THEORY

ROUTE

DATE: December 2023

In preparation for risk calculations along a route, this model takes the definition of the route in the form of the geometric shape of the route and provides discrete locations at which to position the equivalent release points and calculates the appropriate release frequency.

No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
1	September 2006	First time theory is written down	David Worthington	Hugh Cherry	
2	January 2007	Update polyline theory and include discussion on model verification and sensitivity analysis.	Ade Oke		
3	February 2014	SAFETI 7.2 version	A. O. Oke	David Worthington / Mike Harper	
4	June 2014	Prepared for ROUTE appendix use.	A. O. Oke	Colin Hickey	
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6	October 2017	Updates for Safeti 8.0	A.Oke	H. Witlox	
7	March 2020	Updates for Safeti 8.3	A. Oke	David Worthington	
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Date: December 2023

Prepared by: Digital Solutions at DNV

ABSTRACT

In preparation for risk calculations along a route, this model takes the definition of the route in the form of the geometric shape of the route and provides discrete locations at which to position the equivalent release points and calculates the appropriate release frequency.

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1. INTRODUCTION

The route model is used in the risk calculations to represent failures that can occur at any point along a given line representing a ‘route’. Typically this might represent a pipeline or a vehicular transportation route. A collection of events known as a ‘model group’ may be distributed along any number of route ‘segments’ each defined as lines on the map.

This model is a powerful tool in the risk analysis because it allows consequence results to be shared between the many possible equivalent discrete failures that can occur along the route. This saves considerable amounts of user input time, processor time and disk storage.

Each route segment may be assigned a failure frequency on a per segment or per unit length basis. The user may control the event discretisation to suit the output resolution desired. The user may also define ‘parallel tracks’ so for instance shipping channels may be represented with minimum of user input time.

1 EVENT LOCATIONS

1.1 Available shapes

The route is defined as one or more geometric shapes. The allowed shapes are straight lines, polylines and arcs of circles. The list of shapes associated with a route do not need to be physically connected and do not share any properties except being grouped under a particular route folder. In this sense each shape may be considered as an independent route. Each shape may be one or more parallel routes and these parallel routes do share the other properties of the original shape.

1.2 Straight Line Segment

The simplest shape is a single straight line segment. It is defined by the coordinates of two points. This represents the main route. Then there can be any number of parallel tracks (subject to software limitations). These tracks are defined by a fixed translation between the main route and the track such that there is constant offset between the line and the tracks and the offset is normal to the main route. The convention is that the offset is to the right side of the line considering the route to have a direction from point 1 to point 2.

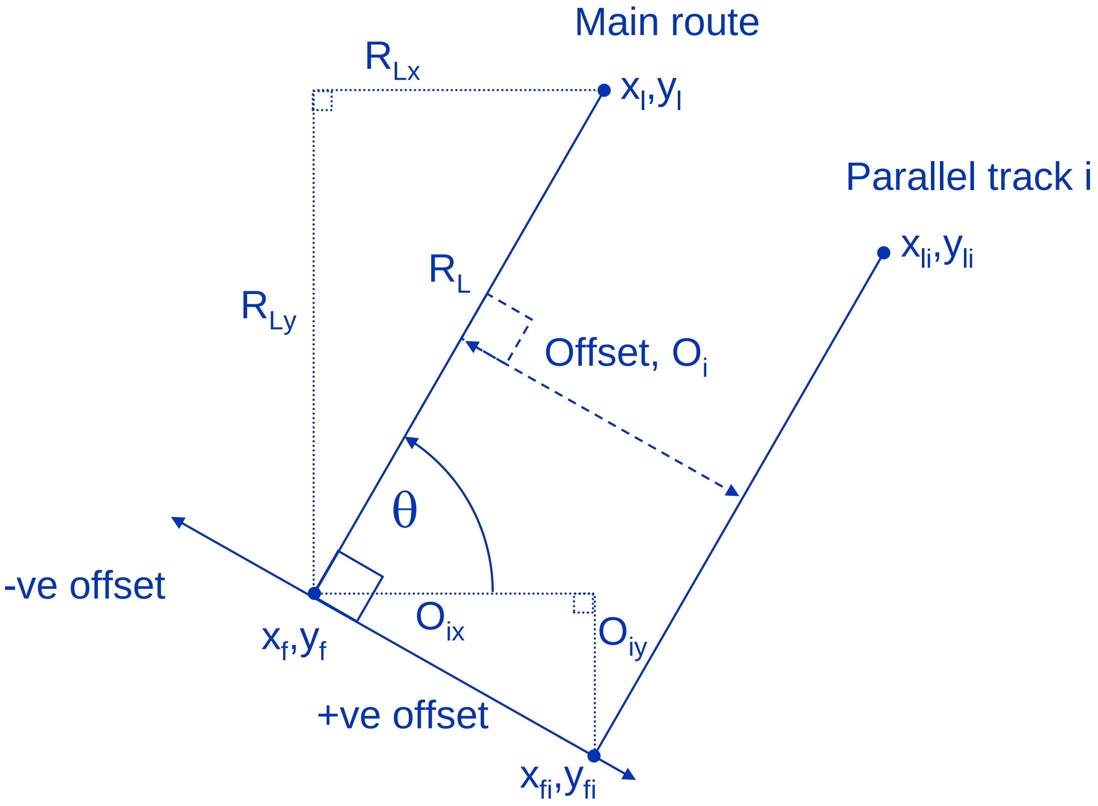

Figure 1 - Straight line route segment with parallel track

The length of the route segment may be obtained by applying Pythagoras' theory. Note that if the length is less than 0.001m then the model will give an error and not run.

The start and end coordinates of the parallel tracks can be calculated by considering the similar triangles formed by the main route and the offset vector. The equivalent position on the transect, i to the main route, R can then be defined as

$$\begin{pmatrix} x \\ y \end{pmatrix}_i = \begin{pmatrix} x \\ y \end{pmatrix}_R + \frac{O_i}{R_L}\begin{pmatrix} y_l - y_f \\ x_f - x_l \end{pmatrix}_R \tag{1}$$

The actual spacing of equivalent events along the lines is guided by the user input ‘spacing of events’ but this will not normally be the actual spacing. The algorithm starts by working out how many points to use first. The formula is

$$\boldsymbol{N = MAX\left|1, INT\left|\frac{R_L}{S_U} + 0.49\right|\right|} \tag{2}$$

Then the points are distributed evenly between the start and finish coordinates of the line using the actual spacing:

$$S_A = \frac{R_L}{N} \tag{3}$$

This in effect gives a half spacing between the start and end coordinates of the line

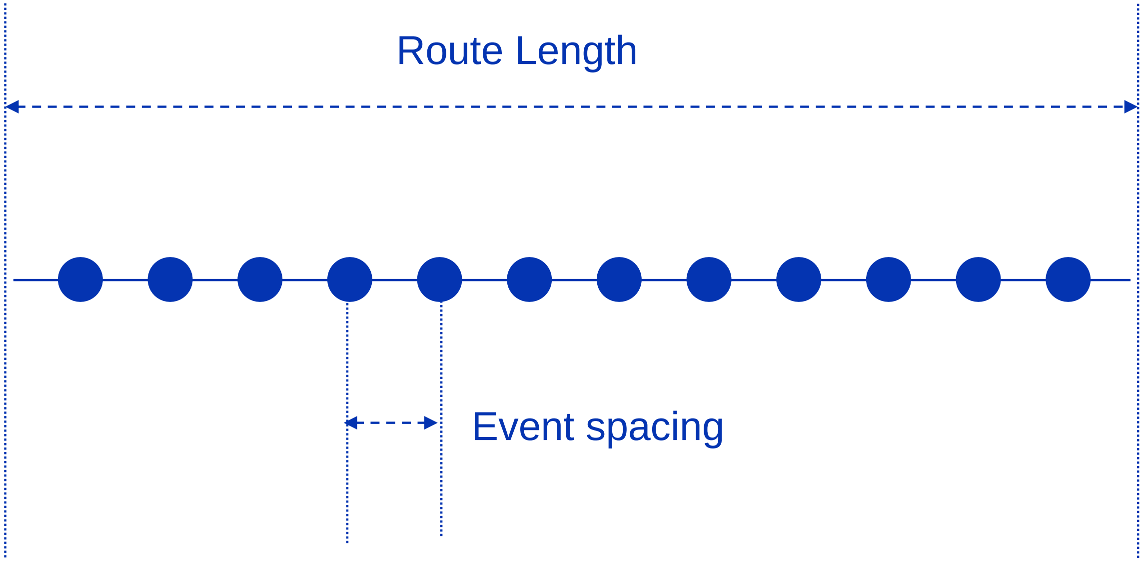

Figure 2 – Even spacing of events along the route

The coordinates of each event, j may then be calculated by interpolation between the first and last points on the line.

$$\begin{pmatrix} x \\ y \end{pmatrix}_j = \left(1 - \frac{j - 0.5}{N}\right)\begin{pmatrix} x \\ y \end{pmatrix}_f + \left(\frac{j - 0.5}{N}\right)\begin{pmatrix} x \\ y \end{pmatrix}_l \tag{4}$$

1.3 PolyLine Segment

Polylines for the main route may be treated exactly in the same way as a number of adjacent and independent straight line segments. However, the parallel tracks require a different treatment to define their behaviour at the intermediate intersections. The approach taken is illustrated below for a 4 points, 3 segment polyline;

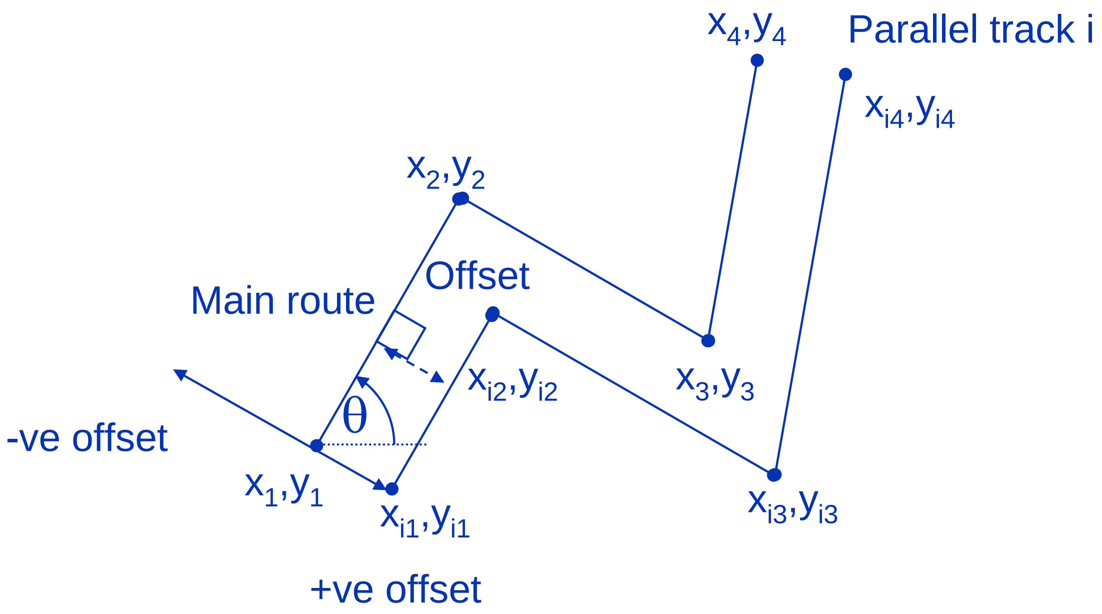

Figure 3 - Polyline geometry with parallel track

The first and last points of the polyline track may be calculated according to the translation method of equation (1).

For the intermediate points we can obtain the position of the parallel track intersection by summing both translations to the location of the common point on the main track. This will then give a new set of coordinate points for the polyline that defines the parallel track. There is no restriction on the polyline shape so that overlaps are possible.

The general equation of each line (*k, k=1,2…m*) on the main route can be written as:

$$0 = A_k x_{R,k} + B_k y_{R,k} + C_k \tag{5}$$

Two non-parallel lines can only intersect at a point. Thus, for two adjacent non-parallel lines (*k* and *k+1*) on the main route *R*, the co-ordinates of the intermediate point formed by the intersection of parallel tracks to *k* and *k+1* at a fixed offset distance O_i must be unique and satisfy equation (1) for lines *k* and *k+1*. Thus:

$$\begin{pmatrix} x \\ y \end{pmatrix}_i = \begin{pmatrix} x \\ y \end{pmatrix}_{R,k} + \frac{O_i}{R_{L,k}} \begin{pmatrix} y_l - y_f \\ x_f - x_l \end{pmatrix}_{R,k} = \begin{pmatrix} x \\ y \end{pmatrix}_{R,k+1} + \frac{O_i}{R_{L,k+1}} \begin{pmatrix} y_l - y_f \\ x_f - x_l \end{pmatrix}_{R,k+1} \tag{6}$$

Rearranging equation (6) yields:

$$\begin{pmatrix} x \\ y \end{pmatrix}_{R,k+1} = \begin{pmatrix} x \\ y \end{pmatrix}_{R,k} + \frac{O_i}{R_{L,k}} \begin{pmatrix} y_l - y_f \\ x_f - x_l \end{pmatrix}_{R,k} - \frac{O_i}{R_{L,k+1}} \begin{pmatrix} y_l - y_f \\ x_f - x_l \end{pmatrix}_{R,k+1} \tag{7}$$

Substituting equation (7) into equation (5) for lines *k+1* and *k* yields the following equation for the point $(x_{R,k}, y_{R,k})$ along the line *k* where the pair of parallel lines to the main route *R* intersect:

$$\begin{bmatrix} A_k & B_k \\ A_{k+1} & B_{k+1} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}_{R,k} = -\begin{bmatrix} C_k \\ C_{k+1} + A_{k+1} S_{k,1} + B_{k+1} S_{k,2} \end{bmatrix} \tag{8}$$

Where

$$\begin{bmatrix} S_{k,1} \\ S_{k,2} \end{bmatrix}_{R,k} = \frac{O_i}{R_{L,k}} \begin{pmatrix} y_l - y_f \\ x_f - x_l \end{pmatrix}_{R,k} - \frac{O_i}{R_{L,k+1}} \begin{pmatrix} y_l - y_f \\ x_f - x_l \end{pmatrix}_{R,k+1} \tag{9}$$

Substituting $(x_{R,k}, y_{R,k})$ in equation (6) yields the co-ordinates of the intermediate point formed by the intersection of parallel tracks at a fixed offset distance O_i from lines *k* and *k+1*. In the special case where lines *k* and *k+1* are parallel (i.e. a straight line), $(x_{R,k}, y_{R,k})$ correspond to the point of intersection of lines *k* and *k+1* on the main route.

Note that as offset distances increase, depending on the sign of the offset, the direction of parallel lines may be reversed relative to the direction of their corresponding line on the main route. For positive offsets, reversal of direction will only affect pair of lines on the main route that are oriented in the same way as the starting pair (i.e. convex orientation), while the converse holds for negative offsets.

1.4 Arc Segment

The arc is defined by 3 points, a first point, an intermediate point and then a last point. These points have to be processed to derive the fundamental properties of the arc so that the route calculations can be performed. The first task is to determine the centre of the circle on which the 3 points lie. The method employed is to construct lines between the lines and then find the intersection between the mid-point normal lines. This intersection will be the centre of the circle.

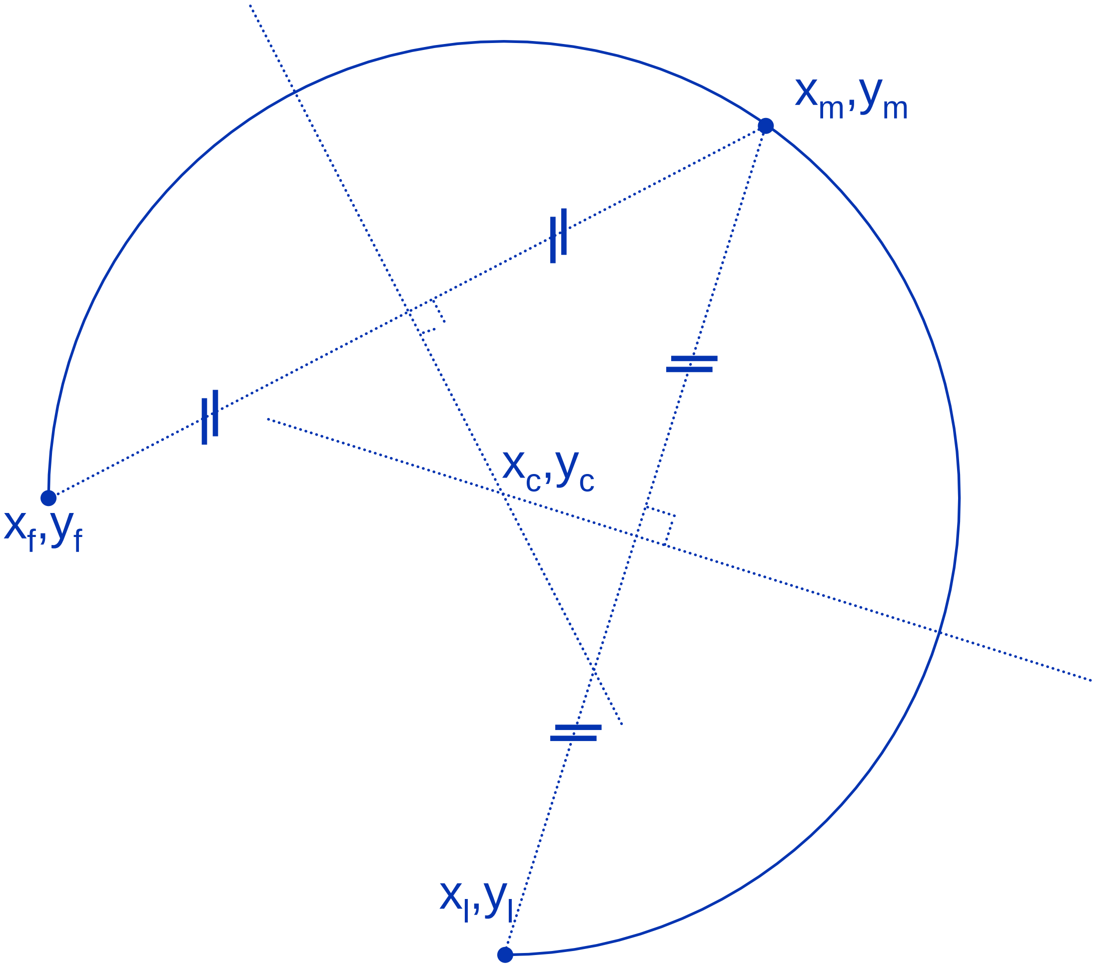

Figure 4 - Derivation of circle centre from 3 points

The derivation of the coordinates of the centre may be found on the web[i] and in text books. The form used in the Route model is

$$x_c = -\frac{y_f\left(x_m^2 - x_l^2 + y_m^2 - y_l^2\right) + y_m\left(x_l^2 - x_f^2 + y_l^2 - y_f^2\right) + y_l\left(x_f^2 - x_m^2 + y_f^2 - y_m^2\right)}{2\left(y_f\left(x_l - x_m\right) + y_m\left(x_f - x_l\right) + y_l\left(x_m - x_f\right)\right)} \quad (10)$$

$$y_c = -\frac{x_f\left(x_m^2 - x_l^2 + y_m^2 - y_l^2\right) + x_m\left(x_l^2 - x_f^2 + y_l^2 - y_f^2\right) + x_l\left(x_f^2 - x_m^2 + y_f^2 - y_m^2\right)}{2\left(y_f\left(x_l - x_m\right) + y_m\left(x_f - x_l\right) + y_l\left(x_m - x_f\right)\right)} \quad (11)$$

The radius of the circle may be calculated using Pythagoras' theory and the coordinates of one of the points and the centre of the circle.

If the model is given a set of three points where two of them coincide then it is assumed that the line between the two points represents a diameter of a circle and the events are distributed over the whole circle. If all three points coincide then the event locations are treated as a single point[1].

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[1] There seems to be an issue of precision here. The comparison made in the code does not include a tolerance so that it is a bit hit and miss whether the identical points are recognised or not and some strange effects can happen. Also the definition of a parallel track for the three coincident points ought to be a circle but it seems to be another point. We could just introduce a tolerance (0.001m as for single line segments?) and trigger an error when all 3 points are the same. 2 the same seems to be a useful way for the user to define a circle. Note that the GUI does not display parallel tracks.

The event locations may then be defined in a similar manner to the straight line segment except that the relevant lengths are along the circle circumference.

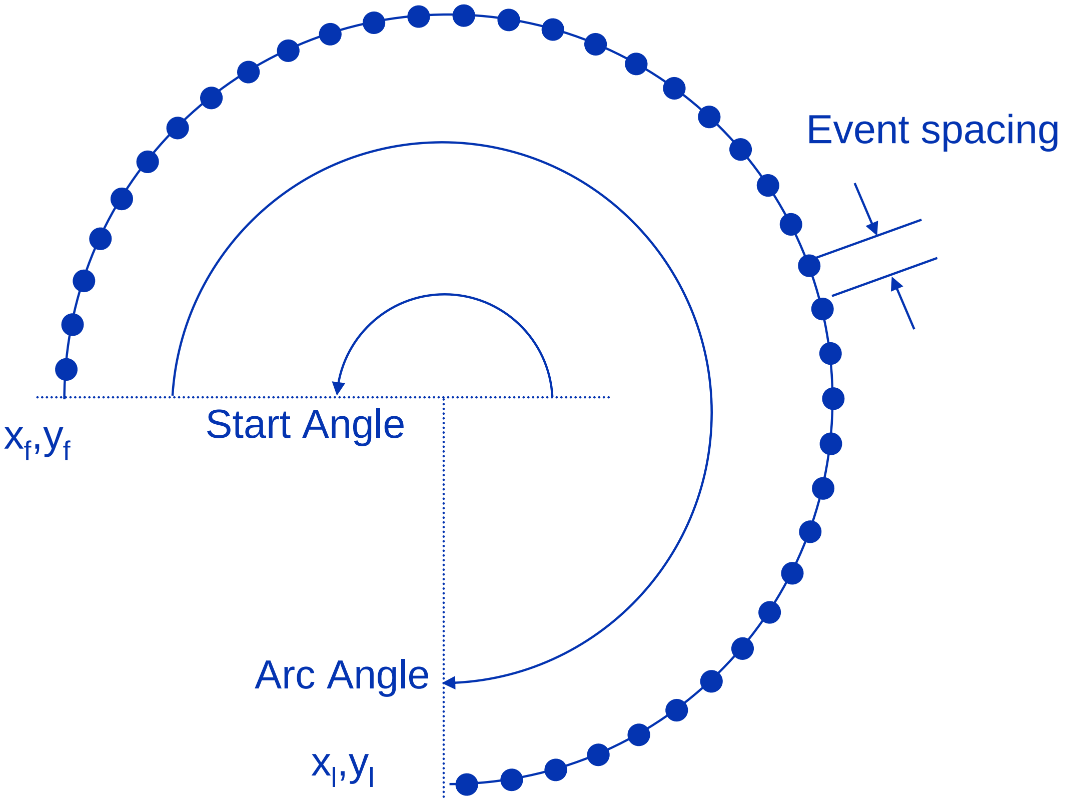

Figure 5 - Spacing of events around the arc

$$\begin{pmatrix}x\\y\end{pmatrix}_j = \left(1-\frac{j-0.5}{N}\right)\begin{pmatrix}x\\y\end{pmatrix}_f + \left(\frac{j-0.5}{N}\right)\begin{pmatrix}x\\y\end{pmatrix}_l \qquad \textbf{(12)}$$

The angle between each event is calculated from the overall arc angle and the number of discrete locations.

$$\Delta\theta_A = \frac{\theta_A}{N} \qquad \textbf{(13)}$$

Then the angle for each location to be calculated may be obtained by interpolation;

$$\theta_j = \theta_f + (j-0.5)\Delta\theta_A \qquad \textbf{(14)}$$

Then the coordinates of the events may be obtained by translation from the centre as;

$$\begin{pmatrix}x\\y\end{pmatrix}_j = \begin{pmatrix}x\\y\end{pmatrix}_c + R_A\begin{pmatrix}\cos\theta_j\\\sin\theta_j\end{pmatrix}_l \qquad \textbf{(15)}$$

The parallel routes for arcs are defined according to the direction of rotation between the first point and last point of the arc. If the rotation is clockwise then the offset is towards the centre of the circle, otherwise the offset is away from the centre. This is illustrated below;

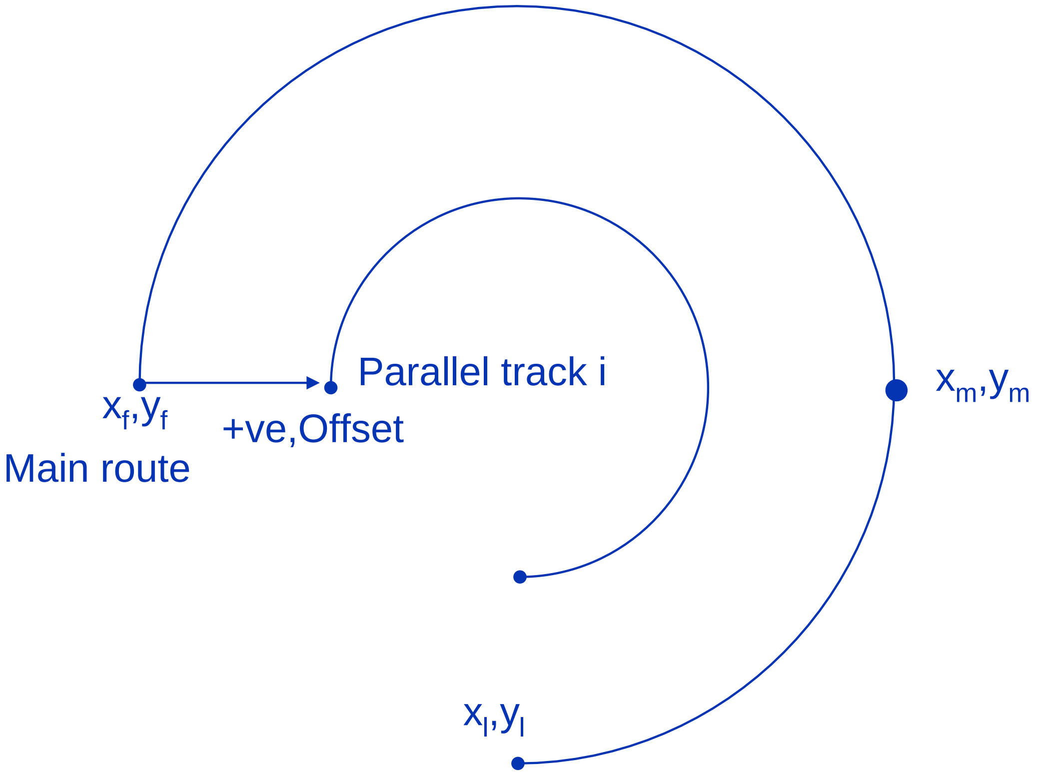

Figure 6 - Definition of parellel tracks for arc segments

It may be seen that the offset becomes an adjustment to the radius while the angles remain the same for each track. Note that if the offset is towards the centre of the arc and greater than the radius then the parallel track is still defined but will appear opposite the main track relative to the arc centre.

1.5 Event Frequency

The failure frequency may be defined by the user on a per segment or per unit length basis. If the per unit length basis is used then the failure frequency for the route segment is calculated as;

$$F_{UR} = \frac{R_L F_U}{L_U} \qquad \textbf{(16)}$$

The frequency per event is derived from this failure frequency and the remaining user inputs. Each event has an event probability used to indicate what proportion of the failures are to be modelled as that type of event. Furthermore if additional tracks are present then there is a further probability used to distribute the failures between the tracks. If there are no parallel tracks then the track probability P_i is 1. In general the frequency per event on a given track *i* is given by :

$$F_i = (P_E P_i)\frac{F_{UR}}{N} \qquad \textbf{(17)}$$

This treatment for frequency is general to each of the geometry types. For the polyline shapes the failure frequency per straight line segment is calculated according to the proportion of the length of the segment to the overall polyline length. Then the normal frequency distribution is applied according to equation (16).

2 VERIFICATION

This following discusses the verification of the Route Model. As a polyline segment is comprised of discrete line segments, the verification exercise will only investigate the validity of simulated results for polylines and arcs.

2.1 Verification of Polyline (line) modelling

Figure 7 illustrates the main route employed in the polyline verification exercise.

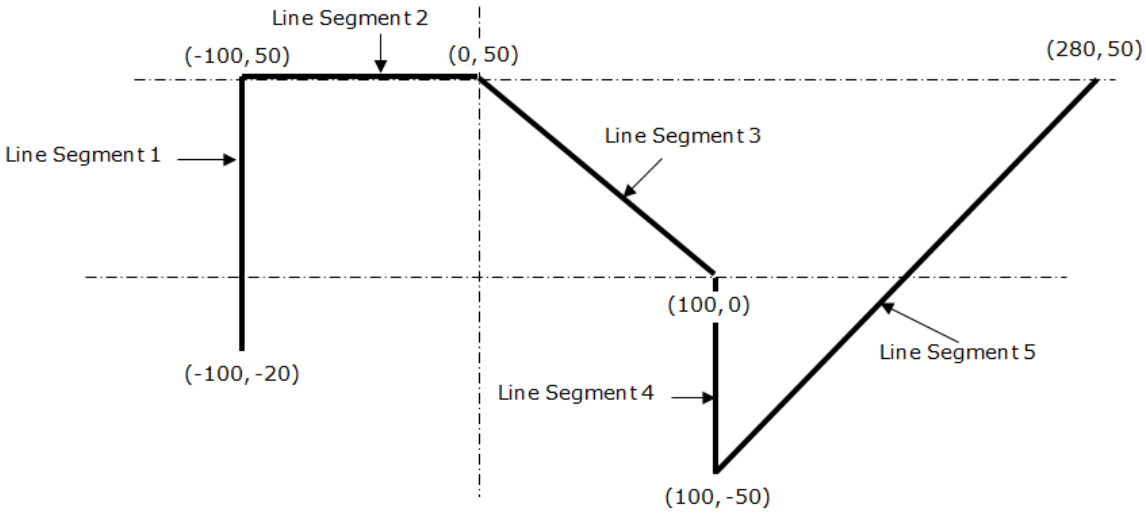

Figure 7 – Polyline diagram for Route model verification

An event spacing of 2m is specified, while the simulation of parallel tracks with offset distances corresponding to 10m, 25m, 40m, -25m and -50m are desired. The following presents simulated results using the Route model.

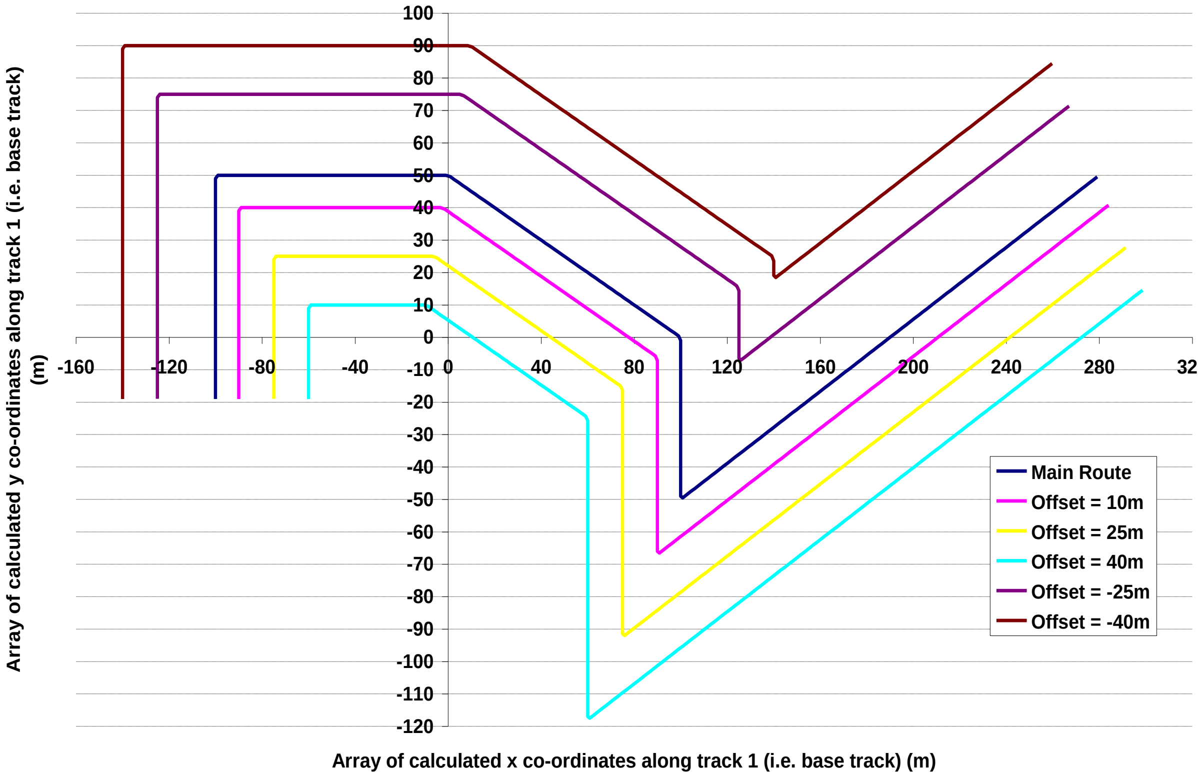

Figure 8 – Simulated results of Main Route and parallel polyline tracks using the Route Model

From Figure 8, it can be observed that each simulated track is parallel to and at the desired offset distance from the main route. As designed, parallel tracks with negative and positive offset distances lie to the left and right of the main route respectively.

	Event Spacing (m)				
	Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 5**
Main Route	2	2	1.996	2	1.999
Offset = 10m	2	1.991	1.986	2.027	2.008
Offset = 25m	2.045	1.974	2.010	1.975	2.003
Offset = 40m	2	2.022	1.991	1.984	1.999
Offset = -25m	2.021	2.014	1.987	2.088	1.993
Offset = -40m	2	1.993	2	2.247	1.999

Table 1 Simulated event spacing for each line segment along the main route and parallel line tracks

Table 1 shows the simulated event spacing for each line segment along the main route and parallel line tracks. For these set of cases, simulated event spacing generally lie within +12.4% and -1.3% of the desired spacing. These values lie within the maximum deviation (i.e. +50% {R_L = 3m} and -99.99% {$R_L \rightarrow$ 0m}) corresponding to the specification of an event spacing of 2m in equation (2).

2.2 Verification of Arc modelling

3 points along the circumference of a circle of radius [R_c] 20m with centre (x_c = 10m, y_c = -5m) are defined in the Route model as follows:

	Θ (deg)	$x_p = R_c \cos \Theta + x_c$	$y_p = R_c \sin \Theta + y_c$
Point 1	17	29.12609512	0.847434094
Point 2	155	-8.126155741	3.452365235

Point 3	317	24.62707403	-18.6399672

It is desired to simulate parallel tracks at offset distances of 5m, 10m, -5m, -25m and -60m with an event spacing of 2m. The following presents simulated results using the Route model.

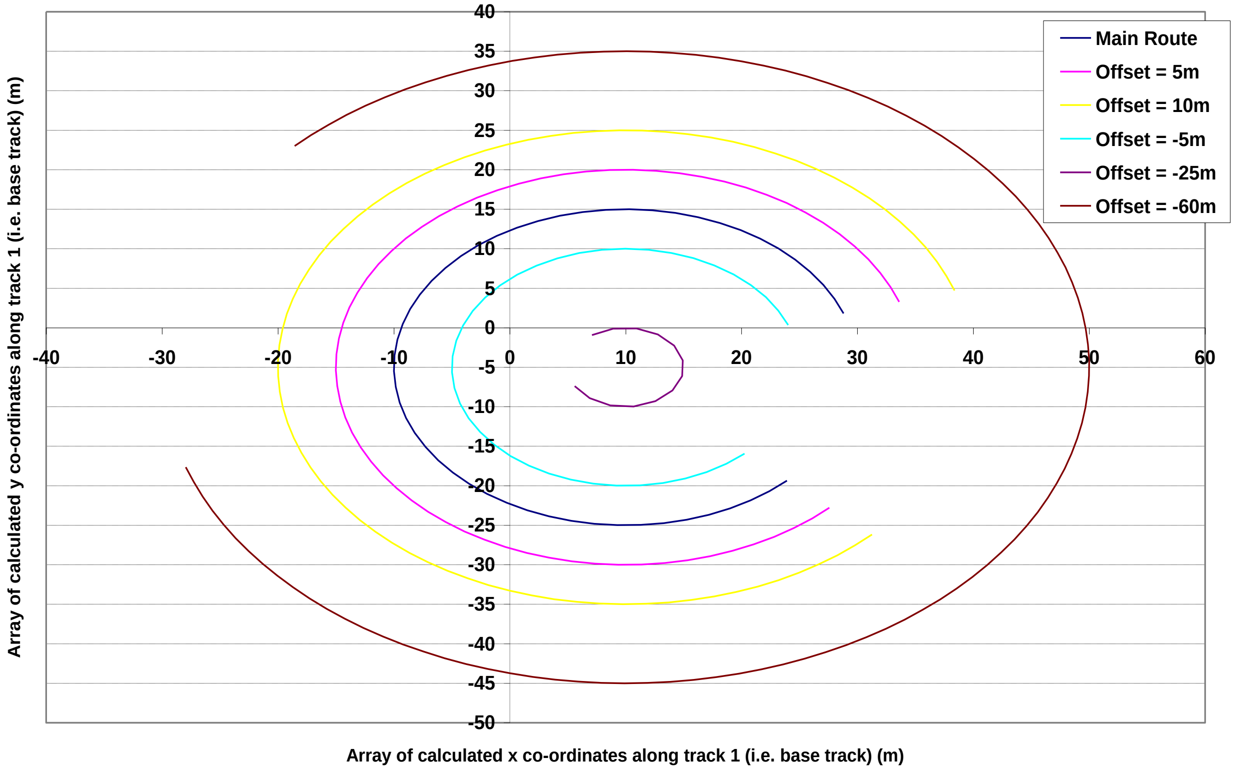

Figure 9 – Simulated results of Main Route and parallel arc tracks using the Route Model

From Figure 9, it can be observed that the simulated main route and parallel tracks are concentric with a common centre at (x_c = 10m, y_c = -5m). As the direction of the main route from the starting point is counter-clockwise, positive offsets are away from the centre of the circle, while the converse holds for negative offsets.

As designed, where the offset is towards the centre of the circle and greater than the radius of the main route (e.g. Offset = -25m and Offset = -60m), the parallel track is still defined but appears opposite the main track relative to the arc centre. The radii of the parallel tracks for these cases correspond to the absolute value of the difference of their offset distances and the main route's radius.

	Event Spacing (m)
Main Route	2.013
Offset = 5m	2.013
Offset = 10m	1.988
Offset = -5m	2.012
Offset = -25m	2.000
Offset = -60m	1.994

Table 2 Simulated event spacing for the main arc route and parallel tracks

Table 2 shows the simulated event spacing for the main arc route and parallel tracks. For these set of cases, simulated event spacing generally lie within +0.65% and -0.6% of the desired spacing. These values lie within the maximum possible deviation (i.e. +50% {*Arc length* = 3m} and -99.99% {*Arc length* → 0m}) for a desired event spacing of 2m.

3 SENSITIVITY ANALYSIS

Simulated results obtained from the Route model are primarily influenced by the specified event spacing and offset distance. The latter is of primary importance as it can affect the final shape (position and orientation) of simulated parallel tracks (see Figure 9). Event spacing on the other hand will only affect the granularity of simulated shapes. The smaller the specified event spacing the finer and better the granularity of simulated shapes. No single value can be suggested as optimum for event spacing as the “best” value will vary with polyline/arc size.

The effect of stipulating a relatively wide range of positive and negative offset distances for arcs has been demonstrated in section 2.2 (see Figure 9). Thus, the following discussion will be limited to the investigation of the sensitivity of polylines to offset distances.

Once again, the main route illustrated in Figure 7 is employed in the sensitivity analysis. A fixed event spacing of 4m is specified, while parallel tracks corresponding to offset distances of -400m, -200m, -100m, -50m, -25m, 25m, 50m, 80m, 100m and 400m are simulated. Simulated results using the Route model are presented and discussed below.

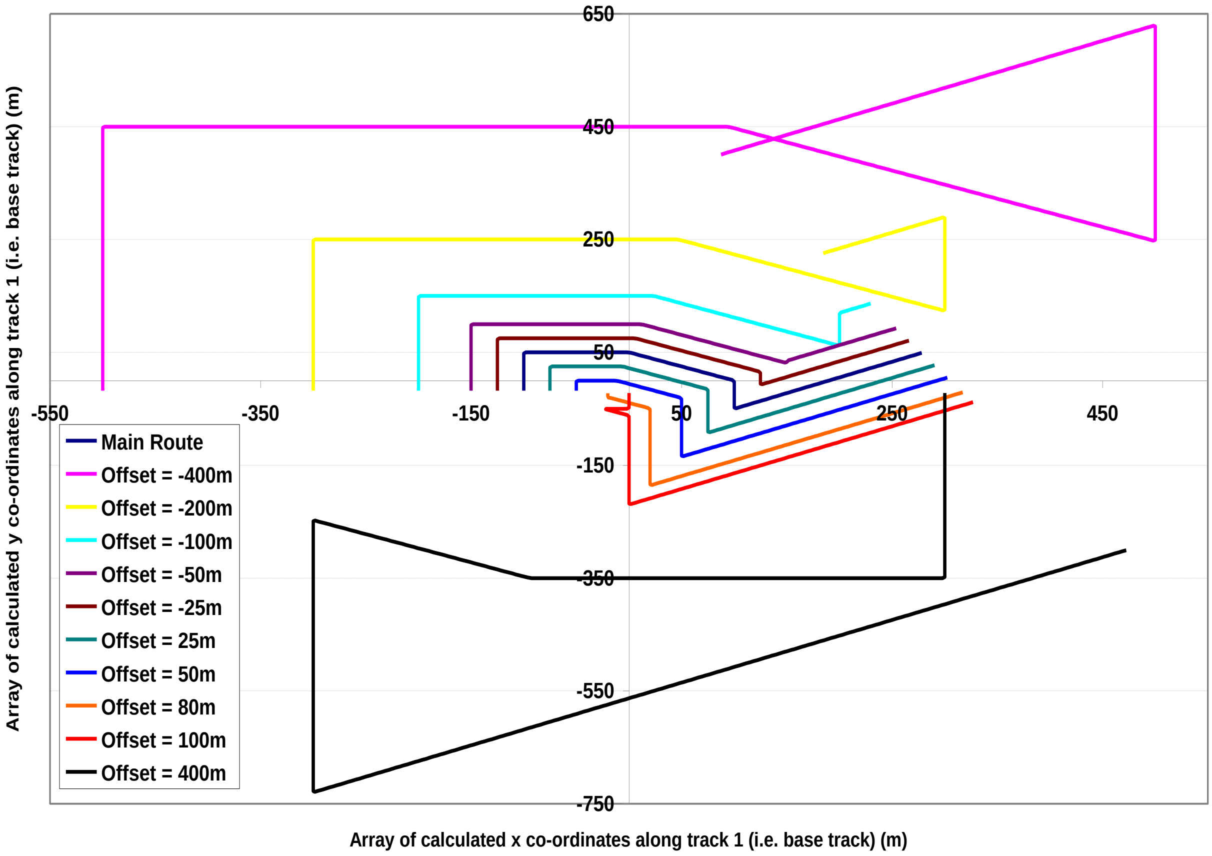

Figure 10 – Simulated results showing main route and parallel polyline tracks following sensitivity analysis of the polyline Route model to offset distances.

From Figure 10, the following can be observed:

- As positive offset distances increase, parallel tracks corresponding to line segments 1, 2 and 3 on the main route gradually reduce in size to a minimum value and thereafter increase. At offset distances greater than ca 70m, parallel tracks corresponding to line segment 1 on the main route are reversed in direction. This reversal in direction is observed by parallel tracks corresponding to line segments 2 and 3 on the main route at offset distances greater than ca 80m and 130m respectively. As mentioned earlier, only pairs of lines with the same orientation as the starting pair show reduction in size and reversal in direction.

- On the other hand, as negative offset distances increase, only parallel tracks corresponding to line segments 4 and 5 on the main route experience a gradual reduction in size to a minimum value followed by an increase. At offset distances greater than ca -46m and -120m, a reversal in direction will be observed for parallel tracks corresponding to line segments 4 and 5 respectively. As mentioned above, only pairs of lines with different orientation (concave orientation) to the starting pair are expected to show this behaviour.

In all, the above illustrates the sensitivity of simulated polyline routes to increasing (and decreasing) positive or negative offset distances. Other than a fixed displacement from the main route, parallel tracks to a single straight line segment will not show any other sensitivity (e.g. size reduction) to increases in positive or negative offset distances.

4 FUTURE DEVELOPMENTS

Potential future developments which may be considered as future implementation in the product are as follows:

- (SI6915) Display parallel tracks in the GUI.
- (SI6761) Tighten up the special cases of coincident points in the arc geometry definition.
- (SI6917) Rationalise the event location reporting.
- (SI6918) Automate the event spacing logic for transportation route scenarios (apply model developed for pipeline route scenarios as described in Appendix A)
- (SI6919) Route model could have other properties such as population and ignition

NOMENCLATURE

R_L	Length of the route segment /m
R_{Lx}	Length of the route segment in x direction /m
R_{Ly}	Length of the route segment in y direction /m
O_i	Offset of parallel track i /m
O_{ix}	Offset of parallel track i in x direction /m
O_{iy}	Offset of parallel track i in y direction /m
N	Number of equivalent discrete failure locations along a route segment
P_E	Event probability /-
Pi	Track proportion /-
S_U	User input failure spacing /m
S_A	Actual failure spacing used /m
x	Coordinate position in x direction /m
y	Coordinate position in y direction /m
θ_A	Total arc angle /rad
$\Delta\theta_A$	Incremental arc angle between failure location /rad
R_A	Arc radius /m
F_{UR}	Failure frequency per segment /av year
F_U	Failure frequency associated with user-defined length /av year
L_U	Length associated with user input failure rate for a given length /m
F_i	Failure frequency per event /av year

Subscripts

c	centre of arc
f	first point
l	last point
m	mid point
i	parallel route index
j	event index

k	polyline track index
R	main route

APPENDICES

Appendix A. Pipeline Route Model in PHAST/SAFETI 7.20 and subsequent releases

This document describes the long-pipeline route modelling design as implemented within the DNV Model Development Environment (MDE) and deployed in PHAST/SAFETI 7.20 and subsequent releases.

A1. Introduction

This document describes the long-pipeline route (LPR) modelling design and algorithm as implemented within the MDE and deployed in PHAST/SAFETI 7.20 and subsequent releases.

Prior to SAFETI 7.2, LPR modelling was undertaken by defining long pipeline releases at representative breach locations and applying simulated consequences in risk calculations at equidistant intervals along transport route segments (see section 1). Simulated consequences did not vary along the pipeline ('transport') route. Furthermore, the user defined pipeline length in these cases had no relationship with stipulated transport route geometry: i.e., it was possible to define transport route geometry segments with overall lengths shorter or longer than input pipeline length. In SAFETI 8.3 and subsequent releases, these 'transport route' based pipeline releases are fully supported as well and may be defined as equivalent pipeline releases ("pipeline points") at specific breach locations. The treatment of 'transport route' releases, including pre SAFETI 7.2 equivalent pipeline releases, are discussed under sections 1 - 4.

The PHAST/SAFETI 7.20+ long-pipeline route (LPR) model is an implementation (and extension) of the various features supported by the bespoke Pipeline Risk Spreadsheet tool ("PipelineXls") within the MDE[2]. The LPR model was developed as part of PHAST / SAFETI 7.2 project and serves as a replacement of "PipelineXls". With the LPR model, users may easily define and develop risk studies within PHAST / SAFETI in line with pipeline QRA methodologies set out in the DNV 'A Guide to Gas Pipeline Risk Modelling using Phast Risk' (2009) and the OGP Risk Assessment Data Directory "Consequence modelling" report (OGP, 2010-434-7). The LPR model also allows the MDE (and clients) to support additional pipeline consequence and risk modelling features not previously supported within "PipelineXls" nor earlier versions of PHAST/SAFETI.

The following is a summary of the various new features available to clients of the LPR model via the MDE and post PHAST/SAFETI 6.7 software releases. These features include:

- Automatic and configurable pipeline segmentation and event spacing based on hazard zone sizing
- Automatic and configurable failure case generation along the pipeline
- Multi-segment valve and inventory interactions
- Buried pipeline release modelling
- Event tree customization for pipeline scenarios

The following sections present the LPR modelling theory, design and algorithm as implemented within the MDE in relation to each of the aforementioned features.

The LPR model has been developed within the existing MDE "Route" model and relies on a number of MDE models in achieving its objectives. These models are:

- **PBRK (and GSPP)**. Calculates initial steady / time varying discharge characteristics including safety system behaviour following pipeline rupture / large leak events.
- **TVD2[3]/DISC**. Simulates time varying / quasi-steady state discharge from small aspect ratio[4] leaks. TVD2 also handles the modelling of impact associated with safety system performance on discharge characteristics. Note that it is planned to support TVD2 and its associated safety system performance modelling features in future versions of PHAST/SAFETI (i.e. post PHAST/SAFETI 8.0).

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[2] Readers may refer to the "PipelineXls" user manual for further details

[3] FUTURE: It is planned to support TVD2 modelling in later versions of PHAST/SAFETI (i.e. post 8.0)

[4] Leak diameter / pipeline diameter

A2. Definitions and Supported Functionalities for Model Clients

The following provides further description of the LPR supported functionalities, input data requirements and pertinent modelling results. It is sub-divided into sections with each describing a key functionality. The design procedure for LPR model execution is to first call a number of initialisation routines (see section A4). Individual methods are then called for the required functionality.

Figure 11 is a simple illustration of a (straight-run) long pipeline system and its various attributes (nodes and sections). The key "flow control" nodes along the length of the pipeline are represented (see Figure 11) by the safety valves at locations A, D and G.[5] Note the subsea release model capability is not yet implemented.

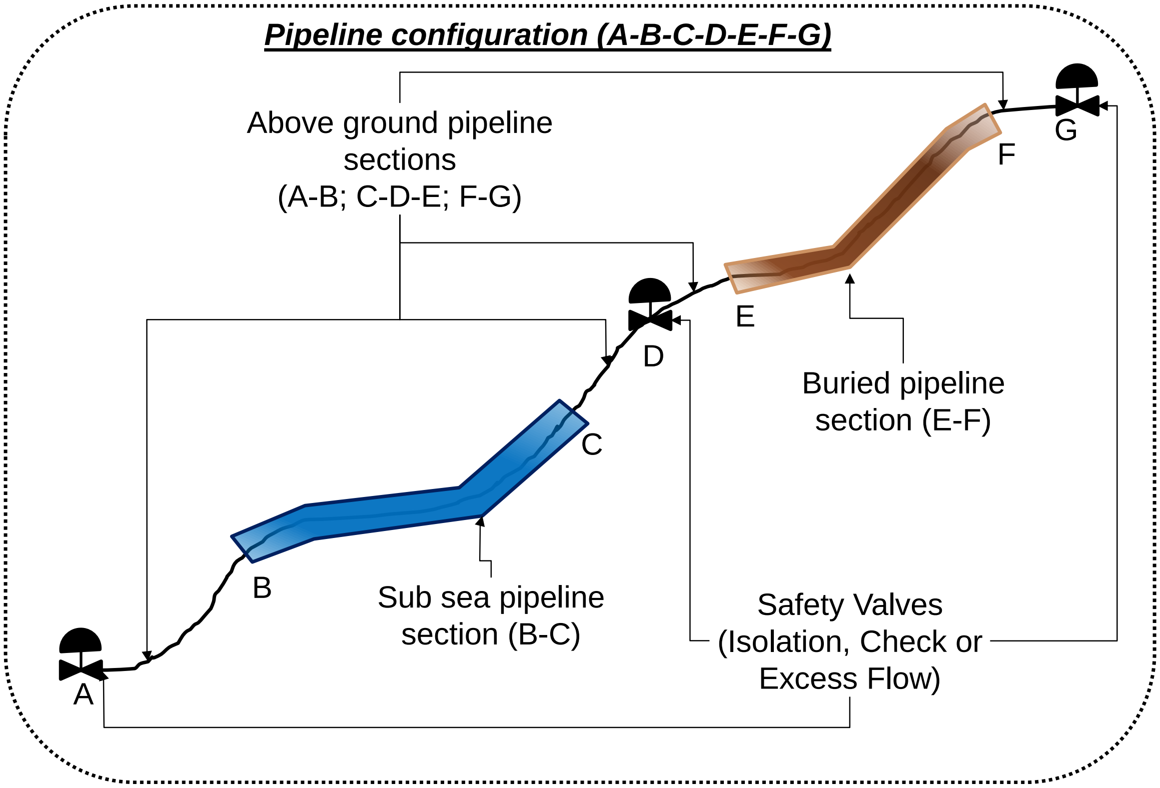

Figure 11. Illustration of typical nodes / features of a long pipeline system

A3. Definitions

For clarity, the following terms are used to describe elements of a pipeline system.

- **Pipeline Section**[6]: This is a region within a pipeline system bounded by isolatable valves, pumps/compressors or any physical attribute that may influence pipeline integrity[7] or flow behaviour following a loss of containment event[8]. The straight-run pipeline system illustrated in Figure 11 can be said to be made up of 6 pipeline sections: A-B, B-C (underwater), C-D, D-E, E-F (underground) and F-G.
- **Pipeline sub-section (or segment)**: A pipeline sub-section is a region within a pipeline section for which flow conditions are taken to be "approximately constant". Loss of containment events within a pipeline sub-section are typically represented by release conditions at the mid-point of the sub-section. A pipeline section may be comprised of 1 or more

---

[6] A region within a pipeline system along which pipeline conditions are "approximately constant"

[6] A region within a pipeline system along which pipeline conditions are "approximately constant"

[7] (e.g. piping class / spec. breaks ➔ different pipe wall thickness, diameter, or material)

[8] (e.g. overburden / burial, underwater conditions)

sub-sections[9]. The rule sets implemented in the LPR model for defining pipeline sections and sub-sections are discussed later.

- **Failure case / Event**: This is an event leading to loss of containment along the length of a pipeline system[10]. These events are typically located at equally spaced distance intervals along a pipeline sub-section or at fixed locations where specific activities with potential to lead to loss of containment events are identified[11]. A failure case may be comprised of one or more release scenarios with their associated event frequency (e.g. “small” 12mm, “medium” 25mm, “large” 75mm leaks and/or guillotine rupture with/without detection and isolation). In a risk study, one or more failure cases may be located along a given pipeline sub-section.
- **Release / accident scenario**: A release scenario is a specific realization of a failure case (e.g. a “small” 12mm leak, followed by detection and isolation). As mentioned above, a failure case may be comprised of one or more release scenarios placed at equally spaced distance intervals along a pipeline sub-section. The consequences associated with a release scenario are assumed to be constant within a pipeline sub-section. For the LPR model, four different types of release outcomes / scenarios may be typically modelled per release size for a fixed set of release parameters[12]:
    - **Un-isolated release**: here safety valves located upstream and downstream of the release event are assumed to fail (remain open) on leak detection / flow reversal or as a result of detection failure[13]
    - **Isolated release**: here, both upstream and downstream safety valves successfully close on leak detection / flow reversal
    - **Upstream isolation fails**: in this case, only the downstream safety valve successfully closes on leak detection / flow reversal
    - **Downstream isolation fails**: here, only the upstream safety valve successfully closes on leak detection / flow reversal

The discharge model selection logic for the various release scenarios detailed above as implemented in Safeti 8.0 is described in detail in Appendix B.

A4. Pipeline and section characteristics (LPR Input / Initialisation)

As a starting point, clients of the LPR model will need to define a pipeline configuration and associated section characteristics. The key input data to the LPR model are summarised below. The LPR model may be initialized via calls to dedicated entry points, along the lines of the data categories defined below. These entry point methods collate and process[14] the provided input for later use (i.e., during model execution).

A4.1. Pipeline Geometry

This will be supplied as a series of unique position vectors (X, Y, Z co-ordinates) spanning a region of interest or the entire length of the pipeline. Where the entire pipeline length is stipulated, the start and end points of the pipeline (e.g. positions A and G, see Figure 11) will need to correspond to the first and last position vectors on the array of position vectors respectively. It is also possible to restrict modelled releases to a region of interest under a pipeline route: in this case, users will need to stipulate the pipeline length upstream of the region of interest, overall pipeline length, as well as the pipeline geometry spanning the region of interest. The length of the region of interest (polyline) geometry may not exceed the user specified overall pipeline length, whilst the region of interest will be treated as the ‘live’ portion of the pipeline route[15].

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9 It should be noted that the terms pipeline section / segment is sometimes used interchangeably. In some texts, what we here refer to as pipeline segment is expressed as a pipeline section. However, for clarity, we define a pipeline segment as a sub-category of pipeline sections (i.e. pipeline sub-section).

10 As defined within the CMPT “Guide to offshore QRA”: failure cases are representations in a risk assessment of the range of possible accidents which might occur in reality. In the context of the LPR, two types of failure cases are modelled: leaks and ruptures. These may stem from a variety of initiating events (collision, excavation, corrosion, overpressure etc.).

11 These activities may include: road crossings, beach crossings, riser splash zones (areas for ship collision impact), excavation / construction sites etc.

12 Release parameters defining the specific dispersion source term characteristics and associated consequences: release direction, impingement option (use final velocity limit, or use velocity modification factor), impinged velocity limit or impinged velocity factor

13 This scenario covers both the detection failure and total isolation failure branches of the LPR risk event tree. Isolation failure may not be modelled following leak detection/flow reversal if zero probability of failure on demand is assigned to valve failure (e.g. fail safe systems). For check and excess flow valves, leak detection is inherent and the probability of detection may be assumed to be 1, whilst the probability of failure on demand is finite (> 0), except otherwise indicated.

14 These methods set up any needed data structures / work arrays (e.g. store local ‘editable’ copies of the input data) plus undertake error and data completeness checks

[15] That is, the effective pipeline route: for the purposes of consequence and risk modelling. Release scenarios may only be modelled within the stipulated region of interest. Note that inventory upstream and downstream of the region of interest may contribute to impact (e.g. due to reverse flow) from simulated releases.

A4.2. Flow conditions

Users will need to specify upstream / pipeline inlet flow conditions as input. The set of data to be specified include:

- Discharged material (identifier): material conveyed within pipeline system (single or multi-component mixture)
- Upstream pressure (N/m^2 gauge)[16]: This could correspond to the compressor / pump discharge pressure or vessel/reservoir (storage) pressure[17]
- Upstream temperature (K): As above, compressor / pump discharge or vessel/reservoir (storage) temperature
- Steady state pump inflow-rate (kg/s): initial steady state pumped inflow rate within pipeline (≥ 0 kg/s).

A4.3. Pipeline sections and characteristics

Clients will need to provide additional information on the physical characteristics of a pipeline and its surroundings as these vary along the length of the pipeline. The default pipeline (section) characteristics will be specified as standard pipeline (scalar) data. However, additional (user-defined) pipeline section information will need to be specified within the "Pipeline Section" input arrays. Where users define additional sections, any areas of the pipeline not covered by the additional sections will be assumed to be represented by the "default section". Details of pipeline configuration data that generally need to be specified by default and may be varied across sections include:

- **Section start distance**: this is the distance of the section start from pipeline inlet[18]. Note that this information is not required for the "default section". The position vector of the section start will be automatically derived from the distance input.
- **Section end distance**: as above, this is the distance of the section end from pipeline inlet[19]. Note that the "distance" of the section end must always be greater than its start. The array of pipeline sections need not be contiguously arranged[20], although sections may not overlap.
- **Pipeline diameter (m)**: The maximum pipeline diameter over all pipe-sections will be employed as basis for detailed consequence modelling. Full-bore rupture scenarios from smaller diameter pipeline sections will be modelled as relative aperture sizes (fractional area) of the largest pipeline diameter[21].
- **Failure frequency model**: Users may specify a number of options, i.e.:
    - **Use pipe thickness correlation**: this option uses the EGIG failure frequency correlation as developed by DNV and detailed in the DNV "Guide to Pipeline QRA" report. Two failure frequency calculation methods are supported but these are not available for selection by users of PHAST/SAFETI:
        - **Use exponential curve fit**: employed by default
        - **Use interpolation**: employ linear interpolation across the EGIG set of discrete failure frequency data.
    - **Specify failure frequency directly**: here, users will need to specify a failure frequency applicable to the section either in terms of:
        - **Overall section length**: failure frequency per year (/yr).
        - **Per unit length**: failure frequency per meter-year (/yr/m)
- **Pipe wall thickness (m)**: used in calculating the overall failure rate (/yr/m) associated with each section and wall-to-fluid heat transfer characteristics. Where required, the failure rate for each pipeline section is calculated using the relevant pipe-wall thickness. However, for wall-to-fluid heat transfer calculations, wall thickness is assumed to be constant across the pipeline length; the "default" (general pipeline data) wall thickness is used for detailed consequence modelling. [22]
- **Pipe roughness**: used in calculating pressure drop along a pipeline section. As with wall thickness, the "default" pipeline roughness data is used for detailed consequence modelling; pipe roughness data may not be specified for additional pipeline sections.

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[16] Material phase is not currently a required input to the LPR model. Users only need stipulate the upstream pressure and temperature to determine the fluid state in the pipeline. Sub-coolled liquids are not currently modelled by PBRK.

[17] Including liquid head if applicable

[18] An alternative will be for clients to specify this input as a position vector. However, supporting a position vector input will require clients to ensure 'valid' values are supplied, i.e., the specified position vector actually exists along the length of the pipeline. In addition, for consistency / convenience any position vector supplied as a section start location may need to be treated as part of the "Pipeline Geometry" information.

[19] Or simply, the distance of the end position from its start position…the method adopted (i.e. end position defined relative to pipeline inlet / section start position) could be defined by a global parameter. By default, it is assumed that section end positions will be defined relative to pipeline inlet.

[20] For example, for the pipeline configuration in Figure 11, users may specify the pipeline system in terms of 2 elements of the "Pipeline Section" arrays, i.e., Section "B-C", and Section "E-F". The LPR model will automatically define 4 additional sections to cover sections "A-B", "C-D", "D-E" and "F-G" each defined in terms of the "Default Section" data.

[21] The modelling of variable pipeline diameter is not currently supported within the MDE long pipeline models (GSPP and PBRK). It is judged that the proposed approach provides a reasonably conservative workaround. Increase in pipeline diameter results in lower pressure drop and higher pipeline inventory (hence, conservative hazard zone / risk results). However, to avoid over-conservative analysis, full bore rupture releases from smaller diameter pipelines will be modelled in terms of an equivalent aperture size, i.e., relative to the largest pipeline diameter, thus ensuring that any reduction in risks due to the effect of lower aperture area is captured. Note that flow-rate $\propto\sqrt{\text{(pressure drop)}}$, while flow-rate $\propto$ aperture area (hence conservatisms introduced due to lower pressure drop and higher inventory across the line are not expected to be very significant as long as the aperture area is correctly accounted for). Where users specify different pipeline section diameters, a warning will be issued by the MDE.

[22] IMPROVE: as with pipeline diameter GSPP / PBRK is unable to model the impact of varying pipe wall thickness on flow characteristics. As such, any data specified for additional pipeline sections will be ignored; only default data will be used.

- **Elevation** (m): the height of the section of the pipeline, with 0m as a minimum[23].

Each section should cover an area where one or more of the aforementioned pipeline configuration characteristics are observed to vary. The section data provided will aid the LPR model in selecting the appropriate source-term models and/or failure frequency data to employ. Where safety valves are located along the pipeline length, additional sections are automatically defined within the LPR model to capture this information (see later for rule-sets / methodology).

A4.4. Location and characteristics of safety valves

This defines the isolation nodes along the length of the pipeline. Appropriate information will need to be specified within the "Valve data" input arrays. These include:

- **Valve location (m)**: specified in terms of the distance of the valve from pipeline inlet.
- **Valve type**: three valve types are supported ➔
  - (Emergency) Shutdown valves: these will close automatically (or on operator action) following confirmed gas (leak) / fire detection.
  - Excess flow valves (EFV): these will close should the flow rate through the valve exceed a set point value
  - Check valves: these will close on detection of (or to counter) flow reversal at valve outlet
- **Valve closure time (s)**: this is the total time from the onset of release detection through to valve actuation/ shutdown[24]. The total time to upstream (pumped) or downstream flow isolation is the sum of the detection and valve closure times. Valve closure time is only relevant for ESDVs. It is assumed that Check valves and EFVs, by nature, are fast acting; as such, the impact of closure time is discounted.
- **Excess flow valve trip / set point (kg/s)**: this defines the set point flow rate for EFV action.
- **Probability of failure on demand (PFD)**: this defines the likelihood of the safety valve failing to perform its intended function[25]

A4.5. Failure cases / Release scenarios

The LPR model supports the modelling of generic and user defined failure cases and ensuing release scenarios

- **Generic failure cases**: users may employ the LPR to model generic failure cases along a pipeline sub-section. Each failure case corresponds to a specific release (aperture) size together with any special release characteristics (release direction etc.). For each aperture size and fixed set of release parameters (e.g. release orientation) up to four different release scenarios may be modelled. For a pipeline sub-section, the consequences associated with each release scenario (per aperture size) are assumed to be constant along the sub-section.
- **User defined (additional) failure cases**: users may also specify additional (single aperture size) failure cases at various points along the active[26] pipeline route. Unlike generic failure cases, a single release outcome / scenario may be modelled per user defined failure case (i.e. isolation or no-isolation).[27]
- For each generic / user-defined aperture size, users will need to specify the following information within the generic / user-defined failure case data input:
  - **Release location**: only applicable to user-defined failure cases. This information should be specified in terms of the distance of the event from pipeline inlet.
  - **Release direction**: this defines the release orientation (vertical, horizontal, horizontal impinged etc.). As with other discharge parameters, it should be noted that only one release direction may be modelled at a time (i.e. for each release scenario).
  - **Buried pipeline**: this flag allows users to specify whether to use the new crater modelling for buried pipeline sections.
  - **Impingement option**: users will need to select any of the following options:

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[23] Releases from buried pipelines are treated as zero elevation releases for the purposes of dispersion modelling: see section A4.5 "Impingement option" for further details.

[24] The valve closure time only relates to the time it takes the safety valve to completely isolate any inflow following leak detection. It should be noted that the time to leak detection (for ESDVs) may not be simply represented by the time it takes the first pressure pulse following a loss of containment event to be detected by say a pressure transducer/control system. Conditions initiating executive action, typically defined within relevant Cause & Effect (C&E) diagrams should be used in defining closing time (e.g. confirmed [2oo3 / 1oo2 etc.] low-low pressure reading or fire/gas detector alarm). Nevertheless, the time to initiation of a low-low pressure reading/alarm (i.e. at a given transducer location) may be estimated from the long pipeline model results.

[25] It should be noted that the valve PFD information, together with the detection time and probability data eliminates the need for clients to specify the "valve close" flag when modelling safety system performance.

[26] The active pipeline route is the portion of a pipeline for which geometry (position vector) information is stipulated.

[27] IMPROVE: allow the specification of all safety system performance scenarios supported for generic failure cases in user-defined failure cases as well.

        - use fixed impinged velocity limit;
        - OR, use impinged velocity modification factor
    - **Impinged velocity limit**: this defines the source term velocity for impinged releases in terms of a fixed (user defined) value. It is only used if release is impinged and “Impingement option” = “fixed impinged velocity limit”.
    - **Impinged velocity factor**: this defines the source term velocity for impinged releases as a fraction of the post-expanded state velocity. Only used if release is impinged and “Impingement option” = “impinged velocity factor”.
    - **Aperture size (m) / relative aperture area (fraction)[28]**: this defines the characteristic aperture size to be modelled per release scenario.
    - **Event probability (fraction) / Frequency (/yr)**: Users will need to specify the event probability or frequency associated with each aperture size or user-defined failure case, respectively. The total event probability for the generic aperture sizes may not be > 1, but may be ≤ 1[29].
    - **Detection time**: this is the total time from the onset of the release up to the time the leak is detected. The total time to shutdown is the sum of the detection time and valve closure time[30]. The detection times for Check valves (flow reversal) and EFVs (time to exceed a pre-set flow-rate) are determined automatically by the long pipeline model.
    - **Detection probability**: This is the probability of successful leak detection and applies only to the action of ESDVs. As with detection time, the likelihood of successful gas detection increases with increase in release size (gas volume).
    - **Immediate ignition probability**: This is the probability that a flammable release ignites at its onset[31]. The immediate ignition probability may be specified directly or calculated (via methods supported within MPACT)[32]. The LPR event tree development particularly applies to the determination of the safety system performance (detection with / without isolation success) end event probabilities[33]. The calculated end event probabilities are provided as input to MPACT per scenario and are applied in the estimation of the base / top-level event frequency for the immediate and delayed ignition branches of the MPACT event trees.

A4.6. User defined / automated event spacing

This defines the method to adopt for spacing generic failure cases along pipeline sub-sections. Users may select (via the “generic event spacing method” flag) either:

- **Automated event spacing**: this is designed to eliminate discontinuous risk / hazard zone contours as shown in Figure 14 (see section A6 for details). Inputs include:
    - **Event spacing method:** Here, users may specifically employ[34] –
        - **Use peak lethality hazard zone radius method**: this implements a one-step optimization based on the hazard zone distances to the peak and 50% peak (radiation / toxic) lethality (or equivalent) impact levels
    - **Cut off duration for immediate ignition effects (s)**: This defines the maximum duration for the calculation of immediate ignition effects (lethality levels). The maximum duration may vary depending on the objectives of the risk study. For the evaluation of risks to people, a value of 20s is typical[35]. It is assumed that any exposed non-immobilized[36] individual is likely to take remedial action (e.g. seek refuge / run away) in response to the ignited event, where a maximum of “20s” is allowed for such action to be taken[37]. For risk to assets, the duration specified may correspond to the release / potential flame duration[38].

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[28] There may be need to support both options. Users will need to define which method applies in either case. For relative aperture area, the maximum value that can be stipulated is 1 (guillotine rupture), while for hole size, the maximum size that may be stipulated = “default” pipeline section diameter (full-bore rupture).

[29] It is possible to have total event probabilities less than 1, particularly where the impact of releases from some aperture sizes (e.g. “very small – 5mm” leaks) are assumed to be negligible (or localized) and may be safely ignored.

[30] It should be noted that the likelihood of leak detection increases with increase in aperture / release size (throughput / gas cloud size). The detection time input is only applied to ESDV action as the detection mechanism for check and excess flow valves are inherent and may not depend on external factors.

[31] The immediate ignition probability is sometimes used interchangeably with the probability of early ignition. However, early ignition allows for ignition at some finite time before the release is isolated and the dispersing cloud is fully developed (as opposed to “late” ignition where the cloud is fully developed or the release has stopped).

[32] There may be need to implement the immediate ignition calculation methods supported in MPACT within a lower service model accessible to both the LPR and MPACT

[33] The LPR model returns normalized end event probabilities per release scenario which will subsequently be multiplied by appropriate event tree probabilities (or frequency) for the pertinent aperture size.

[34] Another methodology recommended in the DNV “Guide to Gas Pipeline QRA” suggests an optimum event spacing equal to the hazard zone radius to a fixed radiation level of 12.5kW/m^2. This method is however of limited benefit as it is only applicable to flammable releases.

[35] The value of 20s largely corresponds to the 100% fatality level for individuals exposed to a 37.5kW/m2 radiation level as derived from the TNO radiation probits.

[36] That is, non-immobilized by the primary (immediately ignited) event or by other circumstances (e.g. disabilities, blocked escape routes, sleep)

[37] (i.e. without experiencing the immediate consequences)

[38] For pool fires, the event duration may be longer than the release duration.

- **User defined (fixed) event spacing (m)**: here users may specify a fixed event spacing which will be applied across all pipeline sub-sections.

A5. Automatic pipeline sectioning and segmentation

The required input data to the LPR entry point routine for automatic pipeline sectioning and segmentation is as detailed in sections A4.1 – A4.4 and A4.6.

A5.1. Rule set for automatic sectioning

The rule-set applied within the LPR model for automatic pipeline sectioning is summarised below and illustrated in **Figure 12**, where:

- Sections upstream and downstream of isolation valves (including Excess Flow Valves but excluding manual valves) are modelled as separate sections.
- User defined sections will be treated uniquely except where an isolation valve is indicated to be present in-between (in which case the section will be split at the isolation valve), but not at, the section's start and end points. Isolation valves are assumed to automatically define the end of an upstream length of piping (section) and the beginning of a new pipeline section. Pipeline parameters that may be varied within a user-defined pipeline section are detailed in section A4.3. A user-defined section should cover an area where one or more of the pipeline parameters are observed to (significantly) vary from adjacent sections.
- User defined sections may not overlap, though they need not be contiguously arranged. The automatic sectioning process will re-arrange and report the final list of pipeline sections contiguously.
- Any areas of the pipeline system not covered by the user defined sections will be assumed to be represented by a "default section". Hence, the automatic sectioning logic will insert "default" sections between any non-contiguous user-defined sections.

A5.2. Rule set for automatic segmentation / sub-sectioning

The rule-set applied within the LPR model for automatic pipeline segmentation is as described in the DNV "Guide to Gas Pipeline QRA" report. The rule-set is redacted below (to align with the definitions in section A3), while Figure 13 shows the amalgamated logic diagram (flow chart) for its implementation in the LPR model per pipeline section[39].

"Pipeline sections should be divided into *sub-sections* along which the flow conditions are assumed to be 'approximately constant':

- The absolute pressure[40] should change by no more than 20% over the length of a sub-section (at initial / steady state conditions).
    - For sub-cooled liquids, the steady-state pressure drop (ΔP) along a given pipeline length, L_{pipe}, with diameter, D_{pipe}, (i.e. relative to upstream conditions) may be easily determined using the Fanning – D'Arcy equation[41].

$$\Delta P = 4 f \rho_{liq} \left(\frac{L_{pipe}}{D_{pipe}} \right) \left(\frac{v_{liq}^2}{2} \right) \tag{18}$$

Where: f is the flow regime dependent fanning friction coefficient, while ρ_{liq} and v_{liq} is the density and steady-state velocity of the conveyed liquid respectively.

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[39] Modified logic diagram as originally presented in "Pipeline modelling user specification for Safeti 7.2" (Hickey, C., and Worthington, D., Oct 2013).

[40] The absolute pressure recommendation will tend to avoid defining too many sub-sections along pipeline sections, particularly where the pressure drop along the pipeline length is insignificant. Note that the 20% of the total pipeline length criterion ensures that there are at least 5 segments along a pipeline irrespective of the pressure drop along its length.

[41] Ignoring any additional loss terms (e.g. due to fittings, constrictions / expansions, gravitational effects). Note also that the Fanning-Darcy equation may be roughly applied in modelling the pressure drop along a pipeline conveying flashing / superheated liquids up until the onset of flashing (cavitation).

  - For pipelines conveying flashing /superheated liquids, the long pipeline model (PBRK) assumes instantaneous (isothermal) pressure drop to saturated conditions along the entire length of the pipeline. Hence, for flashing liquid containment and / or zero pumped inflow, the sub-sectioning algorithm will default to the next set of sub-sectioning criterion (see below: 500 m / 20% of total pipeline length rule-set).
  - For pipelines conveying vapour / gaseous fluids, the pressure drop along the pipeline length is calculated within the MDE long pipeline model (GSPP).
- Sub-section lengths should be at least 500 m and no more than 20% of the total pipeline length. If these conditions are in conflict then the 20% criterion will be satisfied rather than the 500m length.
- Releases from a sub-section should be modelled using conditions (pressure, temperature) at the mid-point of the pertinent sub-section."

It should be noted that both the maximum %age change in absolute pressure across a pipeline sub-section (20%) and the minimum sub-section length (500 m) are user inputs to the LPR model and may be adjusted where required.

A5.3. LPR model outputs

Model outputs from the automatic segmentation LPR procedure are:

- Total number of pipeline sections
- For each pipeline section, the total number of pipeline sub-sections
- The co-ordinates of the start and end position vectors of each pipeline section and sub-section
- The distances of each pipe section and sub-section (start and end positions) from pipeline inlet.

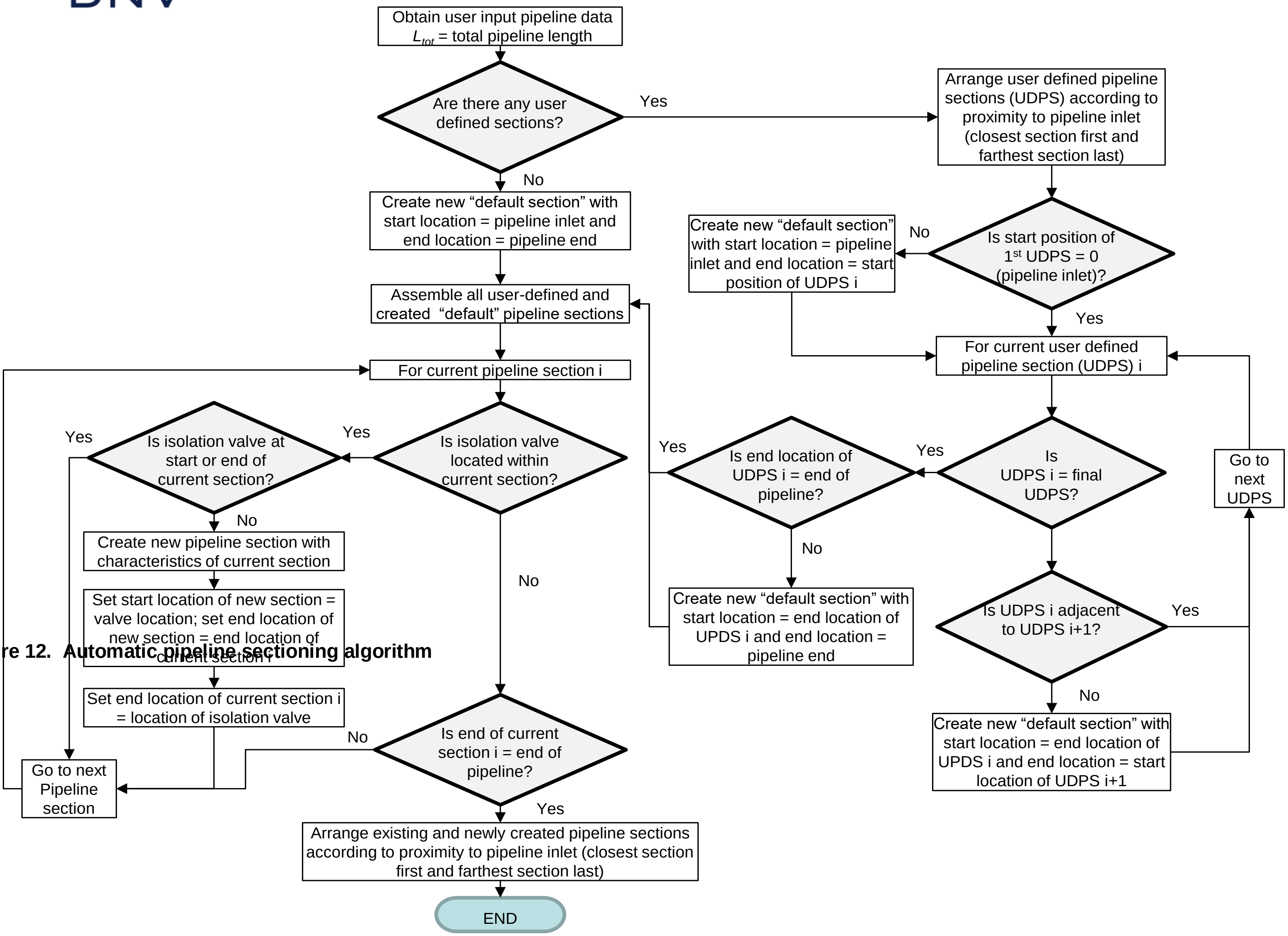

Figure 12. Automatic pipeline sectioning algorithm

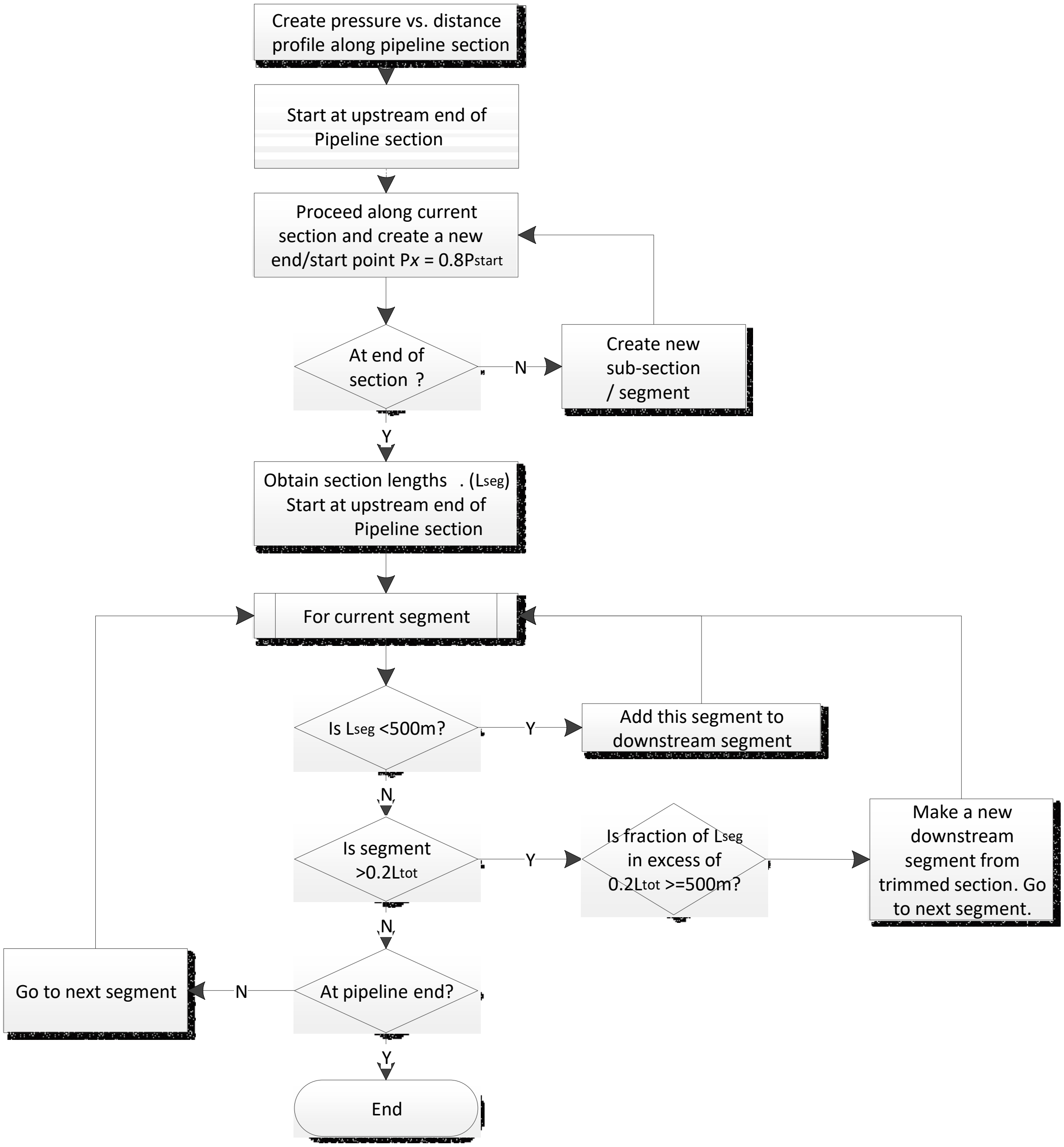

Figure 13. Automatic pipeline segmentation algorithm for a given pipeline section

A6. Automatic event spacing

Figure 14 shows the impact of improperly (too large) sized user defined event spacing on predicted risk (or hazard zone effect) contours along a hypothetical pipeline route. Here, the user defined event spacing is larger than hazard zone sizes predicted for the pertinent loss of containment events.

As discussed in section A4.6, the LPR model supports a method for the automatic determination of event spacing along pipeline sub-sections. This method is designed to eliminate discontinuous risk / hazard zone contours as shown in Figure 14. Additional information on this method is provided below. Note that the method for fixed event spacing along a pipeline sub-section / route is already supported within the MDE via the Route model.

Input data to the automatic event spacing entry point method is as detailed in section A4 together with the output from the automatic pipeline segmentation calculations (see section A5.2).

Figure 14. Risk / hazard zone contours stemming from improperly sized user defined failure case event spacing

A6.1. Peak lethality hazard zone radius

This method employs the hazard zone results employed in the risk analysis. It is based on the premise that the boundaries of the highest risk / hazard zone contour that may be plotted will be driven by the radius to the peak 'lethality' (or equivalent) effect level. Given that the consequences associated with a release scenario are constant along a pipeline sub-section, the point of intersection of the 50% peak lethality hazard radii originating from two adjacent failure cases (i.e. ignoring the contributions from surrounding failure cases) would sum up to the peak 'lethality' effect level[42]. Note that the peak lethality may not correspond to 100% lethality but to the highest (non-zero) lethality value calculated within the effect modelling.

As such, this method determines the event spacing ($D_{i,j}$) of the jth aperture size along the ith pipeline sub-section as given by equation (19) and illustrated in Figure 15. Where:

$D_{i,j}$ = event spacing of the jth aperture size along the ith pipeline sub-section
$A_{i,j}$ = hazard zone radius to the peak lethality level (jth aperture size, ith pipeline sub-section)
$B_{i,j}$ = as above, radius to 50% peak lethality level (jth aperture size, ith pipeline sub-section)

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[42] It is possible to optimize this approach further by including the contributions from a limited number of surrounding release scenarios (e.g. up to a maximum of 5 generic release scenarios upstream and downstream of the inner scenarios ➔ i.e. a total of 12 generic release locations). In this case, we would result to a root-finding problem where the value of $D_{i,j}$ will be altered with $A_{i,j}$ fixed at the mid-point of the innermost release scenario locations (which varies with $D_{i,j}$) such that the sum of the lethality contributions from all the selected release scenarios total the peak lethality level at $A_{i,j}$.

$$D_{i,j} = 2 \times \sqrt{B_{i,j}^2 - A_{i,j}^2} \tag{19}$$

For flammable releases, the radius to the peak and 50% peak effect level is taken (or derived) from predicted (immediate ignition) hazard zone ellipse results[43]. Where a release is 'toxic only', the radius to the peak and 50% peak effect level may be derived from the maximum distance of the release point to the peak and 50% peak toxic lethality level.

The algorithm for the peak lethality method is summarized below:

- Model the release and consequences associated with each aperture size, i.e., using the discharge results based on conditions at the mid-point of each pipeline sub-section
- Obtain the pertinent hazard zone radii to the peak and 50% peak lethality levels for all modelled effect types (jet fire, pool fire, flash fire, toxic cloud etc.) and for all weather conditions.
- Determine the relevant event spacing ($D_{i,j}$) as the minimum event spacing calculated from equation (19) for all effect types and weather conditions for the pertinent release scenario.

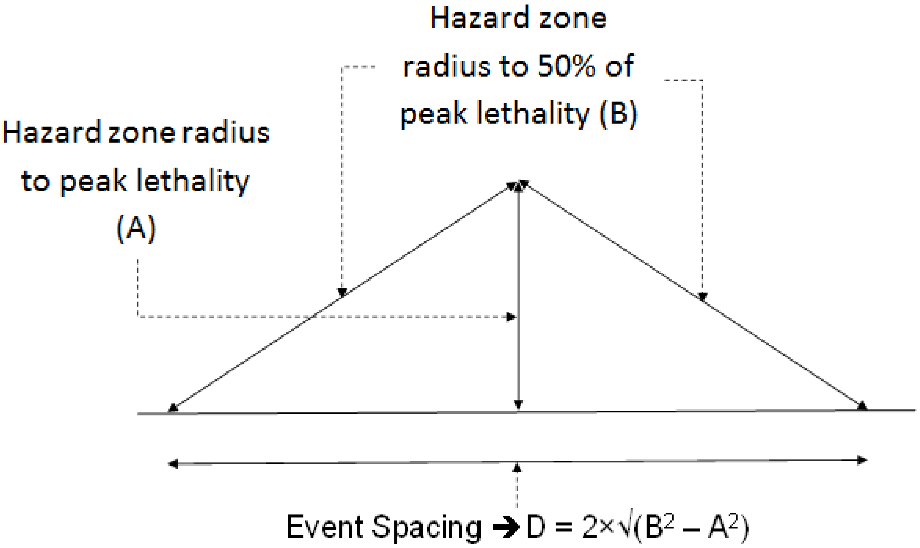

Figure 15. Event spacing based on the peak and 50% peak lethality hazard zone radius

A6.2. LPR modelling outputs

For the automated event spacing methods described above, aperture sizes modelled within a generic failure case may be spaced at different fixed intervals.

As such, clients of the LPR model will be provided with the following output data:

- For each pipeline sub-section and aperture size:
    - The total number of event locations
    - The calculated event spacing based on the methodology adopted
    - The array of failure case co-ordinates

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[43] By default, this would correspond to the (Purple book) flammable probit ellipses. However, this method may be used with any vulnerability method to determine optimum event spacing. The event spacing process is the penultimate LPR modelling analysis step. This process is followed by the event frequency analysis accounting for safety system performance.

A7. Multi-segment valve and inventory interactions

A7.1. Analysis

Multi-segment valve and inventory interactions may be modelled via dedicated calls to the steady-state discharge /long pipeline (DISC/GSPP/PBRK) and time-averaging (TVAV) service models. The discharge model selection logic for the various release scenarios detailed in section A3 as implemented in Safeti 8.0 is described in detail in Appendix B. The execution procedure for the pipeline route discharge modelling / source term definition process is summarised as follows:

- The various release scenarios detailed in section A4.5 (see also A5) will be modelled per pipeline sub-section.
- The release process, in each case, will be assumed to occur at the mid-point of each pipeline sub-section.
- To reduce the number of modelled scenarios, release scenarios with similar discharge results will be rationalized by default. [44]Rationalization will be undertaken per aperture size and not across aperture sizes. The conditions to be satisfied for two or more release scenarios to be represented by a single (rationalized) release scenario are as follows:
    - Each release scenario must have equal number of release segments
    - For all release segments within a given release scenario, the predicted release duration, time-averaged discharge rates, post-expanded state temperature / liquid fractions must lie within a fixed tolerance (±10%[45] by default) when compared against the corresponding item in the base upstream scenario.

  The single (rationalized) release scenario will be selected from the set of discharge results being compared on a worst-case basis (maximum released inventory for all release segments combined). The implementation logic for the discharge results rationalization process is summarised as follows:

    1. Set up an array of pointers for all modelled discharge scenarios
    2. Select an aperture size for discharge results rationalization
    3. For each safety system dependent discharge outcome for the selected aperture size
    4. Start from the first upstream pipeline segment
    5. Compare the discharge results of the upstream segment with the corresponding results from the next downstream segment.
    6. If the rationalization criteria are met, replace the pointers to each set of compared discharge results with the pointer to the worst-case scenario of the lot. Select the next downstream segment and go to step 5
    7. If the rationalization criterion are not met, select the current downstream segment as basis for rationalization (i.e. new upstream segment) and go to step 5
    8. If the rationalization process is complete across segments, move to the next safety system dependent outcome and go to step 4
    9. Finally, for each pipeline segment, compare the set of rationalized safety system dependent outcomes with one another.
        - If the rationalization criteria are met, replace the pointer to the set of compared discharge results with the pointer to the worst-case scenario of the lot.
        - Go to the next pipeline segment and repeat above comparison until all segments are covered.
    10. Select the next aperture size and return to step 3
    11. Compile the set of unique discharge results for reporting.
- Each 'unique' set of release data will be assigned (via the updated array of pointers) to appropriate release scenarios per pipeline sub-section.
- Model pertinent consequences (outside of the LPR model) for each 'unique' release data. As with discharge results, simulated consequences will be assumed to apply across the relevant pipeline sub-section.

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[44] FUTURE: post SAFETI 8.0, it is planned to provide users with options to turn-off scenario rationalization or configure rationalization rule sets as desired via appropriate discharge parameters.

[45] This is a reasonably conservative criterion; a ±20% criterion should still be okay and should be well within uncertainty levels typically assumed to apply in design safety studies and catered for by appropriate design code safety margins.

A7.2. LPR modelling outputs

The output results from the LPR procedure include:

- Total number of ‘unique’ discharge results
- Array mapping each discharge results’ set with modelled release scenarios per pipeline sub-section
- Array of time averaged discharge results data per discharge set (to be used by the dispersion and dispersion post-processing entry points)
- Array of raw time-varying / steady-state discharge rate results per discharge set

A8. Event tree customization for pipeline scenarios

A8.1. LPR Event Tree Analysis

The LPR model supports an inbuilt generic event tree, as illustrated in Figure 16. The generic event tree is employed in the determination of safety system performance end event release scenario probabilities. The event tree tracks the development of the release process following a loss of containment event and terminates at the calculation of safety system performance end event probabilities (i.e. ignoring any primary [immediate ignition] or secondary consequences ➔ explosions, flash fire etc.). The calculated end event (release scenario) probabilities are reported as output to clients (e.g. MPACT) for subsequent use in assessing local (toxic, immediate and/or delayed ignition) hazard frequencies.

The input data requirements for the event tree analysis are as detailed in section A4 together with the outputs from the event spacing analysis, where the end event probabilities ($P_{*,*}$) indicated in Figure 16 correspond to:

$P_{i,j}$	The top event probability for the jth aperture size and ith pipeline sub-section;[46]
$P_{det,j}$	The probability of detecting releases associated with the jth aperture size.
$P_{iso,m}$	Probability of successful isolation of upstream safety valve ‘*m*’.[47]
$P_{iso,n}$	Probability of successful isolation of downstream safety valve ‘*n*’.[47]

A8.2. LPR modelling outputs

The output from the LPR event tree analysis includes:

- Array of end event probabilities for each release scenario per event location per aperture size per pipe sub-section per pipe section[48]
- Array of end event probabilities for each release scenario per aperture size per pipe sub-section per pipe section
- Array of end event probabilities for each release scenario per pipe sub-section per pipe section
- Array of end event probabilities for each release scenario per pipe section
- Array of end event probabilities for each release scenario for the entire pipeline system

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[46] This may correspond to the overall event probability for a generic aperture size (“section breach”) modelled along a pipeline sub-section.

[47] For scenarios with multiple upstream/downstream ESD valves, the probability of upstream/downstream isolation is based on the closest ‘active’ upstream/downstream valve to the release location. An ESD valve is deemed to be ‘active’ where the elapsed time from the loss of containment event to its complete isolation is less than the maximum release duration (i.e. duration of interest)

[48] This information is only reported per pipe sub-section although it accounts for the number of discrete event locations along the length of the pipeline sub-section

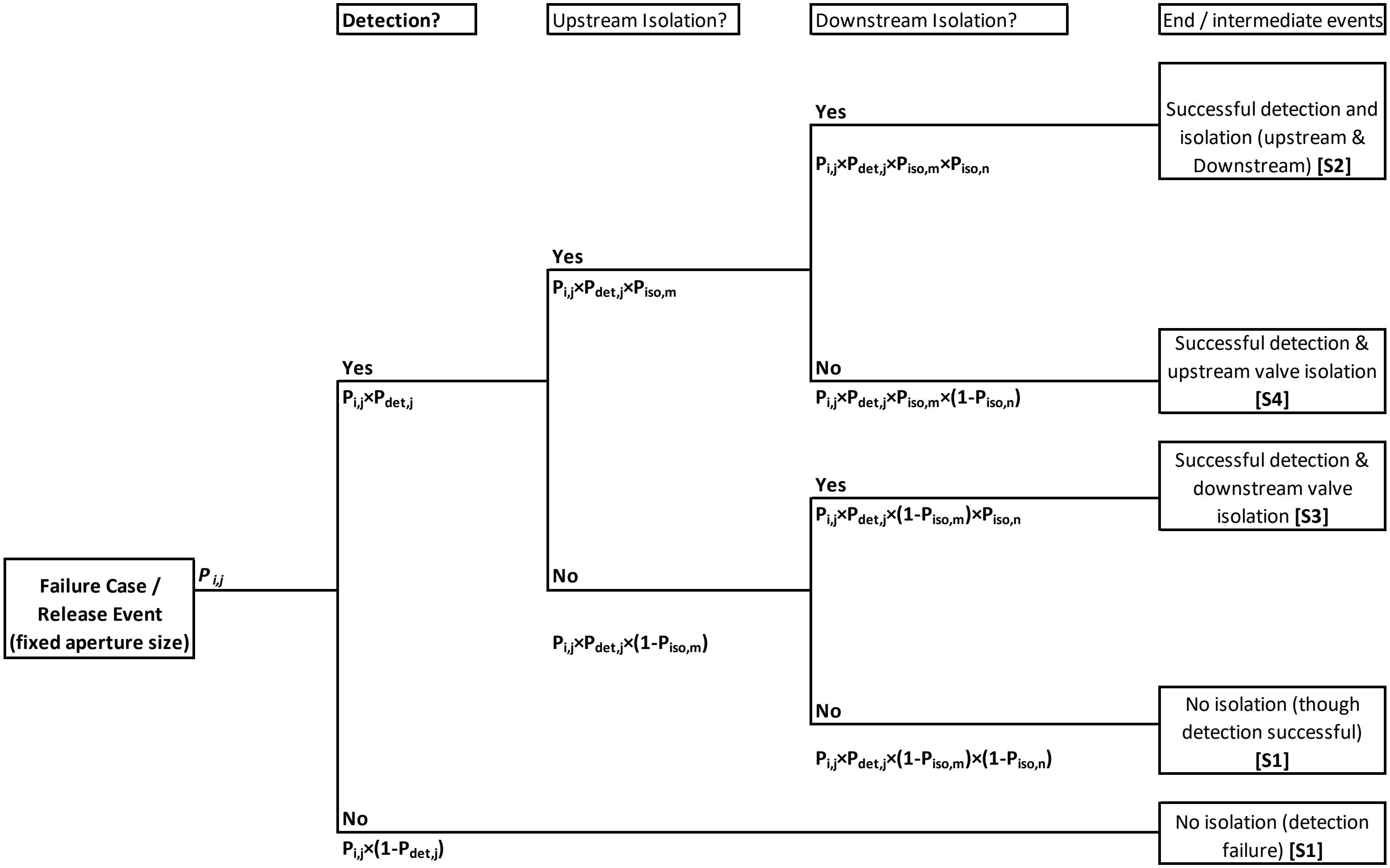

Figure 16. Generic LPR event tree for the determination of safety system performance end event (scenario) probabilities

Appendix B. Discharge modelling selection

Table 3 gives a summary of the selection logic for determining suitable discharge models to employ for a given discharge scenario as implemented in Safeti 8.6. Further details on the rationale behind each selection are provided as "notes" and footnotes to this table.

Aperture ratio (α_r)*	Pumped inflow (kg/s)	Initial Fluid State	Discharge modelling			
			DISC	GSPP	PBRK	TVD2
α_r>= 20%	Inflow > 0	Vapor	–	✓(1)	–	–
		Flashing liquid	–	–	✓(2)	✓(2)
		Sub-cooled liquid	–	–	–	
	Zero pumped inflow	Vapor	–	✓(1)	–	–
		Flashing liquid	–	–	✓(2)	✓(2)
		Sub-cooled liquid	–	–	–	
4% < α_r < 20%	Inflow > 0	Vapor	–	✓(3)	–	–
		Flashing liquid	✓(4)	–	✓(6)	✓(5)
		Sub-cooled liquid		–	–	
	Zero pumped inflow	Vapor	–	✓(3)	–	–
		Flashing liquid	✓(4)	–	✓(6)	✓(5)
		Sub-cooled liquid		–	–	
$\alpha_r \leq$ 4%	Inflow > 0	Vapor	✓(4)	✓(5)(6)	–	–
		Flashing liquid		–	✓(6)	✓(5)
		Sub-cooled liquid		–	–	
	Zero pumped inflow	Vapor		✓(5)(6)	–	–
		Flashing liquid		–	✓(6)	✓(5)
		Sub-cooled liquid		–	–	

Table 3 Summary of discharge model selection logic for LPR accident scenarios as implemented in Safeti 8.6

NOTES

* Aperture ratio: ratio of breach area to pipeline cross-sectional area.

Note that there is currently no support for the modelling of sub-cooled liquid inventories in Safeti.

(1) Use GSPP for aperture sizes that meet the minimum aperture ratio criterion (i.e. >= 20% aperture ratio).

(2) Use PBRK (for single component) or TVD2 (for multi-component fluids) for aperture sizes that meet the minimum aperture ratio criterion (i.e. >= 20% aperture ratio).

(3) For vapour releases, use GSPP for small aperture sizes >4% but less than 20% aperture ratio. GSPP is used instead of DISC because sensitivity results from comparison of simulated release rate versus time profiles in pipelines using a rigorous long pipeline mathematical model as against a simple vessel blow-down model suggests that at aperture ratios < 5% either method yield similar outcomes. Note however that GSPP handles valve and pump interactions as well, while accounting for any pressure drop effects that may prevail along the line (reducing any conservatisms from a simple vessel blow-down modelling approach).

For small aperture sizes (i.e. <20% aperture ratio), three modelling options are provided:

(4) "Steady state orifice method", which runs the ORIF entry point under the DISC model. The predicted release rate accounts for any pressure drop effects along the length of the pipeline due to non-zero initial flow (pump / compressor action). The flow conditions[49] at the local downstream position along the length of the pipeline is applied in the discharge calculations. The predicted release rate is assumed to apply for the entire duration of the release process and no modification to the release rate (e.g. capping at pump/compressor flow rate) is applied.

(5) "Time varying pipeline method", runs TVD2 (for single or multi-component flashing or sub-cooled liquids) or GSPP (as relevant), discharge results for all time steps are used.

(6) "Steady state pipeline method", also runs PBRK (for single component) or GSPP (as relevant). In either case, the method uses the first time step of discharge results and accounts for any pressure drop effects along the length of the pipeline due to non-zero initial flow (as with the "steady state orifice method").

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[49] IMPROVE: apply stagnation conditions in place of local flow conditions

In Safeti 8.1, the “Steady state orifice method” is offered by default for <20% aperture ratio flashing liquid releases and <4% aperture ratio vapour releases. The selected aperture ratio thresholds are based on comparison of simulated long pipeline model results against available field data (flashing liquid releases)[50] and rigorous vapour vessel blow-down time-varying discharge modelling[51].

The (vapour/flashing liquid) “steady state orifice method” and the “steady state pipeline method” are likely to predict more conservative source term conditions when compared against the “Time varying pipeline method” as neither of these methods account for valve isolation effects or post-breach pumped flow effect (i.e. only the inventory in the pipeline at the time of the breach is assumed to be evacuated: any additional inventory from continued pump flow following a breach are unaccounted for).

Note that for flashing liquid releases, the “Steady state pipeline method” and to a greater extent, the “time varying pipeline method”, will tend to under-predict steady-state flow rate for releases with initial release rate below pumped flow rate and line pressures above saturation pressure.

For the “Steady state orifice method”, a few parameters are hard-wired before calling the DISC model. i.e.:

(a) Allow flashing in the orifice: this is always set to “TRUE”
(b) Use Bernoulli model for forced phase liquid discharge: This is always set to “FALSE”

Also, users may choose to specify a fixed discharge coefficient (maximum value = 1) as against employing the default DISC calculated value. The above settings allow DISC to better model the general physics of the release process resulting in better agreement with predicted initial rate discharge results using GSPP / PBRK.

It should be noted however, even with the above adjustments, the predicted flow rate by the DISC model is similar to that predicted by the PBRK model only when line pressures are close to saturation pressure. When line pressure is significantly above saturation pressure, the “Steady state orifice method” could predict significantly higher (e.g. above an order of magnitude) flow rates when compared against the other supported methods. The difference is caused by the fact that PBRK drops the pressure from storage pressure down to saturation pressure immediately, when calculating initial flow rate, whilst DISC does not do this. In reality, although pressure does not drop to saturation pressure “immediately” after release, it does drop quickly. The rate of drop reduces with aperture size, i.e. quicker for larger aperture sizes, slower for smaller aperture sizes. For releases with finite pumped inflow the “Steady state orifice method” is recommended particularly for cases with high storage pressure.

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[50] See section 5, “Pipebreak_theory.pdf”, validation of Phast/Safeti flashing liquid long pipeline time-varying discharge model (PBRK) against Isle of Grain field data.

[51] Confidential data source.

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REFERENCES

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[i] *http:*//local.wasp.uwa.edu.au/~pbourke/geometry/circlefrom3/