Routeing of Dense Phase CO_2 Pipelines in the UK

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National Grid is currently pursuing plans to develop a pipeline system in the North Yorkshire and Humber areas of the United Kingdom (UK) to transport dense phase carbon dioxide (CO_2) from a major industrial emitter to a saline aquifer off the Yorkshire coast. The company's longer term aspiration is to develop the first pipeline into a network configuration that links up multiple CO_2 emitters in the Yorkshire and Humberside area. The planned developments are supported by a European Union grant which has been used to partly fund the required technical studies.

CO_2 is a hazardous substance which in the unlikely event of an accidental release, could cause harm to people.

UK safety legislation requires that the risks associated with high pressure pipelines transporting hazardous substances are as low as reasonably practicable (ALARP). Demonstration of this generally requires compliance with recognised pipeline codes, however when the work commenced, the then current pipeline codes did not apply to dense phase CO_2 or dense phase CO_2 with impurities. The aim of the National Grid COOLTRANS research programme has been to provide data and information to provide the technical justification for the safe operation of dense phase CO_2 pipelines, and the development, scrutiny and publication of code requirements.

In developing the strategy for the COOLTRANS research programme, the research work carried out by the UK gas industry during the 1970s and 1980s for natural gas and rich gas mixtures was reviewed to extract relevant knowledge. This work was used to develop the pipeline design standard IGEM/TD/1 for application to natural gas pipelines, the first edition of which was published in 1977. IGEM/TD/1 specifies the design requirements for natural gas pipelines, and these requirements were adopted in the pipeline design standard BS 8010 for application to high pressure pipelines transporting other hazardous fluids. BS 8010 is now superseded by the BSI published document PD 8010-1 which supports the European pipeline standard BS EN 14161. PD 8010-1 retains the original key principles established in IGEM/TD/1. A key requirement of both IGEM/TD/1 and PD 8010 is the safe routeing of pipelines which may pose risks to the public. This requires that pipelines are located at specified minimum distances to occupied buildings. In defining these distances, both IGEM/TD/1 and PD 8010-1 allow the use of Quantified Risk Assessment (QRA) to assist in decision making in applying the requirements.

PD 8010 has recently been updated to include CO_2 as the UK pipeline code for high pressure pipelines did not directly apply to dense phase CO_2. This paper describes the routeing and design principles specified in the UK pipeline standard and code of practice, and explains how the COOLTRANS research findings have been used in the development and application of a QRA based routeing methodology for CO_2 pipelines, which ensures the principles are applied to these pipelines.

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Introduction

National Grid has proposed plans to develop a pipeline system in the North Yorkshire and Humber areas of the United Kingdom (UK) to transport dense phase carbon dioxide (CO_2) from a major industrial emitter to a saline aquifer off the Yorkshire coast. The company's longer term aspiration is to develop the first pipeline into a network configuration that links up multiple CO_2 emitters in the Yorkshire and Humberside area. In support of these plans, National Grid has carried out a CO_2 in Liquid TRANSport by pipeline (COOLTRANS) research programme into the transportation of dense phase CO_2.

In developing the strategy for the COOLTRANS research programme, the research work carried out by the UK gas industry during the 1970s and 1980s for natural gas and rich gas mixtures was reviewed to extract relevant knowledge. This earlier work was used to develop the Institution of Gas Engineers and Managers (IGEM) pipeline design standard IGEM/TD/1 [IGEM 2008] for application to natural gas pipelines, the first edition of which was published in 1977 [IGE 1977]. IGEM/TD/1 specifies the design requirements for natural gas pipelines, and these requirements were adopted in the pipeline design standard BS 8010:Part 2 Section 2.8 (BSI 1992) for application to high pressure pipelines transporting other hazardous fluids. BS 8010 is now superseded by the British Standard Institute (BSI) published document PD 8010:Part 1 [BSI 2004, BSI 2015] hereafter referred to as 'PD 8010-1',which supports the European pipeline standard BS EN 14161 [BSI 2015]. BS 8010:2.8 1992 and PD 8010:2004 referred to CO_2 as a Category C fluid. PD 8010:2015 refers to vapour phase and dense phase CO_2 as Category E.

PD 8010-1 retains the original principles established in IGEM/TD/1. A key requirement of both IGEM/TD/1 and PD 8010-1 is the safe routeing of pipelines which may pose risks to the public. This requires that pipelines are located at specified minimum distances from occupied buildings. In defining these distances, both IGEM/TD/1 and PD 8010-1 allow the use of Quantified Risk Assessment (QRA) to assist in decision making in applying the requirements. The guidance in PD 8010-1 was updated in 2015 to include CO_2.

This paper describes the routeing and design principles specified in PD8010-1, and explains how the COOLTRANS research findings have been used in the development and application of a QRA based routeing methodology for CO_2 pipelines, which ensures the principles are applied to these pipelines. To achieve this aim, background information related to the development of codes for natural gas is explained firstly. This is followed by a brief discussion on the specific features of CO_2 that mean that a cautious approach may be necessary if a simple formula for the minimum distance to occupied buildings (MDOB) of the type used for other fluids in PD8010-1 is adopted for CO_2. This is explained using findings drawn from QRAs carried out following the approach outlined in PD 8010-3 [BSI 2013] 'Code of practice for pipelines' – Part 3 and titled 'Steel pipelines on land. Guide to the application of pipeline risk assessment to proposed developments in the vicinity of major accident hazard pipelines containing flammables' (hereafter referred to as 'PD 8010-3'). As the use of QRA is a time consuming process normally carried out by specialists and is required only for specific sections of the pipeline route, a simpler screening approach is required by design teams setting out route options and for the detailed design of the majority of the pipeline route, it would then identify any areas where the use of a full QRA is merited. This method is illustrated for a hypothetical case and the way in which more complicated issues, such as major road crossings, can be dealt with is discussed.

Background to the Requirements for Pipeline Routeing in the UK

Natural Gas

Early guidance on high pressure natural gas pipeline design and construction in the UK was based on the US Code ASME B31.8 [ASME 1955]. Detailed guidance on routeing, taking account of UK conditions and in the form still used today, was first published in the then Institution of Gas Engineers (IGE) requirements for high pressure natural gas pipelines, IGE/TD/1 in 1977 [IGE 1977]. Since then this guidance has been progressively developed, based on experimental work and operational data on the causes of pipeline failure and on the consequences of failure, and to take advantage of the availability of thicker walled pipe of adequate quality. These developments allowed higher operating pressures in populated areas on the basis of increasing the pipe wall thickness to limit the design factor to 0.3. This control of design factor at higher pressures in populated (Suburban or type S) areas enabled operation at these higher pressures in Rural (type R) areas at up to a 0.72 design factor where the population density was limited to provide some control of societal risk.

The separation (or proximity) distance, later referred to as Building Proximity Distance (or BPD), from occupied buildings in R type areas was intended to protect individual members of the population from the hazard of more credible failure modes (leaks or punctures) and to provide a degree of control of the risk to society from less credible events (breaks or ruptures). For S type areas, defined at that time by the population density in a corridor five times the R type area separation distance on each side of the corridor centre line, the design factor was controlled such that only leaks would then need to be considered when defining the separation distance. Together with a procedure to determine the extent of any S type area a set of simple workable rules were available to set out the route for new pipelines, to determine any infringements which may need attention, and to identify any planned or anticipated land use developments which would conflict with the design code.

Other Fluids

Pipelines laid under the Pipelines Act 1962, as opposed to natural gas pipelines laid under the various Gas Acts, were covered by the BSI code of practice, BS CP 2010:Part 1 [BSI 1966] and later BS 8010:Part 1:1989 and Part 2, Section 2.8: 1992 [BSI 1992]. The approach was consistent with that in IGE/TD/1 and for methane[1] the requirements were also consistent with IGE/TD/1 Edition 2[2], the separation distance was based on an equation matching IGE/TD/1 for methane and applying a substance factor for other fluids. The population density corridor was three times the separation distance for Category C fluids (non- flammable and including carbon dioxide) or four times for Category D and E fluids (flammable or toxic). A risk analysis, as part of a safety evaluation of the pipeline, could be used to justify operation outside the prescriptive limits.

Use of Quantified Risk Analysis (QRA)

In the 1990s, the Health and Safety Executive (HSE) introduced Land Use Planning (LUP) requirements for hazardous pipelines. A risk based 'Consultation Zone' around the pipelines transporting dangerous fluids is calculated by HSE using the pipeline details notified by the pipeline operator. Any new planning developments within this zone are assessed by Local Planning Authorities (LPAs) in accordance with HSE advice.

The assessment process developed by the HSE uses risk-based inner, middle and outer zones and the type of development which is proposed, to assess the acceptability of the development with respect to the pipeline risk. The zones are calculated by the HSE using pipeline details notified by the operators of major accident hazard pipelines as required by the Pipelines Safety Regulations 1996 (PSR 96). The HSE use this information to calculate risk-based distances to the zone boundaries from the pipeline, defining the levels of risk at each zone boundary as follows:

1. boundary between inner and middle zone – based on an individual risk of 1×10^{-5} per year;

[1] Natural gas mixtures with a high methane content of the type allowed into the UK National Transmission System can be treated as 'methane' in PD 8010.

[2] IGE/TD/1 Edition 2 Used 10 x BPD as the route corridor, and BS 8010:Part 2 Section 2.8 used 8 x BPD. A route corridor width of 8 x BPD was introduced in IGE/TD/ 1 Edition 3 [IGE 1993].

2. boundary between middle zone and outer zone – an individual risk of 1×10^{-6} per year;
3. boundary between outer zone and no restrictions – which is the lesser of:
    - an individual risk of 0.3×10^{-6} per year; or
    - a notified outer zone distance.

The application of these values to numbers and types of development provides a control of societal risk.

The individual risk is calculated for the average householder applying a dangerous dose casualty criterion, where dangerous dose is defined by HSE as a dose of thermal radiation that would cause:

- severe distress to almost everyone in the area;
- a substantial fraction of the exposed population requiring medical attention;
- some people being seriously injured, requiring prolonged treatment;
- any highly susceptible people being killed.

The risk based option in PD 8010-1:2004 included individual risk values to define the Minimum Distance to Occupied Buildings (MDOB) and the routeing corridor. These were 10 chances per million (cpm) and 0.3 cpm, consistent with the LUP inner zone and outer zone distances. Societal risk, as in the prescriptive option, was managed through the design factor for Class 2 (S type areas) locations and population density for Class 1 (R type areas) locations rather than numbers and types of development. Following either approach would normally meet the As Low As Reasonably Practicable (ALARP) requirement for the pipeline operator but may result in inconsistencies with LUP requirements.

In practice, further assessment has shown that natural gas pipelines routed following the above guidance are unlikely to be found to be at variance with the more quantified, societal risk approach defined in IGEM/TD/1, based on the evaluation of an FN curve. That is, in general, the individual risk criteria as applied above generally achieve the same ends as a societal risk assessment and in cases of any conflict, the full QRA allows both types of risk to be considered and provides a framework for assessing risk mitigation measures [Cleaver and Hopkins, 2012].

Routeing of CO_2 Pipelines In accordance with the Pipeline Code PD 8010

A general principle is that pipelines are routed away from populated areas consistent with the many constraints arising from land type and usage.

PD 8010-1:2004

CO_2 is a substance which in the unlikely event of an accidental release, could cause harm to people. As this is the case, compliance with UK safety legislation requires compliance with recognised pipeline codes. National Grid commenced feasibility studies for the development of the Yorkshire and Humber Carbon Capture and Storage (CCS) dense phase CO_2 pipeline in 2012, in accordance with the requirements of the then current pipeline code PD 8010-1:2004.

For the routeing and design of onshore pipelines, PD 8010-1 applies the following process:

1. Categorisation of subsances according to hazard potential.
2. Classification of location in relation to population density in accordance with the hazard category, where the location classes are defined as follows:

Location Class	Description
1	Areas with a poulation density less than 2.5 persons per hectare
2	Areas with a poulation density greater than or equal to 2.5 persons per hectare and which might be extensively developed with residential properties, schools, shops and etc.
3	Central areas of towns and cities with a high population and building density, multi-storey buildings, dense traffic and numerous underground services

3. Calculation of the MDOB and the route corridor to be used to determine the population density based on the distance to the Individual Risk (IR) level of 10 cpm and 0.3 cpm respectively. Where IR values are not available, the MDOB is calculated in accordance with the equation:

$$Y = Q\left[\frac{D^2}{32000} + \frac{D}{160} + 11\right]\left[\frac{P}{32} + 1.4\right]$$

Where Q is the substance factor which reflects the risk posed on release of the substance.

However, the 2004 version of PD 8010-1 does not include a hazard category or substance factor (Q) applicable to dense phase CO_2, so National Grid developed a set of routeing requirements using a risk based approach. The approach developed is described in Section 5 below.

PD 8010-1 was updated by BSI in 2015 to include requirements for CO_2 pipelines at the request of the Department of Energy and Climate Change (DECC). The committee responsible for the update was briefed on behalf of National Grid on the development of the risk based methodology for the routeing of CO_2 pipelines. Information and advice provided was taken into account by the committee in developing the update.

PD 8010-1:2015

Based on research into the requirements for dense phase CO_2 pipelines, National Grid considered that the highest fluid hazard categorisation, E, should be applied to CO_2. This concurs with the fluid categorisation applied in the pipeline standard ISO 13623, and is now included in Table 1 of PD 8010-1:2015. The PD 8010-1:2015 substance factor table (Table 3) has been updated as follows:

Substance	Substance Factor, Q
Ammonia	2.5
Carbon Dioxide	2.0 (dense phase), 1.0 (gas phase)[Note]
Ethylene	0.8
Hydrogen	0.45
Liquid petroleum gas	1.0
Natural gas liquids	1.25
Category C	0.3

The note included for carbon dioxide states that the substance factor given is informative, and the selected value should be supported by reference to joint industry or project specific research and guidance on the routeing of pipelines conveying carbon dioxide.

The value of 2.0 for dense phase CO_2 was selected to be informative, as this lies between the value of 1.25 for natural gas liquids and the value of 2.5 for ammonia, which is highly toxic. PD 8010-1:2015 now states that a more rigorous analysis using a risk-based approach should be used for the final design limits, and for category D or Category E substances, societal risk should be taken into account. In addition, PD 8010-1:2015 states that societal risk calculations should be carried out for pipelines conveying toxic category E substances (e.g. ammonia or carbon dioxide).

QRA of CO_2 Pipelines

Methodology

The National Grid QRA methodology for dense phase CO_2 pipelines is based on the best practice methodologies published in the UK pipeline standards IGEM/TD/2 Edition 2 [IGEM 2013] and the code PD 8010-3 [BSI 2013]. The code PD 8010-3 notes that while the QRA methodology it covers addresses thermal hazards only, the principles presented can be applied to toxic hazards. An overview of the QRA methodology is given in Figure 1:

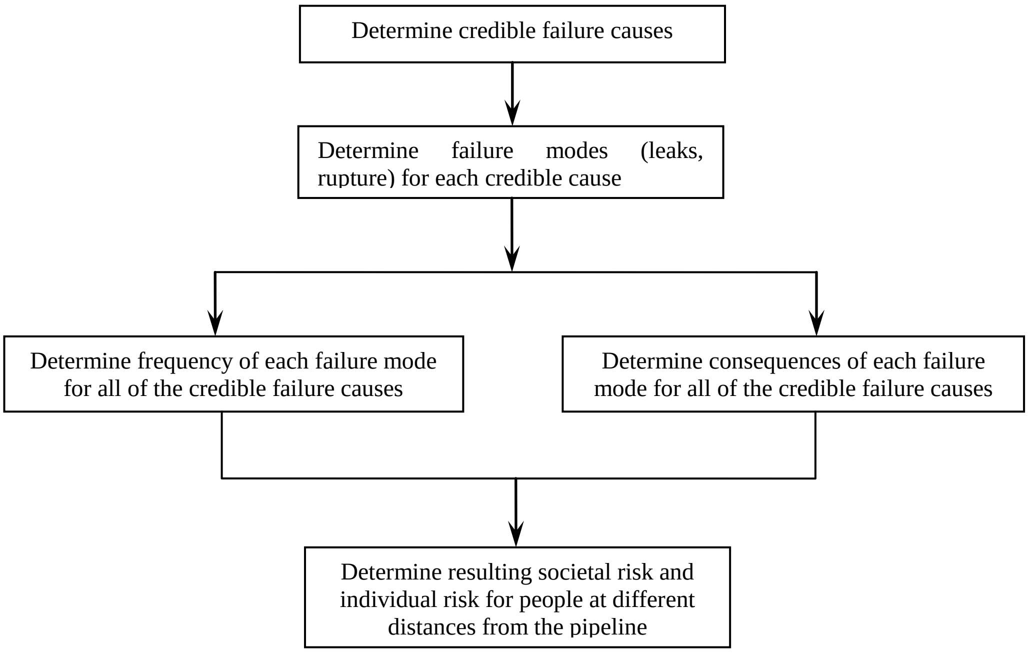

Figure 1 Overview of QRA Methodology

The detailed stages are:

- Identify the failure causes and modes of the pipeline;
- Determine failure frequencies for each of the modes of failure that are being considered;
- Predict the rate of release from the pipeline for each case;
- Evaluate the size of crater that will be produced by the release from each failure;
- Predict the equivalent source conditions that apply for this flow rate entering the specified below ground crater;
- Evaluate the time dependent dispersion of the release, if necessary assuming the simplified equivalent source specified above for a range of wind speeds, directions and atmospheric stability categories;
- For each case, predict the time dependent mean concentration that would be experienced at an array of locations around the pipeline;
- Evaluate the dose experienced at each point, making allowance for the impact of concentration fluctuations within the plume. The dose calculation for a person outdoors initially is repeated, considering a person who decides to attempt to escape and a person who decides to remain stationary at each location. The dose calculation for a person who is indoors initially takes account of the CO_2 ingress and accumulation within a typical domestic property and assumes that a person indoors does not attempt to escape;
- By using an appropriate probit relationship or dose related casualty criterion, the location specific risk at each point can be evaluated for the length of pipeline being considered.

Separate assessments are performed for day and night conditions, as the distribution of atmospheric stability categories are biased in that there is a tendency for stable conditions to arise during the night time and unstable conditions during the day time. The final values take a weighted average of the two results. The location specific risk values can be used to provide a transect of individual risk on a line perpendicular to the pipeline, assuming that a person is present for 100% of the time and spends a certain percentage of time indoors and outdoors.

Individual Risk Transects

The hazards arising from a drifting toxic CO_2 cloud result in individual risk curves that are a different shape to curves produced for a flammable fluid, such as natural gas. This is illustrated in Figure 2, where the individual risk values are plotted against the distance along a line perpendicular to the pipeline (the risk transect) for a typical high pressure natural gas pipeline and for a large diameter, thick walled dense phase CO_2 pipeline. Figure 2 shows that, irrespective of the absolute values of risk, the risk associated with the toxic hazard of the CO_2 pipeline decays much more slowly with distance from the pipeline compared with the relatively rapid decay in risk associated with the thermal hazards from the natural gas pipeline.

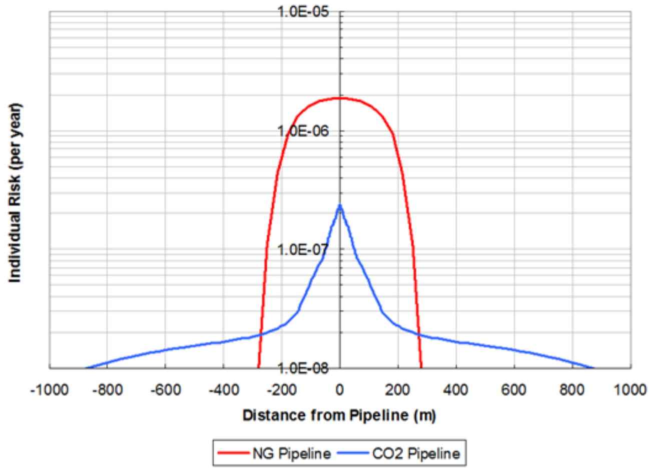

Figure 2 Individual Risk Transect for Natural Gas and CO_2 Pipelines (ruptures only)

The differences in the shape of the risk transects arise as the thermal hazard distances from a natural gas pipeline are less sensitive to variations in the atmospheric conditions, wind speed and topography than the dispersion distances associated with a drifting cloud of CO_2. The sensitivity produces a 'long tail' to the individual risk transect for CO_2 pipelines. The difference in the magnitude of the risk close to the pipelines arises because of the lower failure frequencies associated with the thick walled CO_2 pipelines, which means that the resulting individual risk levels are relatively low. As a result, the balance between individual and societal risk is different for CO_2 pipelines, and while the individual risks are low, the potential for exposure to the low risks at an extended distance from the pipelines raises the requirement for societal risk considerations as, under unfavourable weather conditions, the hazardous cloud may drift to populations at greater distances from the pipeline.

Further, the greater distance and longer time period associated with the CO_2 hazard mean that a number of factors may be more significant in modelling the risk compared with a natural gas pipeline. This includes factors such as the influence of the source conditions and subsequent dispersion from the crater; population factors, including the density of people at larger distances from the pipeline, the time people spend out of doors, escape and shelter assumptions, and the influence of isolation valves along the pipeline.

The more fundamental Computational Fluid Dynamics (CFD) based modelling studies conducted as part of the COOLTRANS research programme have provided the theoretical understanding that is required to address these issues. In parallel, the more practical risk assessment models are being applied to investigate the sensitivity of the results to the above factors and to advise on any modifications required for CO_2 pipelines.

Societal Risks

The approach recommended for societal risk evaluation in PD 8010-3 is to evaluate the risks to the surrounding population from a fixed one kilometre length of pipeline. The total number of casualties, N, can be deduced for each event along the pipeline if the population distribution at different times of the day is specified. The cumulative frequency F with which N or more casualties are produced can be evaluated and a curve showing the variation of F with N can be plotted for comparison with the criterion curve in PD 8010-3.

This process is site specific and is relatively time consuming, especially if full details of the variation in population with time of day are taken into account. However, the results obtained for a CO_2 pipeline, such as that illustrated in Figure 2, indicate that it is possible to construct an example in which the FN curve for a particular location on the pipeline route approaches the criterion curve given in PD 8010-3 despite the individual risk being below 3×10^{-7} per year (0.3 cpm) everywhere even if using a Specified Level of Toxicity (SLOT) casualty criterion. That is, the risks are moving into the region where there is a requirement to think further about risk reduction measures in order to demonstrate that the risks have been reduced to ALARP, despite no one person being subject to a level of individual risk that would cause concern. Societal risk offers an approach that could be used to rank such cases in a logical order and a way of judging the acceptability of each case, by comparison with the criterion curve in PD 8010-3. This suggests the need for further societal risk investigations in planning the route of a CO_2 pipeline. The methodology developed to address this is detailed in Section 6.

Risk Based Routeing of CO_2 Pipelines

The application of the individual risk based distances for the routeing of CO_2 pipelines is complicated by the fact that the thicker pipe wall thickness required for dense phase CO_2 pipelines results in low predicted failure frequencies so the individual risk levels are low. Consequently, for the range of parameters likely to be considered, there is no 10 cpm individual risk level on which to base the MDOB distance, so there is no equivalent means of defining a separation distance as for natural gas pipelines, and the distance to 0.3 cpm is also small. As the results shown in Figure 2 imply, the distances to 0.3 cpm can be very much smaller than the maximum hazard distance if a wide range of weather conditions are taken into account. This indicates that it may not be sufficiently cautious to take the individual risk distance approach to defining the separation distance for the pipeline and a corridor width over which to assess the local population and the use of this approach may result in a route which may not meet the ALARP requirement. A societal risk assessment is therefore required. This however increases the complexity of the risk assessment and may be beyond the scope of a design team. In addition it would be unnecessarily time consuming to apply over the whole lengths of the range of pipeline route options considered.

To address this, a generic societal risk assessment was performed for the specified length of pipeline and an FN curve produced for comparison with the criterion curve in PD 8010-3, which was used to develop a simplified screening approach that can be used to help during the early stages of a project or in the event of a new proposed development near to an existing pipeline, as described below.

Societal Risk Screening Method

A generic societal risk assessment is used to assess the situation sketched in Figure 3.

Figure 3 Generic Societal Risk Assessment Model

The analysis is carried out for different separation distances and population densities on either one side or both sides of the pipeline. The predicted number of casualties is evaluated for a 1 kilometre length of straight pipeline and FN curves are produced.

The results are analysed to present the Expectation Value (EV) for the potential number of casualties per year plotted against the separation distance assumed (m), shown in Figure 4 below, for a typical 914 mm outside diameter natural gas (NG) pipeline operating at a pressure of 85 barg and a 914 mm outside diameter dense phase CO_2 pipeline operating at 150 barg. The curves plotted in Figure 4 below are for different representative values of population density beyond the separation distance.

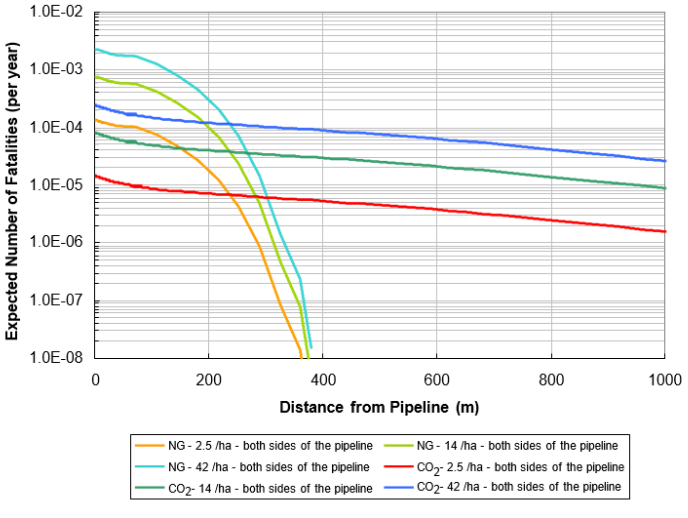

Figure 4 Variation in the Value of Expected Number of Casualties per year with Pipeline Separation Distance for Different Population Densities

If the separation distance of people from the pipeline was set at 200 m, the EV for the case of a population density of 2.5 persons per hectare beyond 200 m would be approximately 7 x 10^{-6} casualties per year for the CO_2 pipeline (red curve), and approximately 2 x 10^{-5} casualties per year for the natural gas pipeline (orange curve). However, if there was a separation distance of 400 m, the EV would be less than 1 x 10^{-8} casualties per year for the natural gas pipeline but just over 5 x 10^{-6} casualties per year for the CO_2 pipeline. That is, increasing the separation distance from 200 m to 400 m for the natural gas pipeline reduces the EV to less than 0.05% of its original value, whereas the equivalent increase in the separation distance for the CO_2 pipeline reduces the EV to only approximately 70% of its original value.

The shape of the above curves follows from the shape of the risk transects. It is possible in certain situations to get quite a significant value of the EV for quite large separation distances from a CO_2 pipeline. Therefore, in general, there is a need to consider the societal risk beyond the individual risk distance of 3×10^{-7} per year for CO_2 pipelines (and equally, the results show there is no requirement for this for a natural gas pipeline). An EV of greater than 1×10^{-4} casualties per year can be used to gauge whether there is potential for an FN curve for the 1 kilometre length of pipeline to go beyond the assumed 'ALARP' curve shown in PD 8010-3 for societal risk. The curves shown in Figure 5 show the value of the uniform population density that would exceed this EV if sited uniformly, either on one side or both sides of a pipeline beyond a given separation distance.

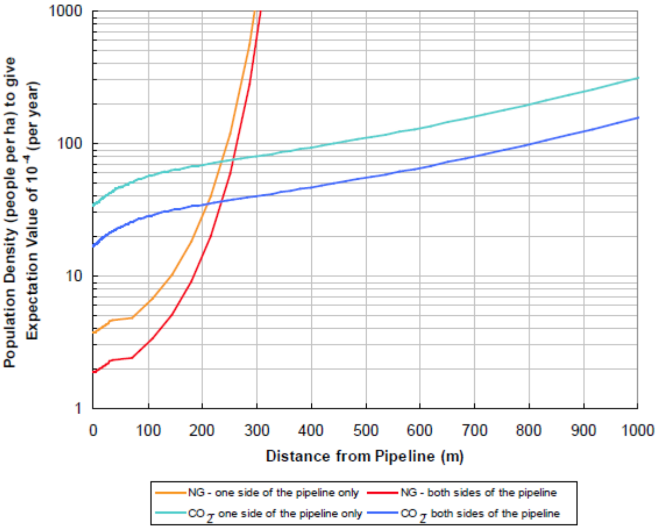

Figure 5 Population Density Giving an EV of 1×10^{-4} Casualties per year for a Given Separation Distance

The above information was extended and used to develop the following societal risk screening procedure for CO_2 pipeline routeing:

- Define three target types of development areas of population:
    - Type 1: Larger clusters and smaller villages
        - Area of development more than 10 hectares OR with a total population of more than 100 people
        - AND an area of development less than 100 hectares
        - AND with total population less than 1000 people.
    - Type 2: Larger villages and smaller towns (suburban type areas)
        - Area of development more than 100 hectares OR with a total population of more than 1000 people
        - AND an area of development less than 500 hectares
        - AND with total population less than 20,000 people.
    - Type 3: Edges of Larger towns and cities
    - Area of development more than 500 hectares OR with a total population of more than 20,000 people.

Assuming that a contribution to the EV of 2.5×10^{-5} casualties per year will be allowed from each of the above development areas for a 1 kilometre length of pipeline.

Step 1: Consider routeing required to avoid larger clusters and smaller villages (Type 1 developments)

- Use the curve for a representative population density of 8 persons per hectare to find a separation distance of people from the pipeline to avoid giving an EV in excess of 2.5×10^{-5} casualties per year.
- Make sure there are no development areas of this type within this distance of the route.

Step 2: Consider routeing required to avoid larger villages and smaller towns (Type 2 developments)

- Use the curve for a representative population density of 32 persons per hectare to find a separation distance of people from the pipeline to avoid giving an EV in excess of 2.5×10^{-5} casualties per year.
- Make sure there are no areas of this type within this distance of the route.

Step 3: Consider routeing required to avoid larger towns or cities (Type 3 developments)

- Use the curve for a representative population density of 80 persons per hectare to find a separation distance of people from the pipeline to avoid giving an EV in excess of 2.5×10^{-5} casualties per year.
- Make sure there are no cities within this distance of the route.

Step 4: Isolated Dwellings and Small Clusters

A check to confirm is made that the contribution to the EV from isolated houses and smaller clusters within the Type 1 distance is not significant, that is, it is below 2.5×10^{-5} casualties per year. A cautious way of undertaking this has been developed, based on checking the number of dwellings within the Type 1 separation distance over a rolling one kilometer length of pipeline to ensure that the population density does not exceed a prescribed maximum limit.

The results of the application of the methodology described above have been checked for actual distributions of population along a possible pipeline route. In general, the approach was found to provide cautious initial guidance which clearly meets the level of safety which is implicit in the routeing and design principles in the UK code of practice PD 8010-1 whilst demonstrating conformity to the ALARP requirements of PSR 96 through compliance with the societal risk criterion given in PD 8010-3. A number of lessons were learnt and the guidance was extended further to deal with a number of specific situations, as discussed below. In particular, it was found that a failure to meet the initial screening did not mean that the risks were unacceptable, just that they required further, more detailed study than provided by the screening approach.

Lessons Learnt in the Application of the Societal Risk Screening Method

The approach defined above was applied to the proposed routes associated with one of National Grid's CO_2 pipeline projects. The findings from this work enabled the guidance to be clarified and further guidance to be developed for a number of specific situations. A summary of the key results is provided below:

Defining the Development Areas Containing Population

At an early stage of application, it was found that in order to apply the definitions given in Section 6.1 above for the three different types of populated areas, there is a need for guidance on where each area begins and ends. As a result, a development separation matrix was developed, as shown in Table 1 below. This defines the required separation distances between the boundaries of the different developments. Each development area must adhere to these separation distances in order for them to be regarded as separate. If the separation distance between adjacent development areas does not meet these requirements, the areas should be combined together and the total populated area categorised by type according to the definitions in Section 6.1.

Development type	Type 1	Type 2	Type 3
Type 1	250 m	500 m	750 m
Type 2	500 m	750 m	1,000 m
Type 3	750 m	1,000 m	1,250 m

Table 1 Matrix of Separation Requirements Between Development Area Types

This not only reduces the number of cases to be considered significantly, but prevents an optimistic view being taken of the population distribution by fragmenting it into many smaller areas.

Preliminary Screening

Conventional graphical software can be used together with maps of any proposed route to illustrate the location of the different development areas. The required separation distances around the development areas can be added to the map to identify any areas of overlap. An example of this process is shown in Figure 6 below, where a number of different areas are shown in proximity to a proposed pipeline route.

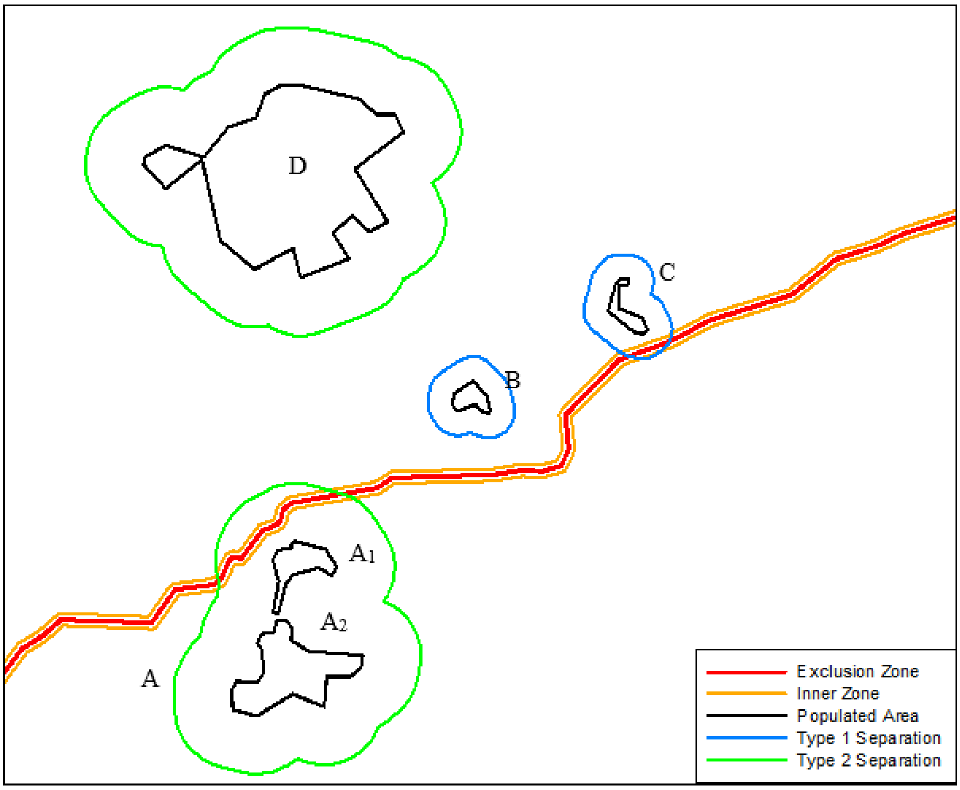

Figure 6 Example of Visualisation of Development Areas and Pipeline Route to Enable Cases of Interaction to be Identified in the Preliminary Screening Stage

In this case, area A_1 is Type 1 and A_2 is Type 2 individually which have been amalgamated to form a new larger Area A, all of Type 2. Areas B and C are of Type 1 and Area D is Type 2. Areas A and C are identified as requiring further assessment, as there is an interaction with the closest point of approach of the pipeline whereas the other areas pass this screening test. In this case, there are no individual houses within the inner corridor around the pipeline.

Further Screening

In the cases identified in the preliminary screening, such as Area A and C in Figure 6 above, the variation of individual risk with distance from the pipeline can be combined with a case specific estimate of the number of people present within each zone, to evaluate more accurately the expected number of casualties from that area. In many cases involving the smaller development areas or individual dwellings or small clusters, it is found to be sufficient to use the value of the individual risk at the closest distance of the populated area to the pipeline multiplied by the total number of people in that area to estimate an upper bound on the potential number of casualties to compare with an overall figure of 1×10^{-4} per year for the relevant 1 kilometre length of pipeline. In contrast, it may be necessary to split the larger development areas into a number of different areas at different distances in order to take the decrease in risk with distance from the pipeline into account, as illustrated in Figure 7 below for one specific Type 2 area.

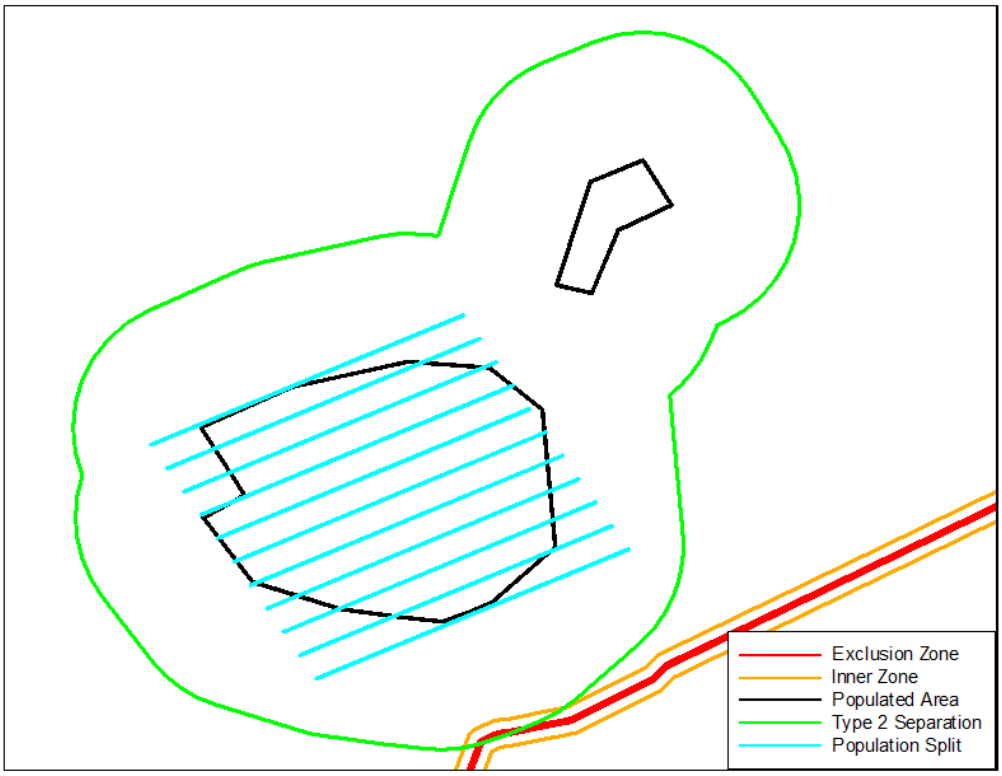

Figure 7 Procedure for Producing a More Refined Estimate of the Potential Number of Casualties per year for one Example Type 2 Development Area

In this case, the two developed areas sketched are not far enough apart to be treated separately and so they have been amalgamated and the required separation distance around all of the amalgamated area is shown in the Figure 7. This interacts with a short length of pipeline at its point of closest approach to the larger of the separate centres of population. Assuming all of the people in this area are at the point of closest approach to the pipeline led to an estimate of the total potential number of casualties from this section of pipeline of 9.9 x 10^{-5} per year, whereas assuming this area was split into the 10 strips sketched in Figure 7, with a single closest point chosen for the upper area of population, gave an estimate of 3.3 x 10^{-5} per year, significantly below the threshold value of 1 x 10^{-4} per year required for further, detailed investigation.

The degree of caution in the preliminary analysis arises mainly as a result of assuming that the representative population density extends everywhere beyond the development at this density, whereas in reality as the examples show, each area is limited in extent. In a number of cases, the results of the screening were checked against a full QRA and for all cases examined, this showed that the screening approach was cautious, by a significant margin.

Further assessment of Area C shown in Figure 6 was carried out using case specific values of the population distribution with distance from the pipeline, as in the analysis associated with the location shown in Figure 7. The analysis showed that the expected number of casualties was significantly below the value of 1 x 10^{-4} per year. A full QRA of the pipeline in this location was carried out, in which the actual position of houses and roads was taken into account. The assessment considered all of the population within approximately 5 kilometres of the pipeline route, centred on the closest point of approach of the pipeline to the development. The societal FN curve constructed for the highest risk 1 kilometre length of pipeline in this location was significantly below the FN criterion given in PD 8010-3 and the EV for the number of casualties per year was below that estimated using the more detailed screening method. This provided confidence that the generic screening approach is cautious and that using the generic screening, followed by more detailed screening and finally a full QRA provides an efficient, staged approach to developing or validating a proposed CO_2 pipeline route.

Exceptional Cases

As with any approach of this nature, situations can arise that do not comply with all of the assumptions applied in the calculations that underlie the screening method. A number of such cases identified so far are discussed in Appendix A. However, it must be noted that the method described is not intended to remove the need for more detailed QRA work for specific situations, a balance must be made between the time and effort required to develop detailed screening against that required to carry out a full QRA.

Summary of a Screening Approach

As a result of the above studies, the current approach to screening routes involves the following stepped process:

1. Characterise the area of interest through which the pipeline passes into the different development types, as specified in Section 6.1, amalgamating the areas as required until the remaining areas meet the separation criteria in Table 1.

2. Propose a possible pipeline route that avoids the developed areas as far as possible and meets other constraints (such as environmental issues, avoids areas where landslip has a higher chance of occurring and allows access for the pipeline to be constructed and maintained, for example).

3. Calculate an individual risk transect for the particular pipeline of interest to allow the variation of the individual risk as a function of perpendicular distance from the pipeline to be generated.

4. Use the individual risk transect to calculate a separation distance for the different development types from the specific pipeline, assuming a population density as specified in Section 6.2 for each area, assuming each development extends outwards continuously beyond this separation distance and an allowed contribution to the total potential number of casualties from a 1 kilometre length of pipeline to be below 3 x 10^{-5} per year.

5. Check that isolated dwellings or small clusters do not contribute significantly to the societal risk, by ensuring that the number of dwellings within the Type 1 separation distance over a rolling one kilometre length of pipeline does not exceed the prescribed maximum limit.

6. Apply a more detailed screening to any development areas that are within their separation distance from the pipeline. This should take into account the actual number of people in the area (from census data etc.) and their individual risk. As illustrated by the example in Section 6.2, this can involve considering multiple areas and different levels of approximation in the calculation of the expected number of casualties per year.

7. Identify any unavoidable situations along the route, such as caravan parks, places of public assembly and hospitals or schools for example, where the assumptions made in deriving the risk transect may not be valid. Consider these locations in turn, taking into account the vulnerability of the people present and the amount of time different numbers of people will be present when estimating their individual risk. (This information would be expected to be available from the calculations performed in deriving the individual risk transect at 3 above).

8. Consider any interaction with significant roads away from the development areas, using the screening approach summarised in Appendix A, which covers exceptional cases.

9. Perform a full risk assessment for any remaining areas that have not been adequately screened using the above steps.

In the longer term, it may prove possible to derive correlations or look-up tables to specify the separation distances required for different diameter or wall thickness pipelines. This has the potential to reduce further the amount of work involved in the preliminary screening.

Conclusions

National Grid has completed a comprehensive research programme to investigate the requirements for the safe design, routeing and operation of dense phase CO_2 pipelines. This research programme has included the development of a risk-based methodology for the routeing dense phase CO_2 pipelines, which complies with the requirements of the UK pipeline code PD 8010-1.

The application of QRA to dense phase CO_2 pipelines has shown that the individual risk levels are low, but as they are associated with a drifting hazardous cloud, they are sensitive to variations in atmospheric conditions, wind speed and topography, and can therefore extend a significant distance from the pipeline. This results in the need to consider the societal risk to populations at extended distances from the pipeline.

A societal risk screening method has been developed using the societal risk criterion given in PD 8010-3 for the routeing of dense phase CO_2 pipelines. This method involves generic screening followed by detailed screening, and the application of site specific QRA to any locations which do not meet the screening criteria. The method has been applied in the development of proposed pipeline routes, and has been demonstrated to be an efficient, staged approach to the development or validation of a dense phase CO_2 pipeline route.

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Appendix A

Exceptional Cases

It has been found that there are a number of situations that can arise in practice where the assumptions made in developing the risk transects are not valid. For example, any case involving long curved sections of the proposed pipeline route that skirt an area of population may require further consideration. This arises because a longer than anticipated length of curved pipeline could interact with a local centre of population. Some parts of the populated area could be at some risk from the whole length of the CO_2 pipeline and this could give rise to an increased individual risk at these locations and a general increase in the societal risk. Depending on the EV of the number of casualties assuming the population are all at the minimum separation distance, such a situation may merit a site specific QRA.

Other cases that have been identified include industrial parks, shopping developments, places where large numbers of vulnerable people may be present and caravan parks. The assumptions that people are present for 24 hours every day may not be justified in such cases, but there may be a high density of people for a short period of time. Depending on the numbers involved and the estimated expected number of casualties based on the more detailed screening approach, these situations may warrant further attention. It may be possible to avoid locating the pipeline near some of these cases. For other cases, the detailed results may be available from the risk calculations performed to generate individual risk transects, allowing alternative transects to be developed with minimal effort, (for example a transect for a person who is outdoors all of the time). Such transects can be used to extend the screening approach. However there may be cases where it is necessary to carry out a full QRA in order to ensure that the different combinations of cases have been assessed appropriately.

A final example of a case that does not conform to the assumptions made in developing the risk transects involves the possible interaction of releases from a pipeline with a major road. Two specific situations have been considered in more detail; the first involving a road that is perpendicular to the pipeline route, crossing it at a specific location. The other is a road that runs parallel to the pipeline for some length along the route. As with a caravan park, account has to be taken in the assessment for the reduced protection afforded to people within cars compared with houses.

A number of generic road types have been considered in the methodology, based on assumptions made about average traffic flows, the vehicle speeds and the number of lanes of traffic associated with each type based on data from the Department of Transport for each road. It is difficult to predict how people driving along a road will react when faced with a visible CO_2 cloud. There is the possibility that in the event of an accident, cars may become stationary in a queue, preventing easy escape from any incident. As a result, assumptions have been made in order to determine the number of vehicles that are considered to be involved in an incident, as follows:

Perpendicular road crossings

It is assumed that cars driving away from the source of the CO_2 cloud will continue to travel away and therefore are not affected by the pipeline release.

For cars travelling towards the source of the release, it is assumed that at some stage soon after the incident starts, a car stops at the pipeline/road intersection point and that there is a resulting build-up of traffic in a 'congested zone' on both sides of the pipeline. This situation is illustrated in Figure A1 (a).

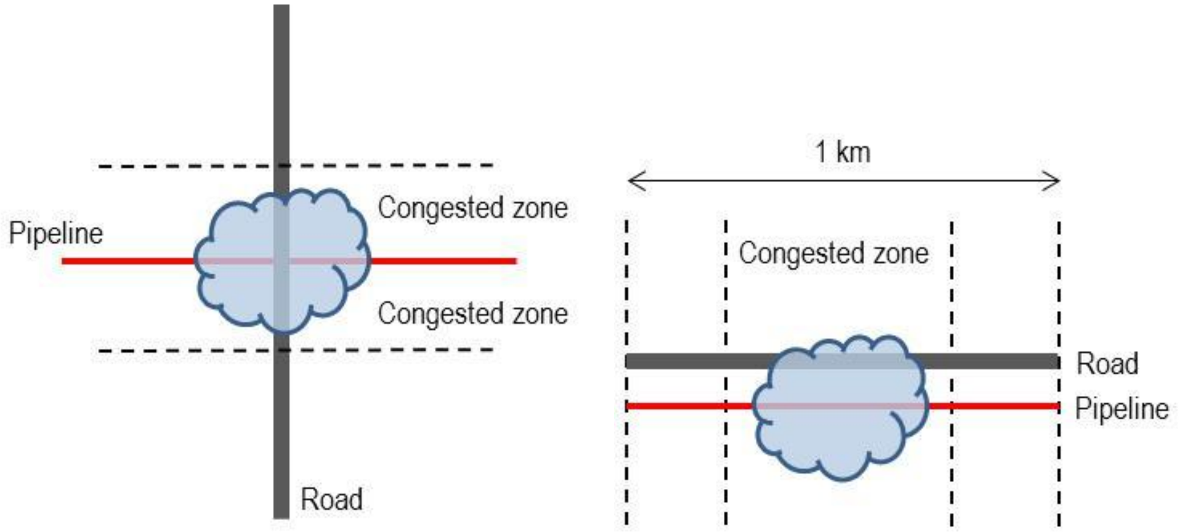
The length of road within the congested zone is calculated by assuming that traffic continues to travel towards the pipeline release for 5 minutes, causing a queue of vehicles spaced at 5 m intervals. This length of time has been chosen for a screening approach although it is acknowledged that it is difficult to predict people's reactions to such an unforeseen event.

Outside of the congested zone, vehicles approaching the accident are assumed to stop at an average spacing determined by the traffic flow and speed assumptions for the road.

Parallel roads

Traffic is predicted to build-up in a 'congested zone'; the number of vehicles involved is predicted by assuming that traffic continues to travel towards the cloud for 5 minutes, causing a queue of vehicles in both directions. See Figure A1 (b).

Outside of the congested zone, vehicles approaching the accident are assumed to stop at an average spacing determined by the traffic flow and speed assumptions for the road. This applies to both sides of the road.



(a) Perpendicular road crossing (b) Parallel road

Figure A1 Schematic Diagram of the Road Methodology

It is assumed that each vehicle carries an average of two people and so the average number of people per metre of road inside and outside of the congested zone can be calculated for each road type for normal traffic flow.

The length of the congested zone is different for each road type and is determined by calculating the number of vehicles that would build up in 5 minutes and by calculating the distance that these would extend if they stopped at 5 m intervals.

This approach has allowed a required separation distance to be defined for each road type in the case of a road parallel to the particular pipeline and a pass/fail preliminary screening to be applied for the case of a road perpendicular to the pipeline, assuming the roads are in rural areas outside of the development areas defined earlier. It is recommended, however, that a full risk assessment should be performed if the pipeline had the potential to interact with a motorway or equivalent major dual carriageway in order to help refine the above approach for these cases as required.