realized above infrastructure with transport of hazardous materials where LPG (Liquefied Petroleum Gas) is transported (see Figure 1). An accident with a LPG-tank may result in a BLEVE (Boiling Liquid Expanding Vapour Explosion), causing injuries and large structural damage to the spanning building and the vicinity. Fortunately, such disasters hardly occurred in such circumstances. However, one should be aware of that such accidents may occur and potential consequences should be minimised. Generally, one may expect that realizing buildings above infrastructure along with the transport of hazardous materials will both increase in the future. However to quantify the consequences and risks, there is little background literature that addresses this type of problem, i.e. structural control of explosion effects on a building spanning an underpass at which the explosion occurs. Suddle [1] assessed risks quantitatively in order to determine physical safety in multiple use of space projects, including the analysis of structural safety measures to buildings above the infrastructure.

Van den Berg et al. [2] derived guidelines to assess the blast loading and response of a tunnel structure due to a gas explosion. The blast load is given as a function of the length of the gas cloud and the distance from the point of ignition. Recently, Van den Berg et al. [3] developed also a method to quantify the blast load from BLEVE accidents. Information on these methods is given in Section 2. Neither Suddle [1] nor Van den Berg et al. [2] provide specific analyses for structural control of explosion effects of buildings above infrastructure with transport of LPG. This has been the starting point of the research by Van Diermen [4]. Van Diermen [4] analysed some possibilities for the building structure above the infrastructure with the transport of LPG. His work has been extended and updated in the current study.

**Figure 1** An impression of the motorway A10 West, Bos en Lommer Office buildings with transport of hazardous materials (LPG).

This paper gives an introduction analysis of possibilities of how to deal with structural control of explosion effects when realizing buildings spanning roads with transport of hazardous materials. In this regard, some types of the main bearing structure of the building above the infrastructure were inventoried, the explosion effect blast was modelled and the dynamic response of the structural elements and the main bearing structure of the building were analyzed using engineering techniques. Also a case study (see chapter 4) was described to illustrate the analysis methodology and the applied models. Recommendations to limit and control the damage are given.

## 2. EXPLOSION HAZARDS CAUSED BY LPG TRANSPORT

### 2.1 Introduction of main hazards due to accident with hazardous materials

The hazard scenarios that may occur on the infrastructure with transport of hazardous materials are collisions, fires, explosions, and leaks of toxic substances (consecutively decreasing in probability of occurrence and increasing in consequences; see Table 1).

**Table 1: Frequency and consequences of hazard scenarios in multiple land-use projects with covered infrastructure [5]**

| | Consequences | | | |
|---|---|---|---|---|
| **Frequency** | Low | Medium | High | Extremely high |
| Extremely high | Local traffic accidents and small fires | | | |
| High | | Fires on the infrastructure | | |
| Medium | | | Explosions | |
| Low | | | | Release of toxic gasses |

These accidents can also be the starting points of others. A fire for instance can cause an explosion and vice versa. The release of toxic gasses hardly initiates other events, but a BLEVE with reactive gas may also lead to a gas-explosion. In this paper we constrain ourselves to the explosion hazard caused by the transport of LPG. Unfortunately quantitative risk analyses are not possible yet for the confined tunnel conditions because probability data on explosion and accidents in tunnels are not available.

### 2.2 Possible explosion scenarios originating from LPG transport

LPG is a highly flammable liquefied gas mixture that is transported by road in 50 $m^3$ tankers. The boiling temperature of LPG under ambient pressure is 231 K. LPG is a highly flammable liquefied gas mixture that is transported by road in 50 $m^3$ tankers. The boiling temperature of LPG under ambient pressure is 231 K. To keep LPG liquid under ambient temperatures it is stored and transported under pressure, i.e. the vapour pressure of the liquid at ambient temperatures. The vapour pressure is highly dependent on the LPG temperature. It rises from 730 kPa at 288 K up to 1000 kPa at 300 K and up to 1800 kPa at 326 K. In today's heavy traffic, an LPG tanker may well get involved in a crash by which it may get leak. When the subsequent LPG spill is not immediately ignited, it will develop a flammable vapour cloud downwind. Such a flammable vapour cloud may - dependent on the leak size and atmospheric conditions - extend up to a substantial distance from the leak. If an LPG tanker crashes in the vicinity of the building, the flammable cloud may fill the entire space underneath the building. Ignition of the flammable cloud will result in a flash fire without pressure effects as long as it develops in the open. The flash fire will however, consume the entire flammable part of the cloud and may meet appropriate boundary conditions to develop a gas explosion in the partially confined space underneath the building.

Another conceivable scenario is that a tanker develops a leak of limited size, which is immediately ignited on the impact. The tanker gets engulfed in a fire. Together with the liquid temperature the internal tank pressure starts rising. At the same time the tank wall looses strength, in particular at locations above the liquid level where the heat transfer from tank wall to tank contents is relatively poor. This may finally lead to a catastrophic failure of the tank that, in particular when the liquid in the tank has been heated up to a temperature that allows an explosive evaporation process, may produce a substantial blast effect. In such an event a large portion of the liquid LPG is quickly converted into vapour, which takes approximately 250 times the volume of the original liquid. It may be true that the probability that such a Boiling Liquid Expanding Vapour Explosion (BLEVE) takes place just underneath the building is very low but the power of such a massive explosive evaporation process may well endanger the building's structural integrity.

### 2.3 Modelling of a gas explosion in a tunnel

Gas explosion is a complex process. CFD models are used to capture all phenomena of the process (under development). There are simplified engineering models developed [2], which are used in this study. The pressure loading of a tunnel structure due to a gas explosion has been numerically approximated by the one-dimensional gas dynamics of a column of perfect gas. The gas dynamics is driven by an energy source, a flame whose velocity development is prescribed according to experimental data [2]. The length of the partially confined space underneath the case study building is 30 m long, which is equal to no more than 6 times the vertical ”tunnel height”. Application of the one-dimensional numerical model, provided with the proper input for flame speed development, shows that a gas explosion in a tunnel tube of that length containing a traffic jam of standing vehicles will develop an overpressure underneath the building that will not affect the structure. Damage to building is unlikely

### 2.4 Modelling of a BLEVE

An explosive evaporation process is accompanied by the development of a large volume that violently pushes the surrounding atmosphere aside. For the time being, a safe and conservative approach in the modelling of blast is appropriate.

Such an approach consists in the simple assumptions that the vessel instantaneously disintegrates and that intrinsically the evaporation of superheated liquid could occur infinitely fast. Then, the evaporation rate is fully determined by the gas dynamics (inertia) of the developing mass of vapour in interaction with the surrounding mass of air. The evaporation rate is now fully determined by the rate at which the developing vapour can expand by pushing the surrounding air aside. This safe and conservative assumption of expansion-controlled evaporation constitutes the starting point for the computation of the gas dynamics induced by the evaporation process [3]. This concept can be framed in a numerical mesh of any geometry. The gas dynamics has been computed by a time stepwise integration of the Euler equations that are the conservation equations for mass, momentum and energy for inviscid compressible flow [5].

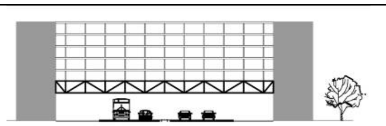
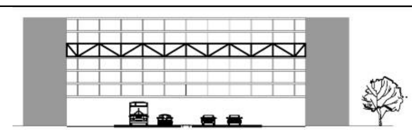
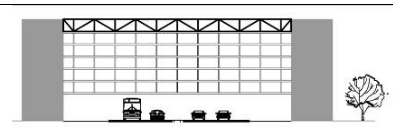
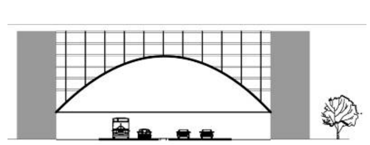
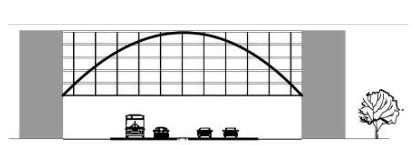
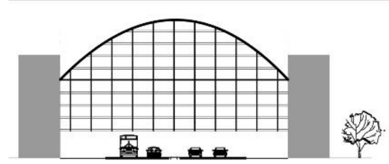
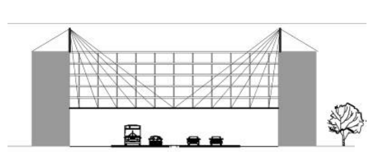
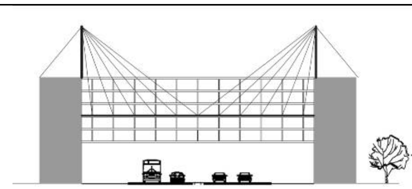
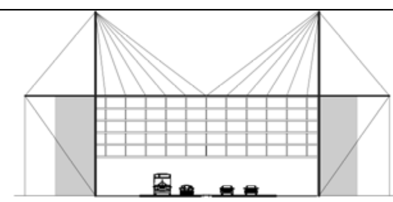
## 3. THE BEARING STRUCTURE FOR BUILDING ABOVE INFRASTRUCTURE

The type of main bearing systems for buildings that cover highways have been inventoried and categorized. In the categorization the bearing structure is considered as an element of the structural safety measures to control explosion effects. The results are summarized in this section. For the current study the span of the structure is defined based on a two times two-lane-road, which resulted in a chosen reference span of 36 meter. Four types of span-structures are considered. In combination with the position of the span-structure in the building, ten types of structural design are distinguished; see Table 2 and 3. The structures are made of concrete and or steel.

**Table 2 Ten types of span structures.**

| Span structure | | Position | | |
|---|---|---|---|---|
| | | under | middle | top |
| Type | Column – beam | Type I | | |
| | Framework beam | Type II A | Type II B | Type II C |
| | Bow structure | Type III A | Type III B | Type III C |
| | Stay structure | Type IV A | Type IV B | Type IV C |

**Table 3 Schemes of span structures**

| Type | A | B | C |
|---|---|---|---|
| I |  | | |
| II |  |  |  |
| III |  |  |  |
| IV |  |  |  |

Comments to the bearing systems:
In this study the function of the bearing systems is to transfer the load of all floors to the towers beside the road.
Type II: The height of the beam-structure is set arbitrarily to the height of one level;
Type III: The structure consists of a pressure bow and tension rod.
Type IV: The tie rods are only designed to carry tensile forces. Consequently, the ties are not suited to resist the load of an explosion under the structure.

## 4. CASE STUDY

The aim of the case study is the assessment of the damage level. By doing so, the critical elements of the structure can be determined. Subsequently the possible countermeasures can be defined. These measures are of course the input for the cost effectiveness assessment.

Structure type II has been selected to study the explosion effects and the structural response quantitatively to illustrate the phenomena and failure mechanisms that have to be covered. The selected building is depicted in Figure 2. The properties of the structural elements are given in [4]. This section on the case study is structured as follows. First the blast load of a representative gas explosion and a BLEVE are given. Next the effect on the building and the structural elements will be described qualitatively, supported with quantitative response data.

### 4.1 Loading of the building

*BLEVE*
To compute the loading of the building by a BLEVE of LPG of 326 K, a tank of $\varnothing 2.5\times 10$ $m^2$ was positioned in the centre of the space underneath the building. This location enables to limit the size of the numerical mesh by two planes of symmetry (figure 2). The building and the LPG vapour source have been configured in a mesh of 120×200×150 cells of 0.2×0.2×0.2 $m^3$. Overpressure and impulse-time developments have been calculated at various target points at the ceiling in both lengthwise and lateral direction of the structure as well as at the facade.

The pressure-time records show a range of load levels (100 – 1700 kPa) and load profiles due to the reflections and rarefaction of the BLEVE blast wave. To simplify the problem and estimate the effect on the building quantitatively, we only consider the first part i.e. the expanding BLEVE blast wave. The load is schematized to triangular pulses and a positive phase duration based on the calculated impulse values. The blast load on the floor level will definitely result in structural damage, while window breakage will occur at the façade and the elevator core at ground level will be damaged.

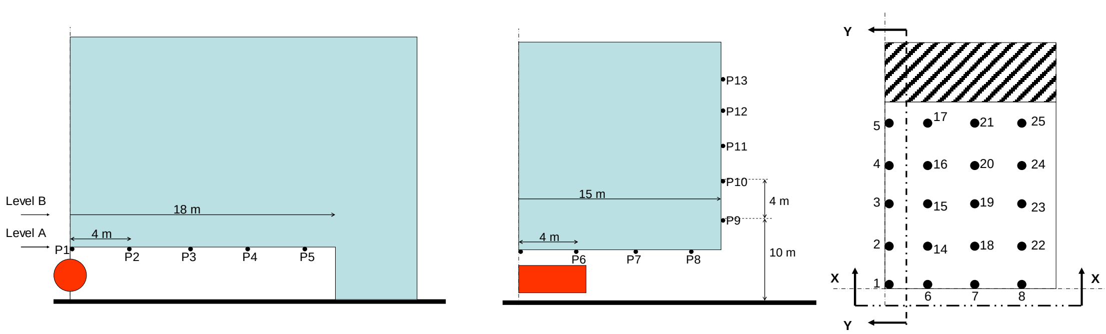



Figure 2: The geometric model of the building in two vertical cross-sections (X-X), (Y-Y) and the horizontal section at level A with target points.

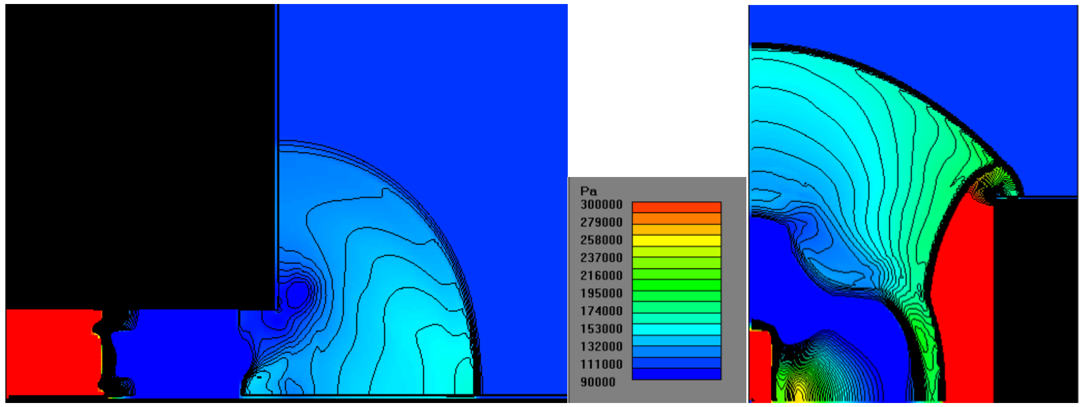



Figure 3: Snapshot of pressure distribution produced by the burst of the LPG-vessel underneath the building.

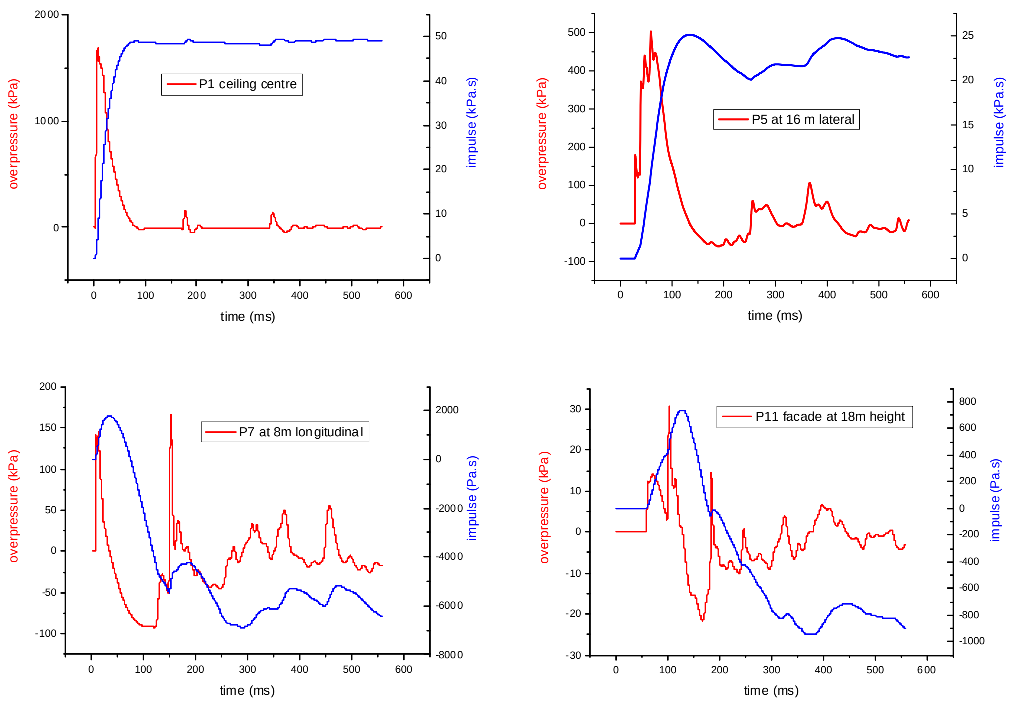



Figure 4: Predicted BLEVE blast loading on building positions 1, 5, 7 and 11.

## 4.2 Qualitative description of structure response

The blast load as predicted in the previous section ranges from overwhelming the structural strength (position 1) to window pane failure (double glass, strength in the order of 10 kPa). To illustrate the analysis procedure, building types 2a and 2c (see Table 3) are selected. The bearing system of the building consists of the primary and the secondary system as depicted in Figure 7. The secondary system consists of (i) columns, (ii) beams and (iii) floor panels. The six levels have a system height of 3.5 m, while the column grid is 3.5 x 10 meters. The primary bearing system consists of 4 beams at an intermediate distance of 10 meters. The elements, i.e. floor panels, beams, columns and primary beam structure were designed by Van Diermen [4] using Dutch guidelines, static floor load of 6 $kN/m^2$ and floor weight of 3 $kN/m^2$.

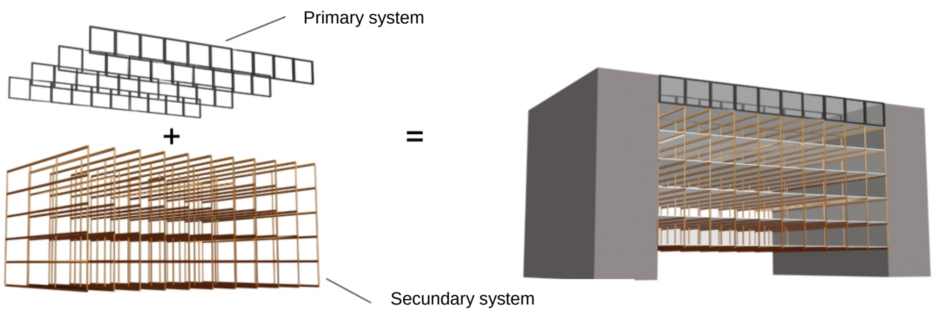



Figure 5: Primary and secondary bearing system

The upwardly directed blast will load the structure and can cause damage after the vertically directed gravity loads are compensated and exceeded. The effect of primary fragments and also thermal damage due to fire are not considered in the current study. The focus is on blast damage. The loading and response sequence due to blast loading is as follows (e.g. building type II C):

- The panels of the lower floor (level A, see Figure 2) are loaded by the blast (100 – 1700 kPa) and transfer the load to the supporting beams. When the panels fail during the loading phase of the explosion, only a part of the loading is transferred to the beams. Furthermore, the blast will penetrate the building and load the second floor (level B) and the internal walls. The load and response and failure sequence has to be analysed as a function in time.
- The beams are supported by the columns. Therefore, the load transfer sequence from panel to beam, to column to principle bearing system has to be determined.
- The location of the main span structure governs the initial element loading conditions during service life time and consequently the effect of the accidental explosion load.

### 4.3 Summary quantitative results on damage analysis

All steps mentioned in section 4.2 were analyzed quantitatively. It is evident that due to the extremely high blast load parts of the building will fail. From the chain of load transfer it emerges that the load on the last element, the primary bearing structure, will increase with increasing strength of the previous links, i.e. the columns, supporting beams and floor panels. To prevent building collapse, or partial failure, one of the preceding links has to be sacrificed. The damage to the building can be controlled by the strength and failure time of the elements in the load transfer chain.

The reference building was only designed for static loading (floors: design load 6 kPa; weight load 3 kPa). The blast loading on the panels at level A, leads to shear or bending failure. Because of the short rise time and high amplitude of the load, the dynamic resistance of the panels is exceeded at a very early stage. The load transfer to the supports is limited and the load impulse is transferred to kinetic energy of the panels. The panels are launched into the first building level and the remaining blast load can partly enter the first level also. The tables in Figure 6 give the load distribution on the floors at level A and B, the colours indicate the shear or bending failure mode. Bending failure occurs at a later stage of the response and consequently will result in lower blast pressures on the next floor level. The threshold for bending failure of the floor panels is about 150 kPa.

| target points floor A | 5 | 17 | 21 | 25 |
|---|---|---|---|---|
| 5 | 500 | 462 | 300 | 233 |
| 4 | 208 | 172 | 131 | 159 |
| 3 | 220 | 162 | 113 | 95 |
| 2 | 350 | 225 | 112 | 88 |
| 1 | 1700 | 1352 | 143 | 100 |
| | 1 | 6 | 7 | 8 |

| target points floor B | 5-L2 | 17-L2 | 21-L2 | 25-L2 |
|---|---|---|---|---|
| 5-L2 | 250 | 230 | 200 | 100 |
| 4-L2 | 250 | 230 | 140 | 50 |
| 3-L2 | 335 | 165 | 41 | 50 |
| 2-L2 | 335 | 165 | 83 | 41 |
| 1-L2 | 667 | 330 | 83 | 83 |
| | 1-L2 | 6-L2 | 7-L2 | 8-L2 |

Figure 6: Load distribution and failure mode of floor panels at level A (left) and level B (right). Location tank at target points 1-6. The target points correspond with figure 4. The peak load is given in kPa; red and blue indicate shear and bending failure resp.

For the building, designed for static loading conditions, the BLEVE accident will lead to complete failure of floor level A and a considerable part of level B. The windows at all levels will fail and will be blown into the building. The additional dynamic loading on the secondary and primary bearing system is very limited and the system will definitely survive. Evidently, the consequences of such a BLEVE accident are not acceptable from safety point of view. Three obvious countermeasures are (i) design the windows for 15 kPa, (ii) the lower level should not be used for offices but storage and supporting facilities with a low population density and (iii) a balanced design of the system at level A so that failure occurs at a later stage and level B does not fail and the dynamic resistance capacity of the bearing system (level A) is used.

## 5. THE COST EFFECTIVENESS OF SAFETY MEASURES

### 5.1 Introduction

The cost-effectiveness analysis is the basis for decisions and defining measures. This issue implies that not the entire spectrum of safety measures can be taken from an economic perspective. In this regard it is interesting to investigate the cost-effectiveness of safety measures, in which the investments of safety measures are compared with their risk reducing effect. In this paper we will provide basic insight to this matter by conducting a very global countermeasure calculation. In this paper however we will focus merely on the human risks. This means that the number of people killed, will be considered in the cost-effectiveness analysis. Other aspects which could be a part of the decision-making process, such as economical, financial or social aspects, are beyond the scope of this paper.

As presented in the previous chapters, without countermeasures, a BLEVE or a gas explosion occurring in the covered infrastructure may cause demolition or severe damage of the building above. The design of countermeasures depends on the considered explosion type and –strength, and thus the load on the structure. Nonetheless, one may consider structural countermeasures that reduce the effects of an explosion towards the building above. To illustrate the cost-effectiveness procedure, we present the analysis of two optional countermeasures.

The first option is adding two extra stories to the building, in which the first two lower floors are designed to be severely damaged under explosive loading forming a buffer zone between the infrastructure and the building above. These first two lower floors shouldn't be used as office rooms or for vital functions but as an area with a low population density, such as a parking garage or storage. Applying such a measure enables a low people exposed to the risk of the explosion.

The second - a more progressive - option to prevent damage to the building above is to implement an *explosion resistant structures* to shield the building above. An example of a simple explosion resistant structures is implementing a steel tube. Other examples can be found in the research about ”optimal control of adaptive building structures under blast loading” done by Saleh & Adeli, (1998). The protective sub-structure may be heavily damaged, which is acceptable when it can be easily repaired or substituted and still protecting the building above and the infrastructure.

In the following sections of this paper, a very global cost-effectiveness analysis of both type of countermeasures is determined.

### 5.2 Explosion resistant tube

A straight forward protective measure is packing the infrastructure by adding a steel tube that can resist the explosive load. A steel tube with a diameter of e.g. 7.0 m (see figure 7) will allow a profile of free space for a single traffic track in that tube, which should be only used for transport of hazardous materials. If a double traffic track in that tube is desired, then the diameter of 12.8 m is required. The effect of such a tunnel is very large, because the effects of an explosion will merely be enclosed in the tunnel. The following practical aspects should be carefully considered. First, the large thickness of the tunnel-tube, which may be difficult to realize, depending of course on both the diameter and the occurring scenario in the tunnel. Secondly, the residual shock waves at both ends of the tube should be analysed. Thirdly, the tube may cause problems if the tube can not be integrated in the urban design of the area in question. A possible solution to the last two problems could be a longer tube than exactly the covering length of the infrastructure.

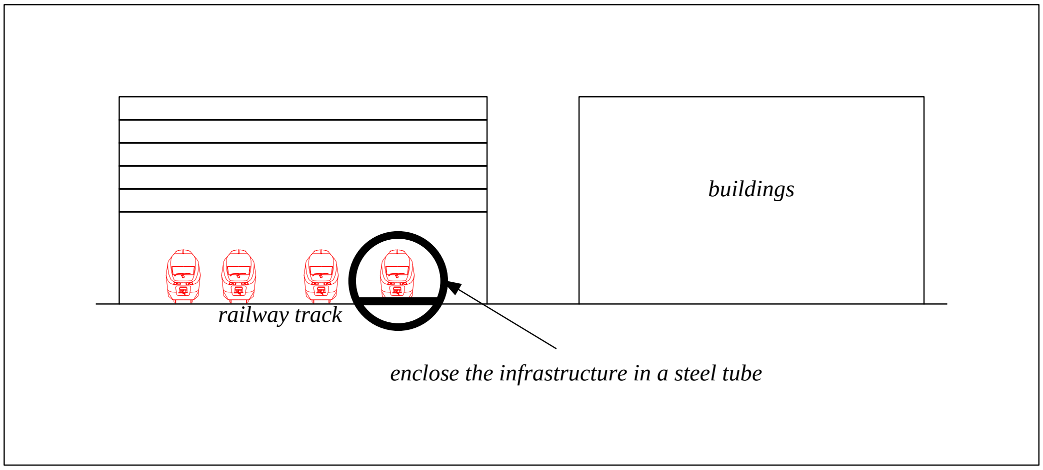


Figure 7: Enclosing the infrastructure in a steel tube.

In order to determine the thickness of the tunnel-tube, some basic calculations have been made using [7,8,9]. Full calculations could be found in [10]. It appeared that the thickness of the tunnel-tube is approximately 20 mm (diameter of 7.0 m) and 36 mm (diameter of 12.8 m) for a gas explosion with a cloud length of 100 m and a peak overpressure of $10^3$ kPa (≅ 10 bar) as mentioned by Berg *et al*. [2], which is also in the range of maximum pressure of the BLEVE incident. If the detonation scenario is considered, the thickness of the tube will increase to 39 mm (diameter of 7.0 m) and 71 mm (diameter of 12.0 m).

It also appeared that, given the peak overpressure of e.g. $10^3$ kPa (≅ 10 bar), the dynamic effects of such a structure leads to a quasi-static design approach, because the ratio of the duration of the load and the response time of the structure ($T_L/T_N$) is large. Therefore, the design of that structure is based on a quasi-static approach including a DLF (Dynamic Load Factor) of 2, which has been discussed by both [7,8]. Furthermore, accepting damage and large deformations of the protective tube, an assumption has been made in the calculation that the steel will deform plastically. As a consequence, welding the profile of the tunnel should be carefully considered [11].

The prise of steel is normally about € 4 / kg, including realising costs [12]. It is assumed that these cost increases by a factor 2, in case of a large thickness of the tube. So, the prise of steel is approximately € 10 / kg. From this, the total costs of the steel tunnel can be estimated, which are $10 \cdot \pi \cdot 0.020 \cdot 7 \cdot 7{,}800 \cdot 10^3$ = € 34,306,000 / km steel tube for single track to € 61,751,000 / km steel tube for double track transport. If the design is based on the detonation scenario, the costs will be much higher (see Table 5). The costs are remarkably high; they range in the order magnitude of a shield driven tunnel. In addition to this, if the traffic has to be lead in the tube, the costs of the realisation to lead the traffic in the tube by fly-overs and traffic junctions and interchanges should also be taken into account. If one needs to realise traffic junction on a different height level of the infrastructure on both ends, one has to make investments of € 75,000,000 / junction. Furthermore, this measure should not be implemented solely as well; additional fire resistant layer is required.

Table 4: Thickness and the investments of profiles by different peak overpressures.

| **Peak overpressure** | **Radius *r* = 7.0m** | | **Radius *r* = 12.0m** | |
|---|---|---|---|---|
| | **Thickness profile** | **Investments profile ($km^{-1}$)** | **Thickness profile** | **Investments profile ($km^{-1}$)** |
| $1 \cdot 10^3$ kPa (≅ 10 bar) | 20 mm | € 34,306,000 | 39 mm | € 66,900,000 |
| $2 \cdot 10^3$ kPa (≅ 20 bar) | 36 mm | € 61,751,000 | 71 mm | € 121,800,000 |

Considering the fact that the explosion is mostly enclosed into the tube, the probability that the building above or besides the infrastructure will collapse (or severely damaged) will be a factor 100 smaller. The risk is not reduced to zero, because of residual risks from heat radiation and external blast effects. It is clear that this measure is applicable for external safety variants, i.e. people present in the building above and adjacent the road infrastructure, but no protection is given to the buildings or people present at the ends of the covered infrastructure. From this point, both ends of the covered infrastructure should be carefully analysed because a gas explosion in the covered infrastructure may cause damage to the building above or near the ends as well, because there is a large concentration of shock waves at both ends. Therefore, the building above the tube should be designed to resist the blast load or it should be realised with a large setback, otherwise the shock waves may damage the building above after all (see figure 8). For the BLEVE accident it was shown that the damage to the side walls of the building is limited to window failure. It should be noted that the internal safety decreases in the tube, because it is covered and some consequences of scenarios are intensified in the covered infrastructure.

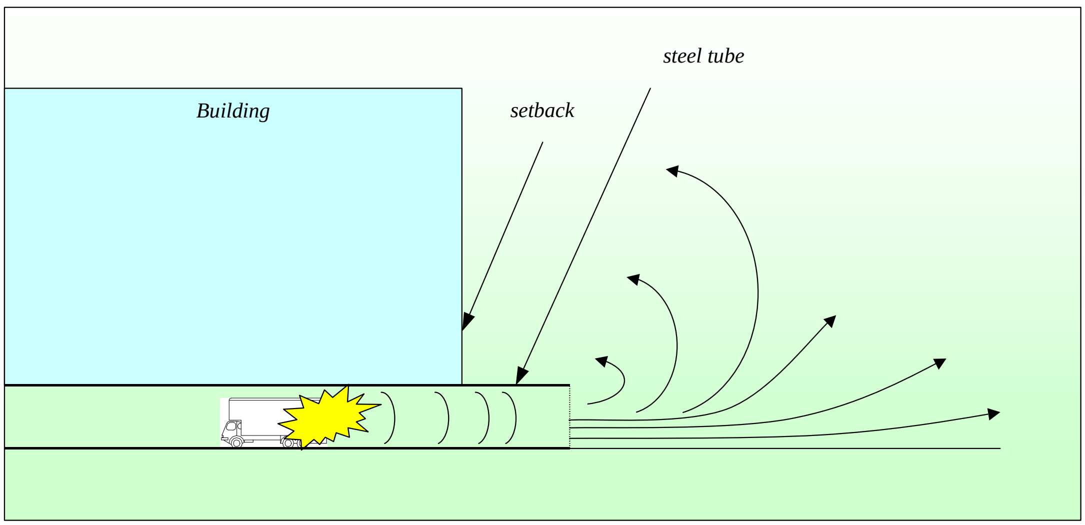


Figure 8: Damage may occur on both ends of a covered infrastructure.

In order to reduce the costs of such a measure, one may realise an explosion resistant covering of infrastructure of concrete in stead of steel, or a steel-concrete sandwich variant. These alternatives are not discussed in this paper.

### 5.3 Buffer zone

Another manner to minimise the effects of an explosion towards the building above may be realising part of the structure that, in case of an explosion accident, is accepted to fail and functions as a buffer for the rest of the building, see figure 9. The costs of two additional storeys is estimated at $1 \cdot 10^6$€.

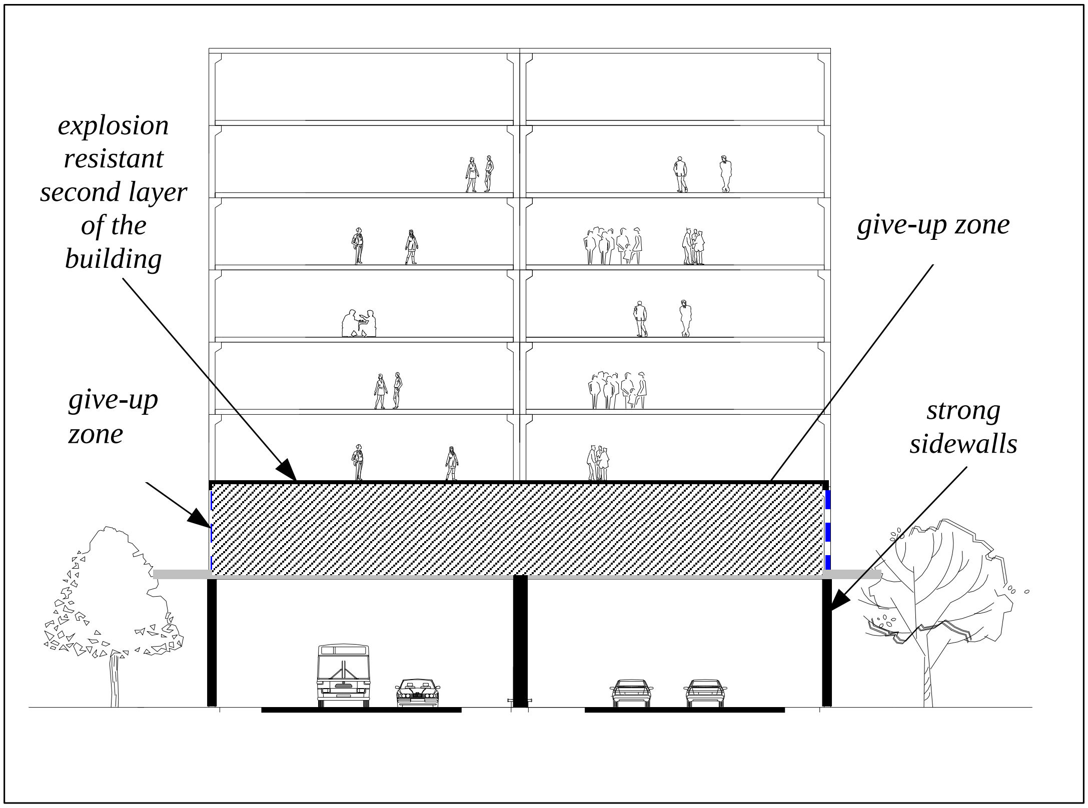



Figure 9: Illustration of the buffer zone concept to protect the building above.

### 5.4 Results of cost-effectiveness of safety measures

The purpose of this chapter is not to present an extensive cost-benefit analysis of the earlier presented safety measures, but to illustrate a brief introduction whether such large investments in safety measures are worth against their risk-reducing effect. It should be noticed that this section should not be considered as "the exact cost-effectiveness diagram" for all multiple use of space projects, but as indicator of cost-electiveness of safety measures, because the presented results belong to the specific case of this paper. For other cases, these results may differ entirely.
Now we follow the steps of the procedure presented in [1] to determine the cost-effectiveness of safety measures against blast effects. Input data for the QRA such as the basic probabilities of events that may occur on the infrastructure with transport of hazardous materials and the quantities of transport of hazardous materials were derived from [13]. The average population density in the vicinity can determined from [13]. Table 5 shows the input parameters for the QRA. It should be noticed that in this case only the probability of the BLEVE occurrence is considered, since the simplified sample provides the insight of complex decision-making process.

Table 5: Input parameters for the QRA.

| **Characteristics of the QRA** | | | **Reference** |
|---|---|---|---|
| $P_{fi}$ | Probability of a BLEVE occurrence for 5000 transports [$year^{-1}$] | $5000 \cdot 10^{-8} = 5 \cdot 10^{-5}$ | [13] |
| $P_{d\|fi}$ | Probability of a person being killed given a BLEVE occurs | 0.9 | [13] |
| $N_{pi}$ | Number of participants in the building (total of 6 stories) | 432 | Assumption |

Using the input of table 5 and formula 1 (step 1 of figure 15), the $E(N_d)_0$ - the number of killed people in the initial situation - can easily be derived. Without taking measures the expected number of people killed $E(N_d)_0$ in such a situation is $10^{-5}$. We now consider the risk reducing effect of the two earlier proposed safety measures. We assume the risk reducing factors λj 0.01 and 0.5 for the steel tube and the buffer zone concept, respectively.

Now that both the investments costs and risk reducing factor of the safety measures is estimated, the risk reducing effect of safety measures can be determined in the early mentioned ways (step 4 of figure 11. The results hereof are presented in table 6 and figure 10.

Table 6: Results of the cost-effectiveness of safety measures.

| **Safety measure** | $\lambda_i$ | $P_{fi}$ | $P_{d\|fi}$ | $N_{pi}$ | $E(N_d)_0$ | $E(N_d)_j$ | $\Delta E(N_d)_j$ | $C_0$ [€] | CSX = α |
|---|---|---|---|---|---|---|---|---|---|
| **0. Initial situation** | 1 | $5 \cdot 10^{-5}$ | 0,9 | 432 | $2 \cdot 10^{-2}$ | $2 \cdot 10^{-2}$ | 0 | 0 | - |
| **1. Two extra stories** | 0,5 | $5 \cdot 10^{-5}$ | 0,9 | 432 | $2 \cdot 10^{-2}$ | $1 \cdot 10^{-2}$ | $2 \cdot 10^{-4}$ | $1 \cdot 10^{6}$ | $1 \cdot 10^{8}$ |
| **2. Steel tube** | 0,01 | $5 \cdot 10^{-5}$ | 0,9 | 432 | $2 \cdot 10^{-2}$ | $2 \cdot 10^{-4}$ | $2 \cdot 10^{-2}$ | $6 \cdot 10^{6}$ | $3 \cdot 10^{8}$ |

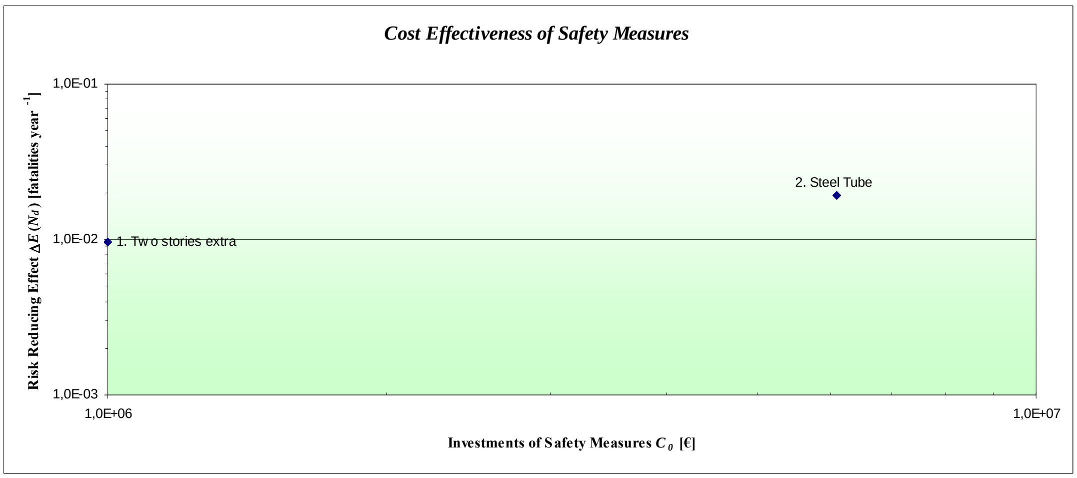



Figure 10: Cost-effectiveness of safety measures.

From table 6 it becomes evident that a steel tube has a larger risk reducing effect than adding two extra stories as a buffer zone. However, the steel tube is much more expensive than adding two extra stories as a buffer zone. If we consider the CSX, than we see that the CSX for the steel tube is much higher than adding the two extra stories as a measure. The costs being made to safe a statistical life (CSX) are in same order of magnitude, which is round about $10^8$ €. Though this value is higher than the normal used monetary value of a human according to [14,15], the value is the same order of magnitude according to the value given by Suddle [1], which is based on a recent case.

Furthermore, it can be stated that when the investments in safety measures are included in the risk picture, the improvement in human risks is limited/marginal. This phenomenon is controversially emphasised when different monetary values α of human beings (or CSX) are taken into account. Both table 7 and figure 16 show that the total costs depend upon the height of monetary value per human being α (or CSX). So, the height of monetary value per human being α is very important for decision-making, because the α determines the total costs. Furthermore, this case also stresses the problem that the investments in safety measures are relatively high in contrast with their relatively low human risk reduction. For the presented case of, it would be interesting to evaluate more accurately the additional costs of a well-designed buffer zone and blast resistant glazing [18]. It is expected that the costs can be limited to $0.5 \cdot 10^6$€ with new developments of blast resistant glazing at TNO DSS. The risk reduction factor will probably be in the order magnitude of 0.01, resulting in a CSX of 3 $10^{-7}$.

## 6. CONCLUSIONS & RECOMMENDATIONS

The reported study shows that controlling explosion effects in multiple use of space projects is important and complicated. The explosion blast loads and the dynamic response up to failure of the elements and the overall building system have to be modelled to classify the risks quantitatively. The reported study shows that the potential consequences of an accident with LPG can be quantified using relatively simple models that were developed. The presented models and approach can be used to estimate the potential consequences of an LPG-accident as an input for risk analysis and identify countermeasures and subsequently to integrate these measures into both structural and building design. For the considered building the consequences of the accident and recommended countermeasures are:

- (i) no damage to the primary and secondary bearing system, (ii) first floor completely fails (iii) secondary floor partly fails, (iii) windows breakage at all levels, (iv) human risks too high at all building levels;
- (i) safety integrated design engineering (structural and functional) (ii) design the windows for blast loading, (iii) the lower level should not be used for offices but storage and supporting facilities and (iv) a balanced design for the floor system at the first level, so that damage is limited to the first level and the dynamic resistance capacity of the bearing system is used.

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