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Cost-benefit Analysis of Deploying or Retrofitting External-based Leak Detection Sensors

DT Contract No. 693JK31810004

Project Debrief Presentation

By Mathew Bussière

Project Details

- Project Budget: USD 349,346
- Project Team:
  - Mathew Bussiere (C-FER): Project management/conclusions and recommendations
  - Mark Stephens (C-FER): Project reviewer
  - James Powell (PHMSA): Project AOR
- Technical Advisory Panel:
  - Lorne Daniels (Trans Mountain)
  - Yue Chen (TC Energy)
  - Scott Medynski (Enbridge)
  - Jon Van Reet (Plains All American Pipeline)
- Project public page: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=741

Objective

- To develop a framework outlining a methodology for performing CBA on candidate ELD systems for use on hazardous liquid and natural gas transmission pipelines.
  - The framework will inform technology deployment decisions, and
  - Enable operators to tailor system requirements and deployment configurations to their pipeline systems.
- To demonstrate and illustrate the application of the framework through a demonstration exercise

Background

- ELD systems can be costly, especially when deployed retroactively and over significant distances.
- it is important to understand and consider the trade-offs that exist between the cost of deploying a particular ELD system and the associated performance that would be expected
- Technology selection should not be based solely on the expected performance of the ELD technology.
- Consideration should be given to whether the overall benefits associated with ELD deployment justify the costs.
- CBA provides a systematic means of weighing the benefits of a course of action against the associated costs
- It also provides a basis for comparing or ranking investment options based on the value of one or more objective evaluation metrics.

Framework Outline

- Deployment Configuration Identification
- Cost Estimation
- Benefit Characterization
- Cost-Benefit Analysis

Deployment Configuration Identification

- Objective: to prioritize the identified deployment configurations such that only those with the most potential to generate favorable cost-benefit scores are carried forward (i.e. the preferred deployment configurations).
- Main Sections
  - Identify Candidate ELD Technology Vendors
  - Establish Deployment Configuration Characteristics
  - Define Deployment Configurations
  - Rank Deployment Configurations

Cost Estimation

- Objective: sourcing and consolidating the information required to accurately estimate the initial costs associated with ELD system procurement and installation, and the recurring costs associated with periodic maintenance expenditures required to ensure system functionality over the operating life of the pipeline
- Main Sections
  - Initial Costs
    - Procurement
    - Installation
  - Recurring Costs
    - Operation and Maintenance
    - Responding to False Alarms
    - Interference with Pipeline Operations

Benefit Characterization

- Objective: evaluating and quantifying the benefits that can be achieved by ELD implementation for each of the preferred deployment configurations
- Main Sections
  - Environmental Protection Enhancements
    - Baseline Release Volume
    - Reduced Release Volume
    - Failure Rate
    - Monetization
  - Life Safety Enhancements
    - Baseline Fatality and Injury Estimate
    - Reduced Fatality and Injury Estimate
    - Failure Rate
    - Monetization
  - Calculation Approaches

$$\text{ENVIRONMENTAL PROTECTION BENEFIT} = (V_{BL} - V_{RED}) \times R_F \times R_M$$

$$\text{LIFE SAFETY BENEFIT} = (FI_{BL} - FI_{RED}) \times R_F \times R_M$$

Cost-Benefit Analysis

- Objective: combining the calculated costs and benefits into a meaningful evaluation metric, which can be used to objectively compare different ELD deployment alternatives.
- Main Sections
  - Discounting
    - Discount Rate
    - Temporal distribution of costs and benefits
    - Discounting Approaches (present value, annualized values)
  - Evaluation Metric
    - Net Present Value (NPV)
    - Benefit Cost Ratio (BCR)
    - Cost Effectiveness Ratio (CER)
  - Sensitivity Analysis
    - Single Variable Testing
    - Scenario Analysis
    - Monte Carlos Analysis

Framework Demonstration

- Objective: The objective of the demonstration exercise is to demonstrate and illustrate the application of the CBA Framework
- Approach:
  - A hypothetical CBA was performed to evaluate and compare three ELD systems for possible implementation on a hypothetical new-construction pipeline (i.e. the "demonstration pipeline").
  - The demonstration steps through the various sections of the CBA Framework and makes reference to the guidance and methodologies outlined in the CBA Framework

Demonstration Pipeline

- The selection of the demonstration pipeline was guided by two primary considerations:
  - To provide a clear and practical demonstration of selected key aspects of the CBA Framework
  - To make the findings of the demonstration exercise as broadly applicable as possible
- Key attributes of the demonstration pipeline are summarized as follows:
  - New construction, subsurface, onshore
  - Transporting crude oil
  - CPM system deployed and operational
  - Nominal operational life cycle of 50 years
  - ELD considered on a155-mile section traversing sandy soil with minimal amounts of silt and clay
  - Leak simulations over operating pressures ranging from 100 to 500 psi
  - Operator response time of 2 hours

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Demonstration – Deployment Configuration Identification

- Three hypothetical ELD vendors, representing the following ELD technology types were selected:
  - Distributed acoustic sensing (DAS)
  - Vapor sensing tubes (VST)
  - Distributed temperature sensing (DTS)
- A comprehensive market survey can be expensive and time consuming
- A detailed demonstration of an ELD market survey with real ELD technologies is already outlined in a 2018 report prepared for PHMSA
- The concepts and guidance provided in the CBA Framework can be demonstrated effectively with hypothetical ELD vendors

Demonstration – Deployment Configuration Identification

- The candidate ELD technologies are all distributed, cable-based technologies with assumed omnidirectional (i.e. axisymmetric) sensitivity profiles.
- The following characteristics were used to characterize the various deployment configurations in the demonstration exercise:
  - Sensor Position: the sensor's location relative to the pipeline, as well as other relevant references objects or reference geometries.
  - Placement Environment: relevant physical characteristics of the environment surrounding a particular ELD sensor or group of sensors.
  - Use of Auxiliary Structures: whether or not the ELD sensor is to be installed with a passive structure, such as conduit.

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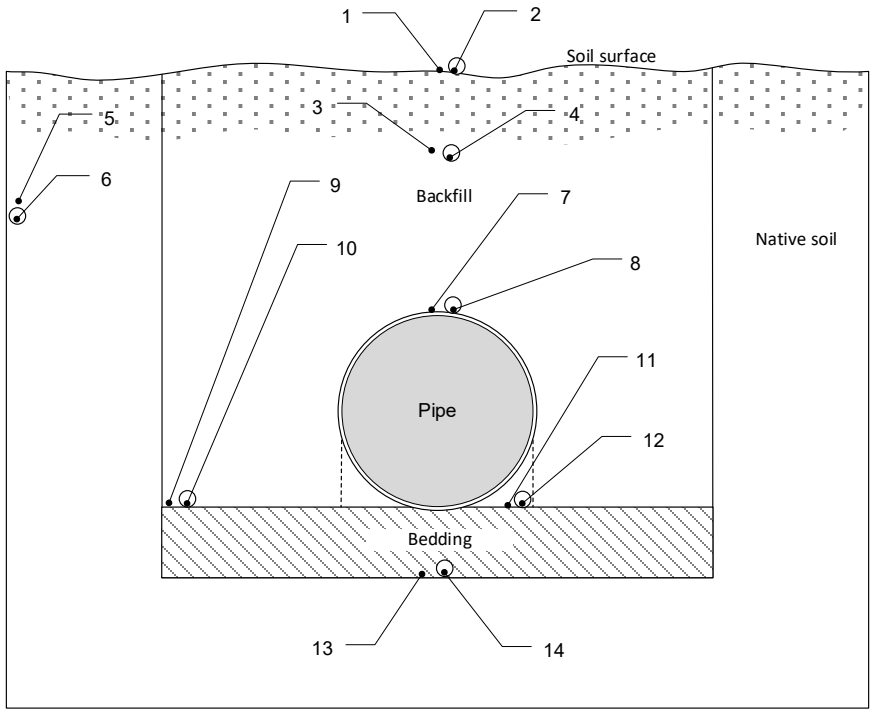
Demonstration – Deployment Configuration Identification

- Sensor position and placement environment characteristics involve continuous variables
- It is recommended to categorize continuous deployment configuration parameters such that the subsequent categories result in distinct degrees of perceived deployability and interference:
  - Deployability is defined as the ease of installation associated with a particular deployment configuration.
  - Interference is defined as the predicted level of impact that an ELD system (or sensor) associated with a particular deployment configuration would have on the pipeline's operation

Demonstration – Deployment Configuration Identification

- A total of 14 deployment configurations for each of the three candidate ELD technologies were identified

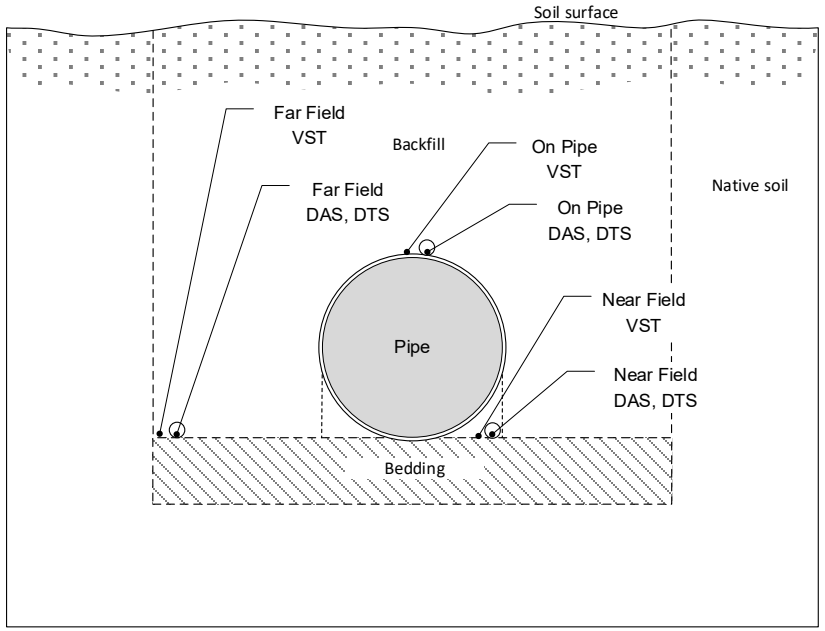
Deployment Configuration Number	Sensor Position	Placement Environment	Auxiliary Structures
1	On soil surface, 12 o'clock	Surface	Bare cable
2	On soil surface, 12 o'clock	Surface	In conduit
3	In trench, above bedding, 12 o'clock	Unconsolidated backfill	Bare cable
4	In trench, above bedding, 12 o'clock	Unconsolidated backfill	In conduit
5	In native soil, 10 or 2 o'clock	Native soil	Bare cable
6	In native soil, 10 or 2 o'clock	Native soil	In conduit
7	On pipe surface, 12 o'clock	Unconsolidated backfill	Bare cable
8	On pipe surface, 12 o'clock	Unconsolidated backfill	In conduit
9	On bedding layer, 8 or 4 o'clock	Unconsolidated backfill	Bare cable
10	On bedding layer, 8 or 4 o'clock	Unconsolidated backfill	In conduit
11	On bedding layer, 5 or 7 o'clock (shadow)	Unconsolidated backfill	Bare cable
12	On bedding layer, 5 or 7 o'clock (shadow)	Unconsolidated backfill	In conduit
13	Bottom of bedding, 6 o'clock	Bedding	Bare cable
14	Bottom of bedding, 6 o'clock	Bedding	In conduit



Demonstration – Deployment Configuration Identification

- Ranking
  - Relative cost score
  - Relative benefit score
  - The relative cost and benefit scores were multiplied to obtain an overall score

Deployment Configuration	Sensor Position	Placement Environment	Auxiliary Structures
DAS - On Pipe	On pipe surface, 12 o'clock	Unconsolidated backfill	In conduit
VST - On Pipe	On pipe surface, 12 o'clock	Unconsolidated backfill	Bare cable
DTS - On Pipe	On pipe surface, 12 o'clock	Unconsolidated backfill	In conduit
DAS - Near Field	On bedding layer, 5 or 7 o'clock (shadow)	Unconsolidated backfill	In conduit
VST - Near Field	On bedding layer, 5 or 7 o'clock (shadow)	Unconsolidated backfill	Bare cable
DTS - Near Field	On bedding layer, 5 or 7 o'clock (shadow)	Unconsolidated backfill	In conduit
DAS - Far Field	On bedding layer, 8 or 4 o'clock	Unconsolidated backfill	In conduit
VST - Far Field	On bedding layer, 8 or 4 o'clock	Unconsolidated backfill	Bare cable
DTS - Far Field	On bedding layer, 8 or 4 o'clock	Unconsolidated backfill	In conduit



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Demonstration – Cost Estimation

- Guidance provided revealed that a relatively wide range of deployment costs are possible.
- The cost range provided by the TAP and ELD vendors are based on pilot project installations.
  - Pilots are more expensive on a per/mile basis and therefore do not necessarily reflect the true costs of deploying similar ELD systems on larger scales.
  - The costs used in the demonstration are on the lower range of the costs range provided by the TAP and ELD vendors.

Deployment Configuration	Initial Costs			Recurring Costs
	Procurement (USD/mile)	Installation (USD/mile)	Total Initial Costs (USD/mile)	Operation and Maintenance (USD/mile-year)
DAS - On Pipe	40,234	96,561	136,794	2,414
VST - On Pipe	20,117	120,701	140,818	32
DTS - On Pipe	43,452	96,561	140,013	1,609
DAS - Near Field	40,234	64,374	104,607	2,414
VST - Near Field	20,117	80,467	100,584	32
DTS - Near Field	43,452	64,374	107,826	1,609
DAS - Far Field	40,234	32,187	72,421	2,414
VST - Far Field	20,117	40,234	60,350	32
DTS - Far Field	43,452	32,187	75,639	1,609

Demonstration – Benefit Characterization

- The dominant benefit category for the demonstration pipeline is assumed to be environmental protection enhancements.
  - The demonstration pipeline transports crude oil which is assumed to have a relatively low ignition likelihood
  - The pipeline section, along which ELD deployment being considered, is assumed to traverse low population areas.
  - The candidate ELD systems are assumed not to have encroachment detection capabilities. Therefore, potential for break prevention is assumed to be minimal.
- Given the relatively low life safety risks associated with the transport of crude oil in the demonstration pipeline, life safety benefits are assumed not to be significant and are, therefore, not considered in the benefit characterization exercise.

Demonstration – Benefit Characterization

- The general calculation approach categories outlined in the CBA Framework are:
  - Deterministic approaches
  - Probabilistic approaches
  - Hybrid approaches
- Due to their simple nature, deterministic approaches are not well suited to demonstrating all the elements of the developed Framework
- The demonstration pipeline is a new build pipeline and therefore it is assumed that there is no ILI data from which to leverage a full probabilistic approach.
- A hybrid approach provides the most practical means of calculating the required estimates, while also accounting for the inherent uncertainty in some of the input data.

Demonstration – Benefit Characterization

- Reminder of the key elements in the benefit characterization section
  - Baseline Release Volume
  - Reduced Release Volume
  - Failure Rate
  - Monetization

$$\text{ENVIRONMENTAL PROTECTION BENEFIT} = (V_{BL} - V_{RED}) \times R_F \times R_M$$

Demonstration – Benefit Characterization

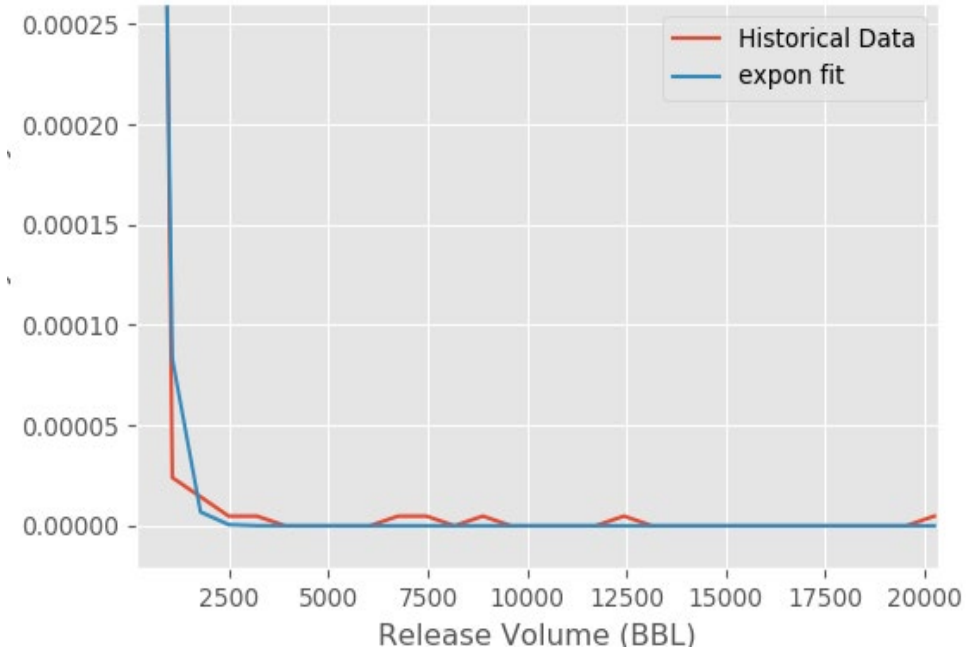
- Baseline release volume estimation methods
  - Analytical (direct)
  - Historical (inferred)
- In the absence of a well-established approach for directly calculating the subsurface fluid propagation and, therefore, the expected release volume, the baseline release volume was estimated based on historical incident data
- This approach is simpler to implement than the analytical method.
- However, the results obtained will not be line-specific or as accurate as those obtained with analytical methods.

Demonstration – Benefit Characterization

- The historical incident data used in calculating the baseline release volume database comes from the 2010 to 2019 PHMSA Hazardous Liquid Pipeline Systems Accident Report.
- The resulting database was limited to release events originating from onshore pipelines that are deployed below ground and are transporting crude oil
- CPM performance was accounted for implicitly in the incident reporting data:
  - The proportion of reported releases that were detected by CPM, given CPM was confirmed to have been installed and functional at the time of the incident, is 4% for leaks and 67% for breaks
  - CPM, as portrayed in the PHMSA incident reporting database and subject to the adopted data field filters, is reasonably effective at detecting breaks but not leaks
  - It was assumed that ELD systems are unlikely to be capable of offering significant improvements over existing CPM systems with regard to break detection

Demonstration – Benefit Characterization

- Distribution Fitting
  - Depending on the general approach used, the baseline release volume can either be a random variable or a deterministic value (e.g. average, median, etc.).
  - An exponential distribution was found to fit the filtered incident data best and was, therefore, used to characterize the baseline release volume random variable



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Demonstration – Benefit Characterization

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Demonstration – Benefit Characterization

- The CBA Framework identifies two mechanisms by which ELD systems can reduce the expected release volume:
  - reduced detection time
  - release frequency reduction
- Reduced release volume is quantified by first identifying releases that fall within the ELD system's detection range. The release rates of the detectable releases are then calculated and multiplied by the overall response time.
  - Release magnitude → release rate
  - Release rate → $Q = \frac{\pi C_d d^2}{4}\sqrt{\frac{2p}{\rho}}$
  - Operator response time → 2 hrs.
  - ELD detection threshold
  - ELD response time

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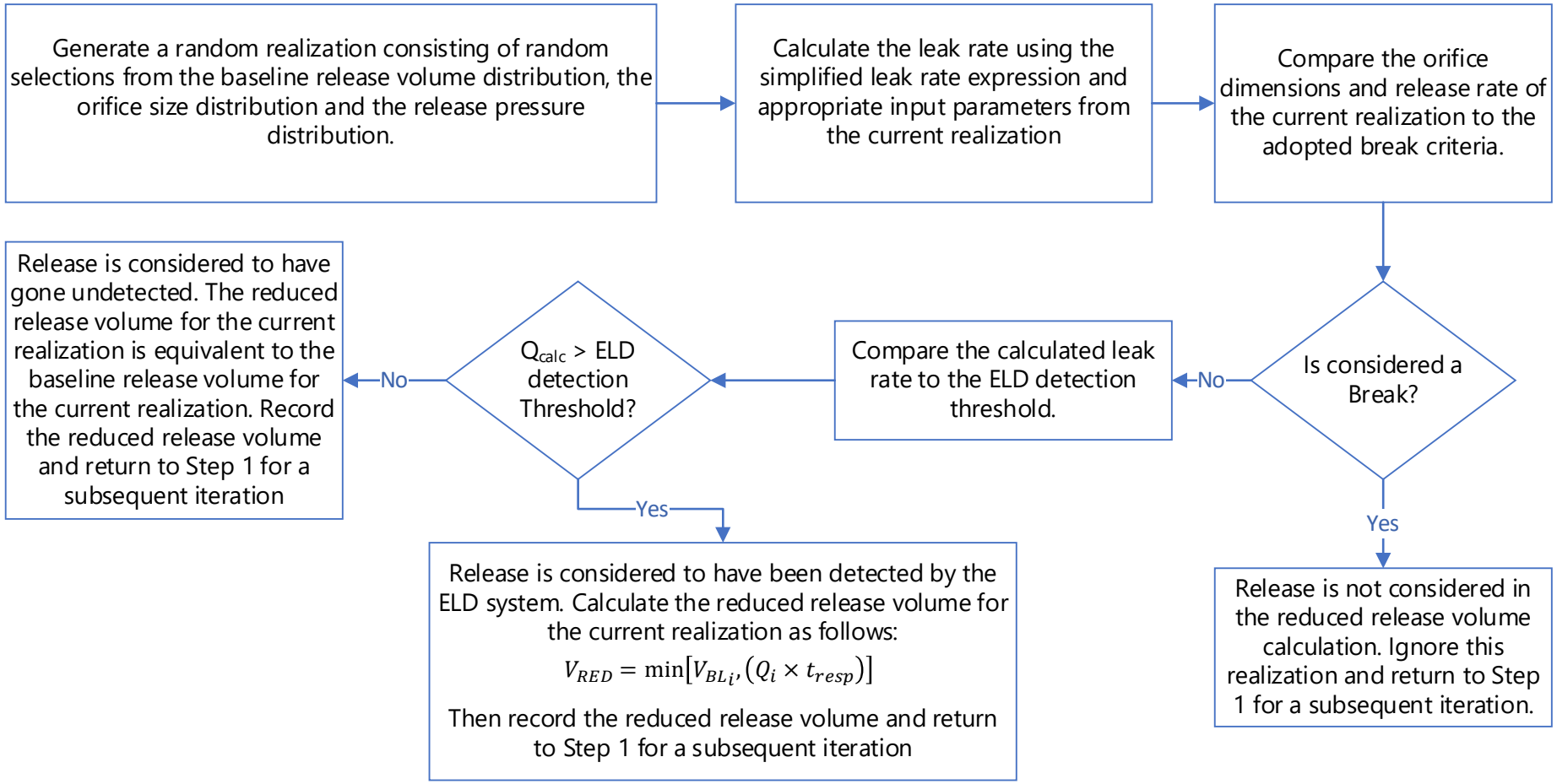
Demonstration – Benefit Characterization

- ELD detection threshold (in terms of release magnitude), and ELD response time for each of the identified deployment configurations

ELD Technology Type	Deployment Configuration	Detection Threshold (GPM)	Response Time
DAS	On Pipe	0.264	1 minute
	Near Field	1.321	1 minute
	Far Field	3.963	1 minute
VST	On Pipe	0.005	48 hours
	Near Field	0.005	24 hours
	Far Field	0.005	48 hours
DTS	On Pipe	3.963	3 minutes
	Near Field	2.642	6 minutes
	Far Field	6.604	10 minutes

Demonstration – Benefit Characterization

- Analysis procedure (hybrid approach)



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Demonstration – Benefit Characterization

- The CBA Framework recognizes three general approach categories for quantitatively estimating pipeline failure rates:
  - SME opinion
  - historical failure data
  - and engineering models and reliability analysis methods.
- Given the available information for the demonstration pipeline, it was decided that the best avenue for calculating the expected failure rate is through historical failure data.

$$F = \left[\sum_{N_{years}}^{i=1} \left[\frac{N_{leaks_i}}{m_i} \right] \right] \frac{1}{N_{years}} = 6.4 \times 10^{-4} \text{ leaks per mile-year}$$

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Demonstration – Benefit Characterization

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Demonstration – Benefit Characterization

- The adopted monetization model for the demonstration is based on previous work in which a model capable of assessing the combined socioeconomic and environmental impact of low vapor pressure (LVP) hydrocarbon liquid product spills from onshore pipelines was developed.

$$BENEFIT = F \times C_{c_r} \times \beta \times \frac{\sum_{N}^{i=0}\left(V_{BL_i}{}^{\alpha} - V_{RED_i}{}^{\alpha}\right)}{N}$$

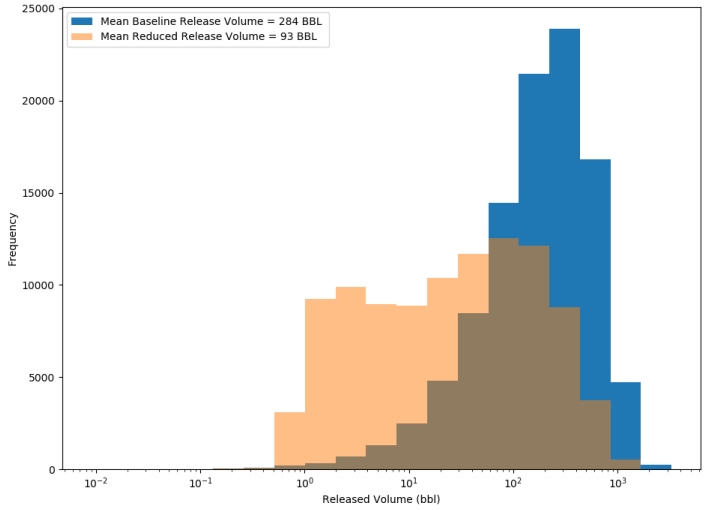
- An assumed reference spill impact value of 40,000 USD/bbl was therefore used in the simulation
- An average location ns, and an average location factor of 1.

Location Category	Location Sub-category	Location Factor	Percentage of Mileage Within Respective Location Category	Mileage-weighted Location Factor
Non-HCA	Forest	1.3	36%*	1.5
	Grassland/rangeland	1.3	37%*	
	Agricultural	2.0	27%*	
HCA	High Population Area	4.2	47%†	4.5
	USA – drinking water resource	4.2	30%†	
	USA – ecological resource	5.4	23%†	

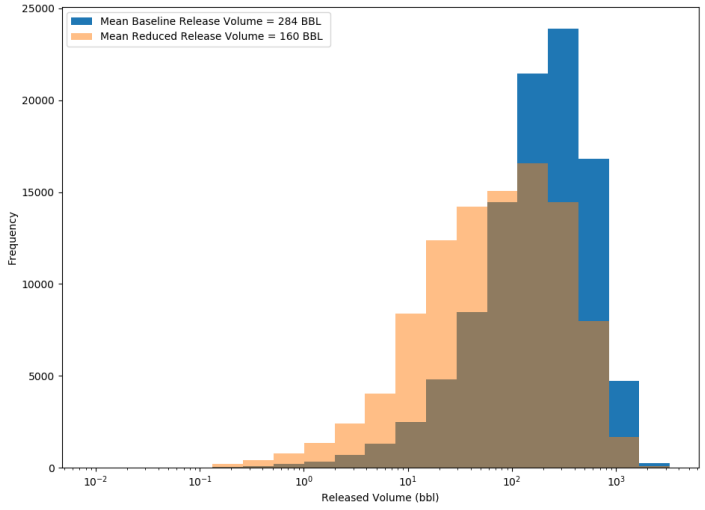
* USDA (9)
† NPMS-PHMSA (10)

Demonstration – Benefit Characterization

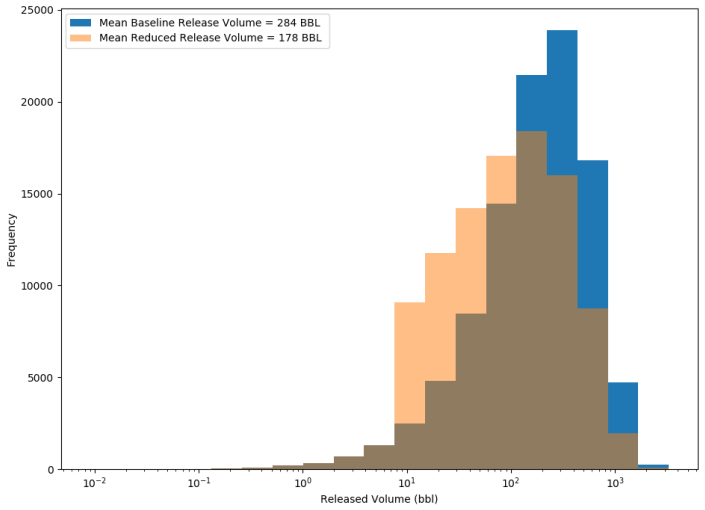
- Results
  - 100,000 simulations per deployment configuration
  - histograms comparing the baseline and reduced release volumes associated with the best performing (i.e. highest expected annual benefit) deployment configurations for the candidate ELD vendors



DAS



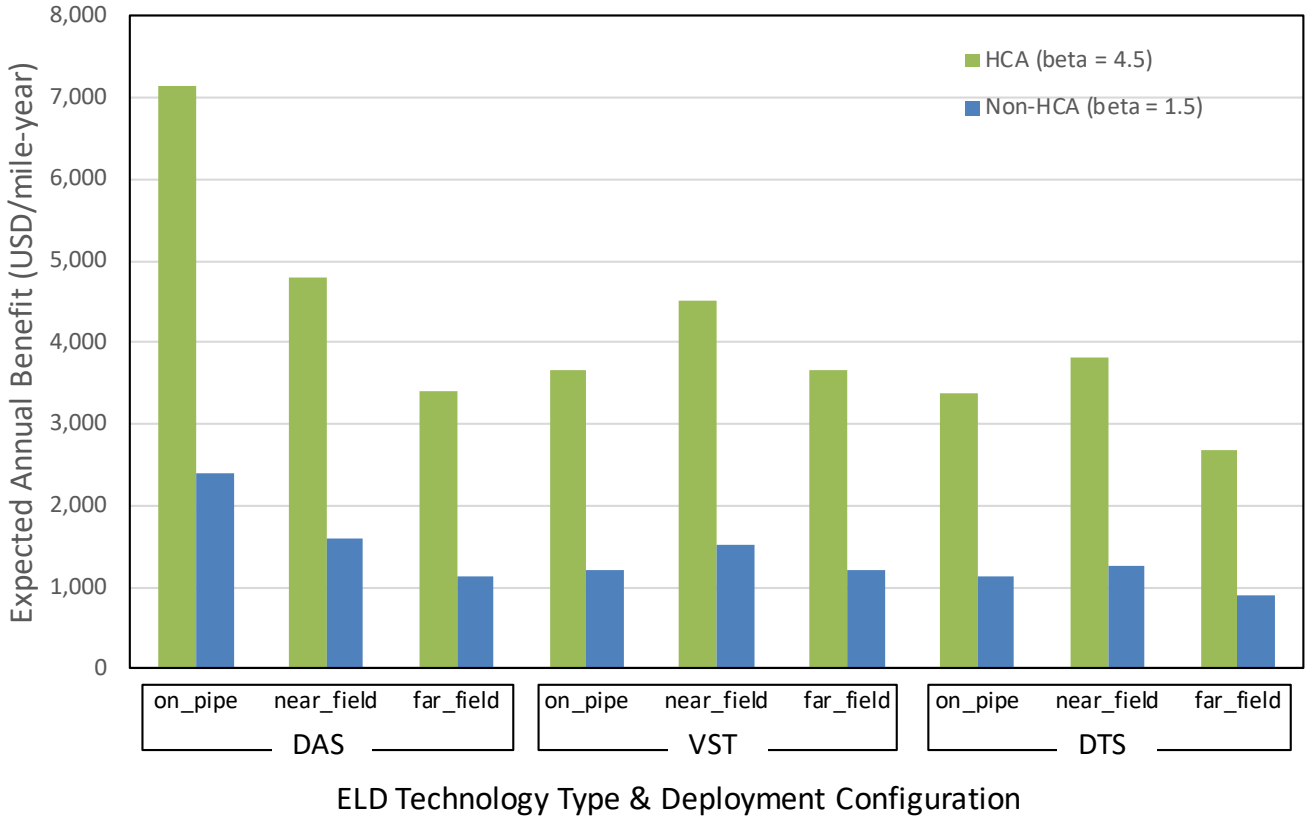
VST



DTS

Demonstration – Benefit Characterization

- Expected annual benefit (USD/mile-year)



Demonstration – Cost-benefit Analysis

- Reminder of the key elements in the cost-benefit analysis section
  - Discounting
  - Evaluation Criteria
  - Sensitivity Analysis

Demonstration – Cost-benefit Analysis

- A nominal social discount rate of 0.03 was used
- $PVB = \sum_{t=0}^{n} B_t d_t$, $PVC = \sum_{t=0}^{n} C_t d_t$, $d_t = \frac{1}{(1+r)^t}$
- Temporal distribution of costs
  - Procurement and installation
    - Procurement and installation of the candidate ELD systems is assumed to occur concurrently with pipeline construction and is assumed to be complete prior to pipeline operation.
    - The total procurement and installation costs are incurred prior to the first year of pipeline operation.
  - Operation and maintenance
    - Maintenance costs are assumed to be uniformly distributed throughout the operational life of the pipeline.
    - A uniform maintenance cost distribution is more conservative compared to a back-loaded maintenance cost distribution

Demonstration – Cost-benefit Analysis

- Temporal distribution of benefits
  - ELD system performance
    - The candidate ELD systems are assumed to be operational prior to the demonstration pipeline's first year of operation (i.e. Year 1).
    - The VST and DTS systems are assumed to be optimized and performing at their full potential in the first year of operation
    - DAS system is assumed to require a two-year ramp-up period, during which time system performance is attenuated somewhat to reflect baselining and optimization.
    - Specifically, the ELD response time is increased twofold and the ELD detection threshold is reduced by 50% during the ramp-up period
  - Pipeline failure rate
    - The calculated failure rate is assumed to be constant throughout the demonstration pipeline's operational life.
    - A review of incidents reported to PHMSA from 2002 through 2009 found that 85% of reported incidents were not correlated to the pipeline's age.

Demonstration – Cost-benefit Analysis

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Demonstration – Cost-benefit Analysis

- Reminder of the key elements in the cost-benefit analysis section
  - Discounting
  - Evaluation Criteria
  - Sensitivity Analysis

Demonstration – Cost-benefit Analysis

- Two evaluation criteria were selected:
  - Net present value (NPV). The arithmetical difference between the present benefits and the present costs (i.e. $PVB - PVC$);
  - Benefit-cost ratio (BRC), The ratio obtained by dividing the present benefits by the present costs (i.e. PVB/PVC)
- NPV is adopted as the primary CBA evaluation metric.
- BCR will be used as an additional evaluation metric to evaluate possible alternatives that might yield similar NPV values

Demonstration – Cost-benefit Analysis

- Reminder of the key elements in the cost-benefit analysis section
  - Discounting
  - Evaluation Criteria
  - Sensitivity Analysis

Demonstration – Cost-benefit Analysis

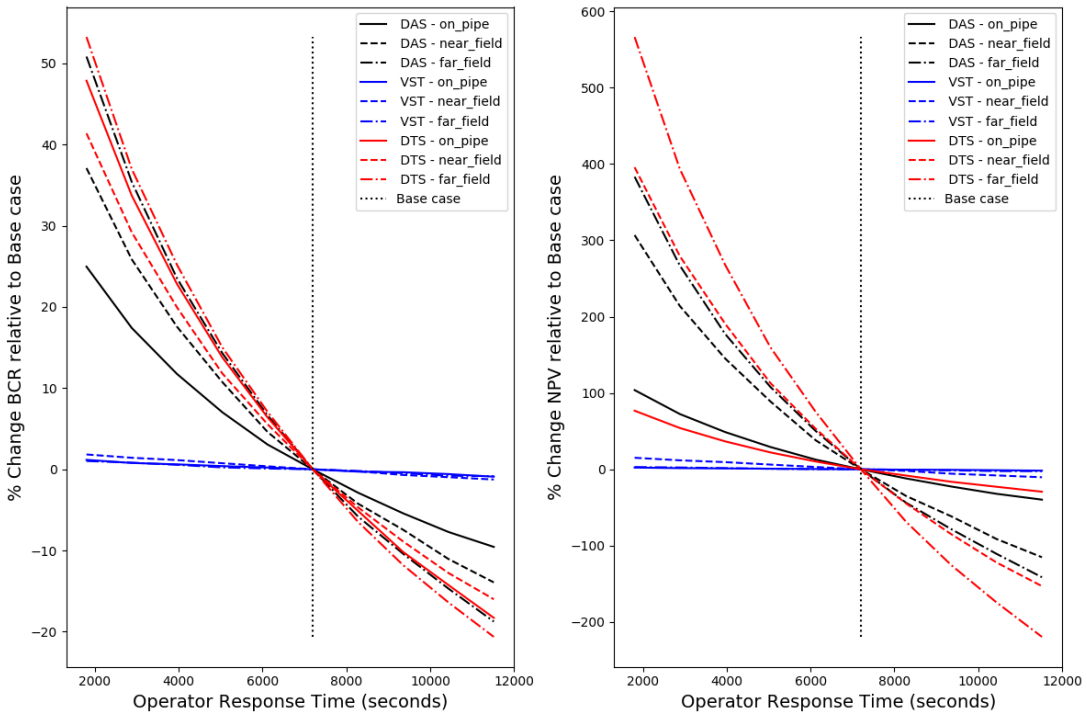
- Single variable testing
  - Model parameters
    - Operator response time
    - Maximum release pressure
    - Pipeline length
    - Pipeline flow rate
    - Pipeline operating life
    - Discount rate
  - Effort was focused on input parameters having non-trivial relationships with the evaluation metrics
    - The location factor, β
    - The reference spill impact value, c_r
    - The initial ELD costs
  - These variables were altered by fixed quantities one at a time while holding all other variables fixed.
  - The resulting percent change in BCR and NPV (relative to the base case) was then recorded for each variation

Base case model parameters

Parameter	Value
Operator Response Time	2 hours
Release Pressure Range	100 to 500 psi
Pipeline Length	155 miles
Pipeline Flowrate	19,800 GPM
Pipeline Operating Life	50 years
Spill Impact Attenuation Factor	0.8
Discount Rate	3%

Demonstration – Cost-benefit Analysis

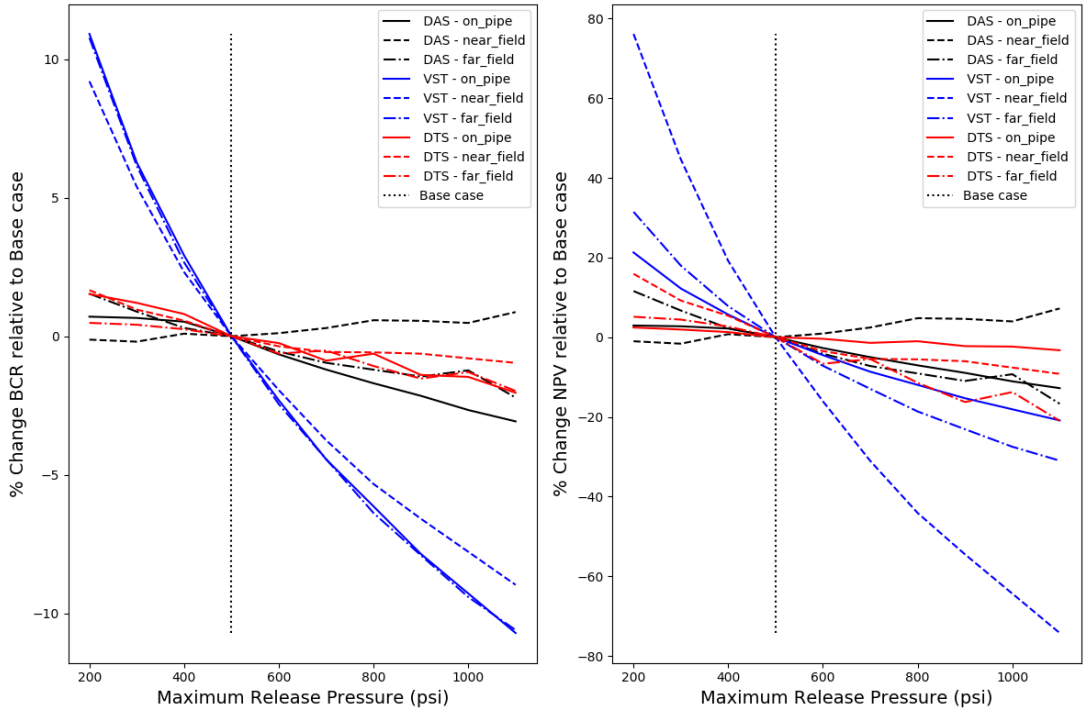
- Single variable testing
  - the percent change in BCR provides a clearer understanding of the effects of varying the input parameters compared to the percent change in NPV.
  - Conclusions of the single variable testing analysis, are informed primarily based on the BCR sensitivity curves



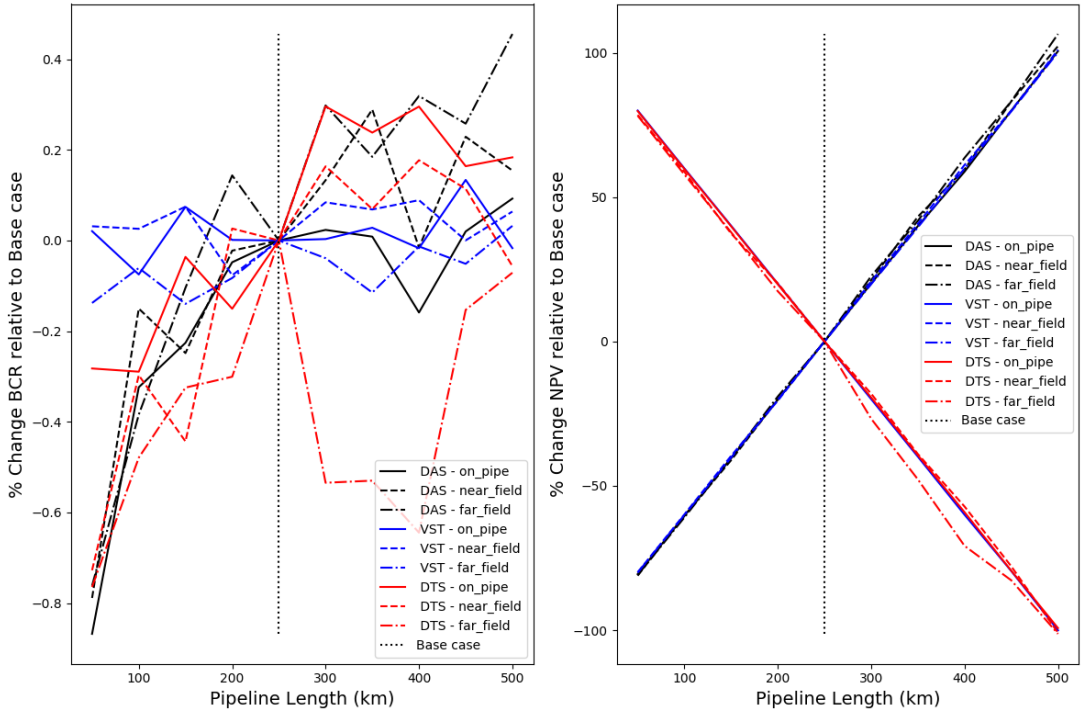
Operator Response Time

Demonstration – Cost-benefit Analysis

- Single variable testing



Maximum Release Pressure



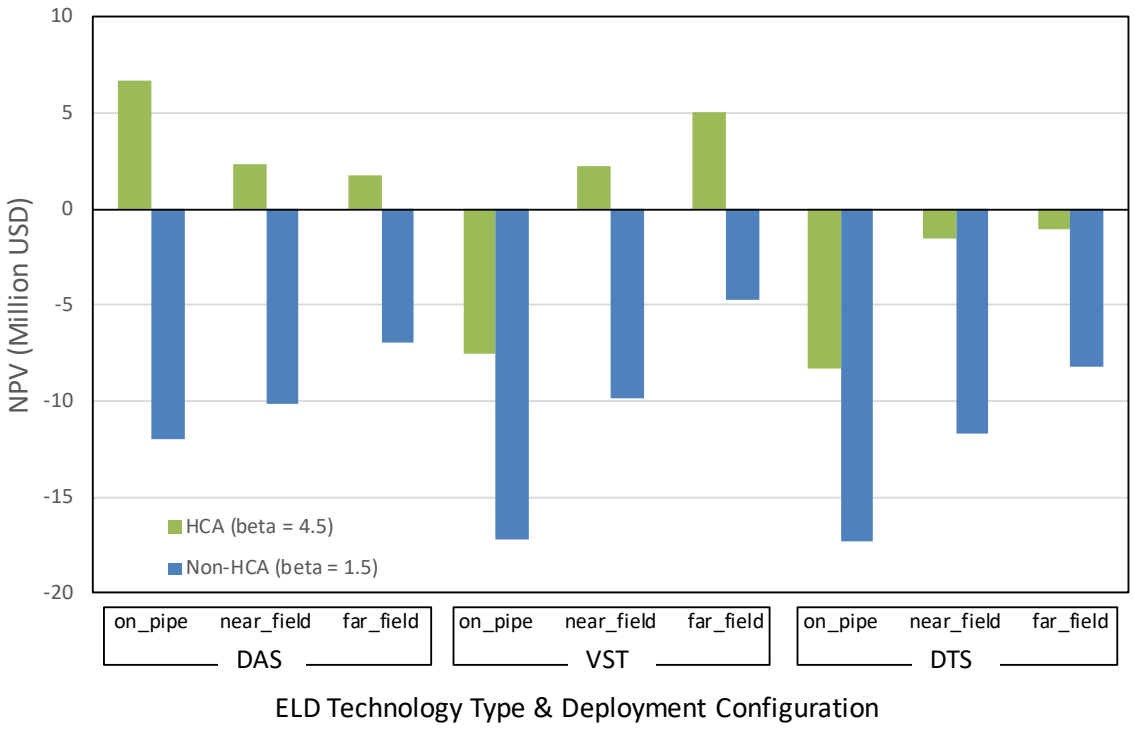
Pipeline Length

Demonstration – Cost-benefit Analysis

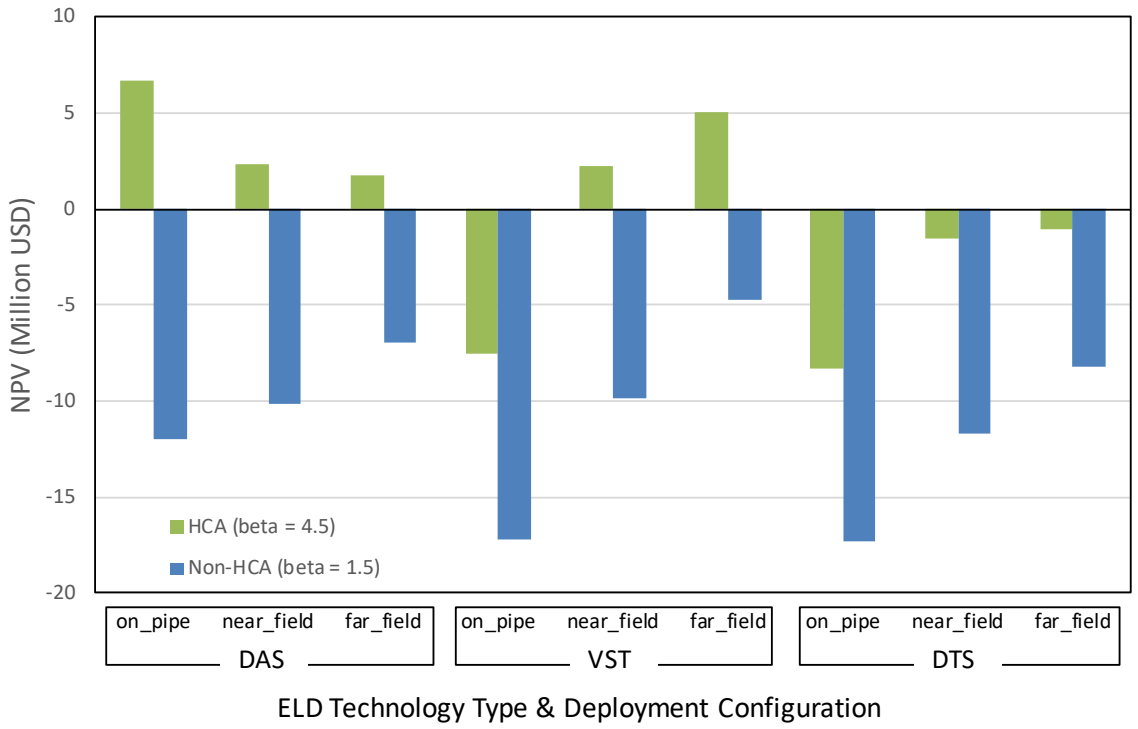
- Scenario analysis
  - The nine deployment configurations identified
  - The two area sensitivity levels previously
    - non-HCA characterized by an average location factor of $\beta = 1.5$
    - HCA characterized by an average location factor of $\beta = 4.5$

Demonstration – Cost-benefit Analysis

- Scenario analysis



NPV



BCR

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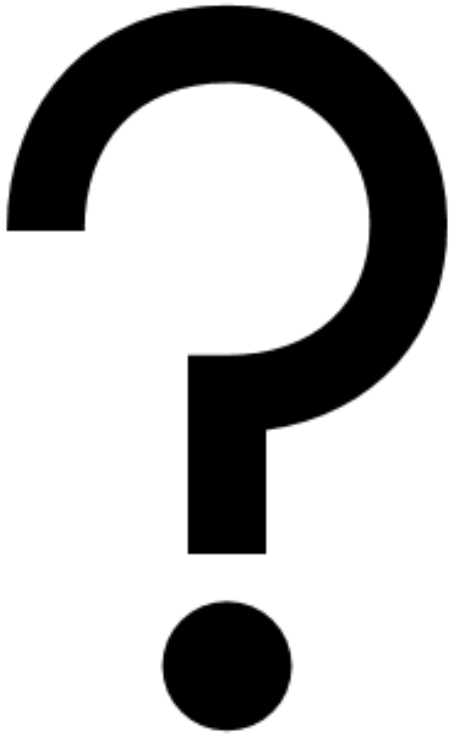

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