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PERFORMANCE OF ILI TECHNOLOGIES FOR DENTS WITH INTERACTING FEATURES
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ABSTRACT

Pipeline integrity management considers pipeline condition (e.g., pipe size, existence and size of features), operational/environmental and line pipe material property data which are input parameters for engineering assessment tools to evaluate operational risk. This paper presents the details of in-line inspection (ILI) system performance trials reporting pipeline condition information. These pull and pump through trials of magnetic, ultrasonic and caliper-based ILI technologies consider detection, identification and sizing performance for isolated corrosion, dents with a variety of shapes including those without coincident features and those with corrosion, gouges, cracks, cracks and corrosion. The presentation describes trial protocols including new feature characterization techniques that consider the position of the coincident feature in the pipe wall deformation. The trial results consider various technologies, the effect of speed and relative position of the dent and coincident feature on probability of detection, identification and sizing accuracy with unity plots and observed statistical variation and trends. The final objective of this work is to consider the performance of ILI systems in detecting, characterizing and sizing coincident features within dents such that this information can be used to support the pipeline integrity management process and provide feedback to ILI service providers to support technology development.

DISCLAIMER

This work was funded in part, under the Department of Transportation, Pipeline and Hazardous Materials Safety Administration. The views and conclusions contained in this document should not be interpreted as representing the official policies, either expressed or implied, of the Pipeline and Hazardous Materials Safety Administration, the Department of Transportation, or the U.S. Government.

1.INTRODUCTION

The pipeline industry is constantly driving improvements in its integrity management programs. A key focus area for the industry is in improving the understanding of the factors and variables that affect the performance of ILI systems. ILI systems are relied on extensively as the primary tool for pipeline operators to inspect pipeline assets to identify, characterize, and size anomalies and features. A significant amount of focus has been placed recently on the ability to detect and respond to interacting features in a pipeline. This includes the closely aligned or coincident features within dents/deformations in pipelines. The failure of mechanical damage with coincident features resulted in recommendations being issued to PHMSA by the Transportation Safety Board (NTSB) to promulgate new regulations that provide revised dent acceptance criteria [1]. To support mechanical damage integrity management, the energy pipeline industry, including the Pipeline Research Council International (PRCI), identified mechanical damage feature management as a strategic research priority and has sponsored a number of inspection and assessment research projects to fill industry gaps. This project (NDE-4-18 Phase I) focusses on an improved understanding of the performance of ILI systems.

To develop the desired ILI system performance, this research project was initiated including five primary stages including:

1. Fabrication and characterization of a set of pipe samples with a range of dent and coincident features and construction of a pipeline pull test string using these samples to demonstrate inspection performance of ILI systems for dent/deformation features,
2. Development of a trial protocol drawing on the definitions in API 1163 [2] and API RP 1183 [3], but reaching beyond to specifically consider the requirements related to mechanical damage,
3. Completion of blind test trials using a range of ILI Systems considering the effects of tool speed on ILI system performance to detect, identify and size the dent and coincident features,
4. Analysis of the ILI trial data using techniques specifically developed for mechanical damage with coincident features and provide feedback to the ILI Service Providers and Pipeline Operators, and
5. Recommendation for the direction of future trials and development of mechanical damage integrity management tools and programs.

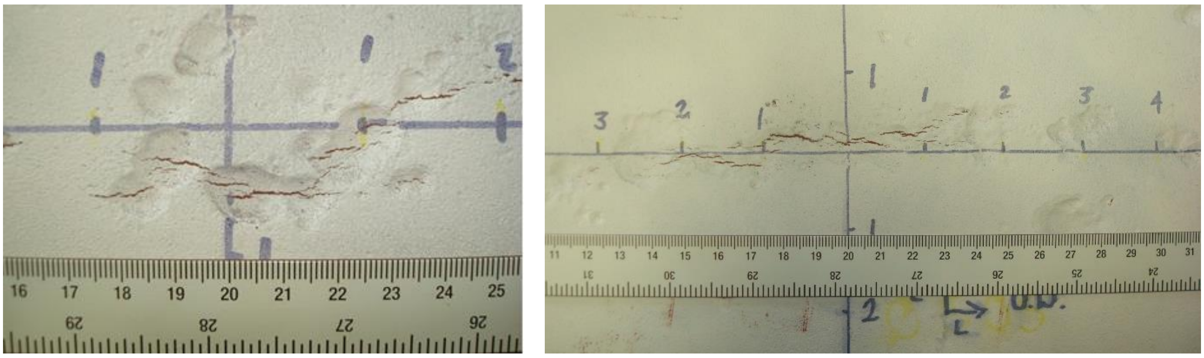
The sections that follow provide summary descriptions of the work completed in this project in each of the five stages. Further details and project results will be published by PRCI as part of the NDE-4-18 reporting.

2. STAGE 1 - PRODUCTION AND CHARACTERIZATION OF MECHANICAL DAMAGE TRIAL SAMPLES

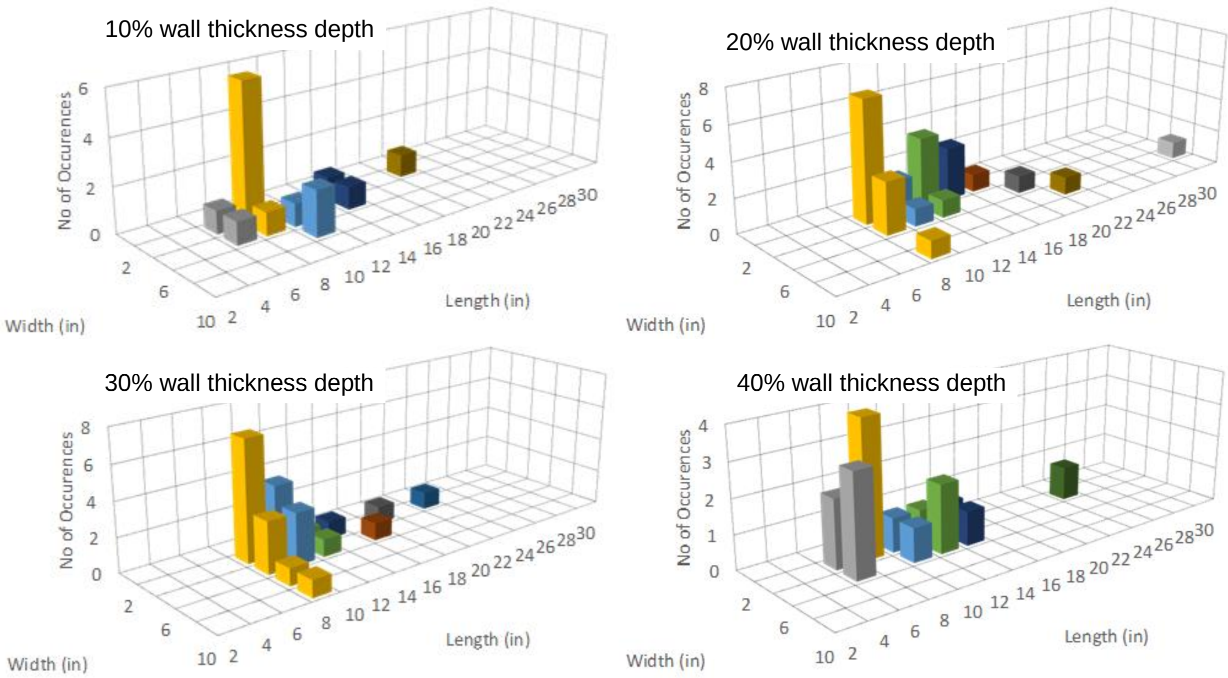
The objective of this stage in the project was to collect and prepare test specimens, including a range of mechanical damage features with interacting features including corrosion, gouges and cracks. These features were included in five- to eight-foot long 20-inch diameter pipe specimens including:

- Metal loss (natural corrosion removed from service),
- Dents on metal loss (natural corrosion removed from service),
- Dents on metal loss (natural corrosion removed from service) with fatigue cracks grown in the corroded areas through full-scale internal pressure cycling of the corroded dent feature,
- Dents with gouge specimens formed with an excavator tooth, and
- Plain dents with fatigue cracks grown in full-scale internal pressure cycling.

The pipe samples used in generating the trial specimens were all removed from service (i.e., former in-service pipe) and some of the pipe segments included metal loss (corrosion) features with depths ranging from 10 to 40 percent of the pipe wall thickness. The corrosion features were of a range of aspect ratios such that they represent the corrosion feature definitions (e.g., pitting, grooving, general corrosion) defined in API 1163. Figure 1 illustrates a sample of the pipe outside diameter (OD) surface with corrosion features and provides statistics of the range of features considered in the project. The trial specimens included corrosion features within dent features and those outside of dents so that the performance of the ILI tool in detecting identifying and sizing corrosion and corrosion coincident with dents could be compared.



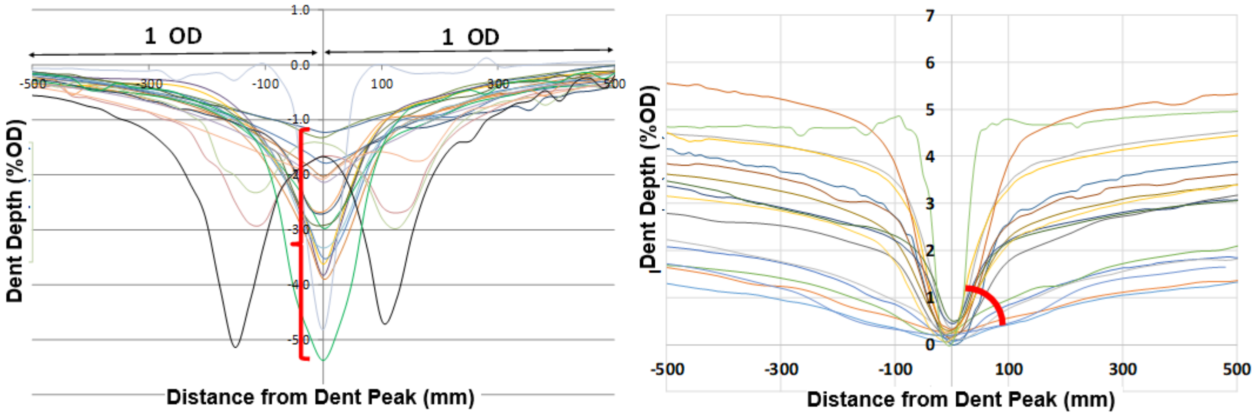
a) Sample corrosion features after cyclic loading to form fatigue cracks near the dent center



b) Corroson feature size statistics

Figure 1: Sample Corrosion Feature and Size Statistics

The dent features were created in a test laboratory by pressing indenters into the pipe segments. The pipe segments were cut from the former in-service pipe samples supplied for the project and included sections with and without corrosion features. End caps were installed on each end of the samples such that the samples could be pressurized. A range of dent features were generated by applying different indenter shapes and forming the dent features while the pipe sample was at different pressure conditions. Both single and multiple peak dents were generated in this manner. Dents with depths ranging from one to five percent of the pipe diameter were developed with a range of shapes as illustrated by the axial profiles of the deformed pipe wall presented in Figure 2. The data in this figure is presented by aligning the pipe OD surface to illustrate the range of dent depths and by aligning the deepest point in the dent to illustrate the range of dent peak curvature or included angle.



a) Axial profiles aligned to pipe OD b) Dent axial profiles aligned to dent deepest point

Figure 2: Illustration of the Range of Dent Axial Profiles Considered

After the test specimens were created with isolated and coincident features, they were characterized to develop "Truth" (reference) data as the basis for evaluating the ILI system performance. For the sake of brevity, the term Truth data is used in this description even though it is recognized that all measurements have the potential to contain some uncertainty and thus, are simply reference measurements. Access to the Truth data was restricted such that the ILI system trials could be considered blind trials. The truth data set was collected in four stages as follows:

1) A five part-wall hole reference mark was established on each pipe specimen to align the Truth data for each feature created and ILI reported feature locations. In the event that the reference mark was not identified or available, the 12 o'clock position on the girth welds attaching pipe specimens was used as an alternative reference point. The geometry and position of the reference points are illustrated in Figure 3.

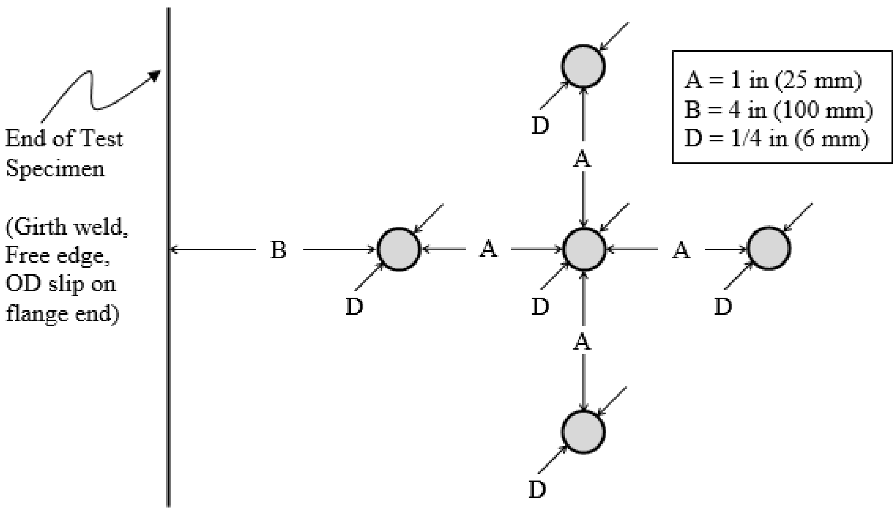


Figure 3: Illustration of Truth Data Reference Mark

2) Pipe specimen feature location and geometry were documented using a surface laser scanning (Creaform) system. Spot measurements using a pit gauge and pipe diameter caliper measurements were used to confirm the validity of the data from the laser scan system with regards to corrosion feature depth and pipe ovality. The full circumference pipe surface scan provides the dent and corrosion feature geometric truth data (i.e., position and shape). A sample surface scan is presented in Figure 4.

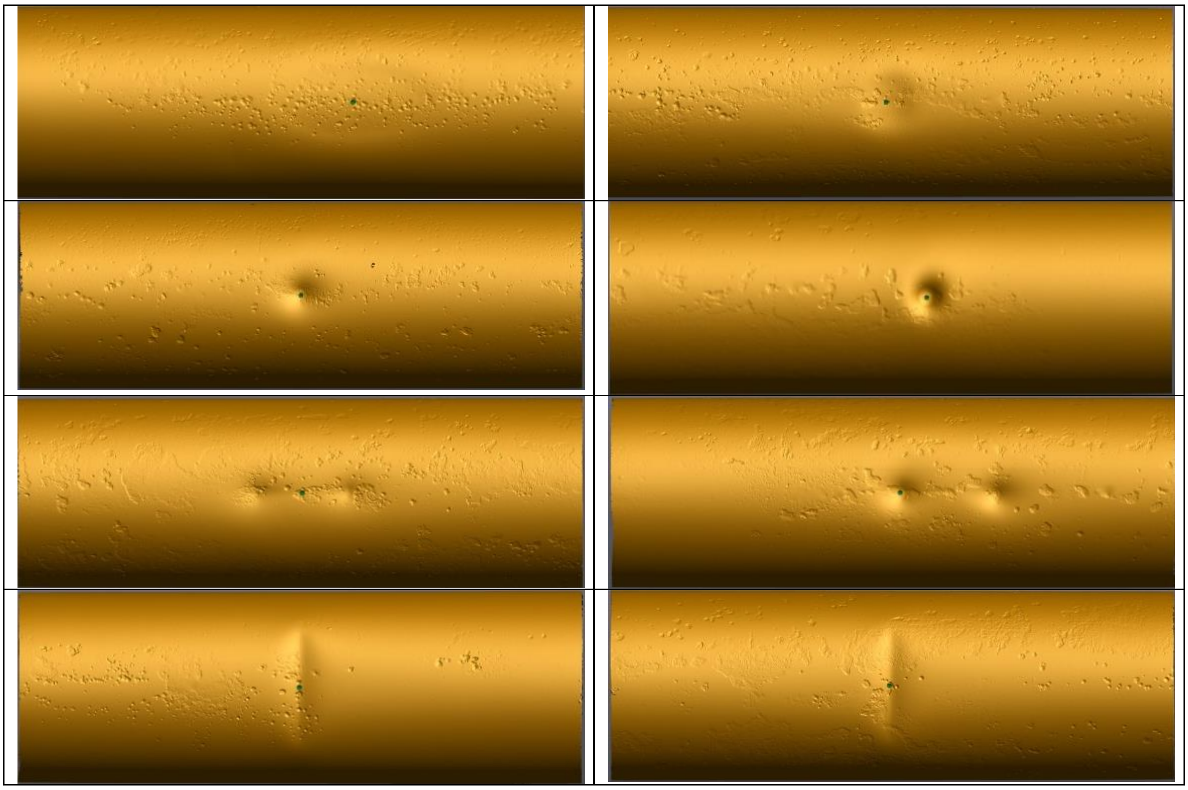


Figure 4: Illustrations of Pipe Sample Surface Scans Showing Dents and Corrosion

The location and length of surface breaking crack features were documented photographically using magnetic particle inspection. The position relative to the dent center of each crack feature was identified in this manner as illustrated in Figure 1a for the cracks located in corrosion features positioned near the deepest point (center) of the dent, as identified by the origin inscribed on the pipe surface with a black marker. Ultrasonic crack measurements were taken to estimate the depth of the crack features.

The crack features were formed in dents subjected to cyclic internal pressure cycling. The depths of the dent features varies, and the dents were in the restrained and unrestrained condition when cycling. As such, the cracks formed in the pipe specimens were of various depths from 10 percent of the wall thickness to through wall cracks with combinations of the following characteristics:

- Axial and circumferential cracks,
- Isolated and clusters (colonies) of cracks,
- ID and OD initiated cracks, and
- Surface breaking and through-wall cracks.

3) The assembly of the pipe samples into pipe strings for the trials was completed at the PRCI Technology Development Center (TDC) in Houston, Texas. The assembly was documented to identify the pipe specimen position and orientation in the pipe string. To demonstrate correct alignment of the pipe and quality of assembly, a cleaning pig and a gauge pig were run through the pipe strings and this data was provided to the ILI Service providers to document the maximum pipe diameter obstruction and assure them of the cleanliness of the pipe string.

   For the pull trials, two pipe strings were assembled to accommodate magnetic and caliper ILI technologies. A 90-degree bend with a radius equal to five pipe diameters was attached to the pipe strings to support a pump through process for liquid coupled ILI technologies. The test assembly is illustrated in Figure 5. The pipe tally was provided to the ILI Service Providers defining pipe specimen lengths prior to the performance trials.

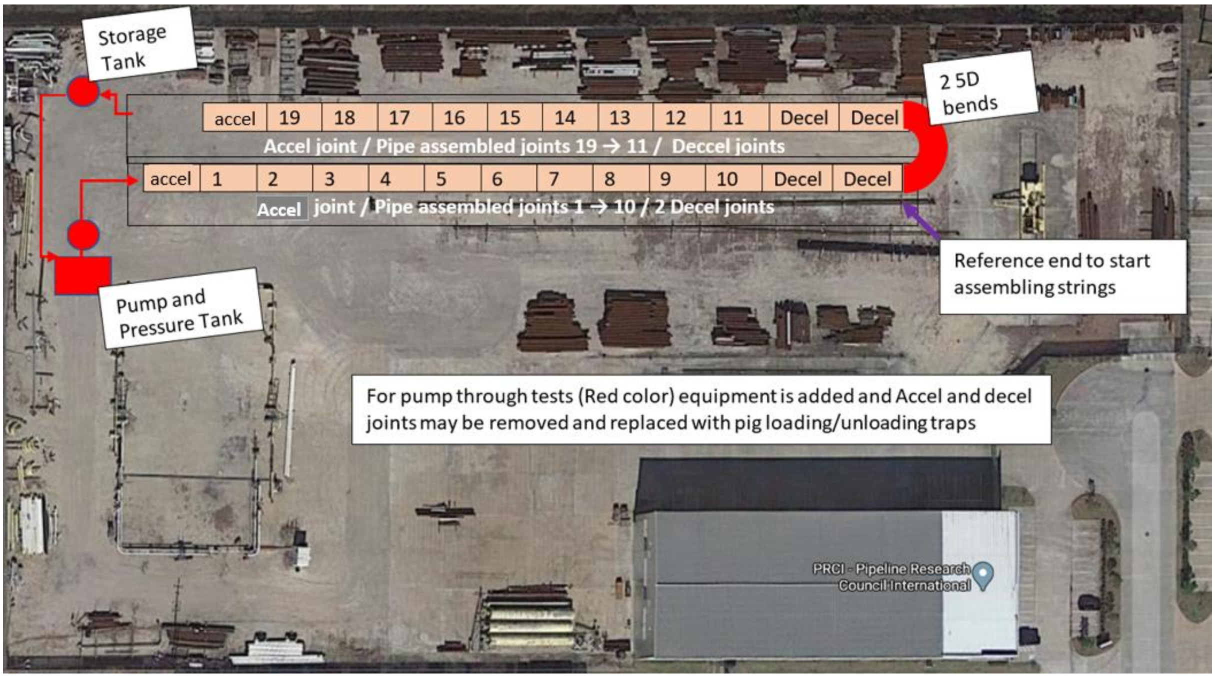


Figure 5: Schematic of the Trial Assembly (Red Components added for Pump Through)

4) After the ILI trials, a small number of pipe specimens with cracks were identified for destructive sectioning. This process was used to provide detailed crack depth profile data for the selected samples and augment the ultrasonic crack depth measurements. Sample pipe segments were also subjected to computed tomography (CT) scanning to characterize the crack sizes.

   After completion of the ILI pull trials and performance evaluations, a subset of the Truth data will be provided to the participating ILI Service Providers to support ILI system development. Some of the trial specimen data will not be disclosed, such that these specimens may be re-used in future blind ILI or NDE performance trials. Details on future trials as provided in the project Stage 5 are included in the paper concluding remarks.

3. STAGE 2 - DEVELOPMENT OF A TRIAL PROTOCOL

The objective of this stage in the project was to define the trial process, data reporting, performance evaluation and communication processes for the project. A detailed performance trial protocol was written and distributed to the Participants (i.e., Project team, PRCI and ILI Service Providers) for review and comment. This document was written primarily for the pull trial process; however, it was applicable to the pump through process as well. The document included:

- A statement of the project objectives and scope of the trials along with definition of participants and their responsibilities and authority in the trial process,
- A summary of the test specimen characterization and documentation process,
- A detailed description of the trial process, conditions and test design,
- A description of the pull trial facility and test system including availability of support equipment, cleanliness of the specimens and site health and safety requirements,
- A listing of the data provided to the ILI Service Providers prior to the trials,
- Preparations for testing and test execution including data collection and exchange including the inspection reporting content and format,
- Performance evaluation process and metrics, and

- Reporting, communication and confidentiality.

The trial program included a minimum of 10 passes (tests or runs) through each test string of samples in order to have two passes at each of five tool speeds. An effort was made to standardize the trial speeds at approximately 0.5, 1.5, 2.5, 3.5 and 5.0 m/s (1.1, 3.3, 5.6, 7.8 and 11.1 mph). Slower test speeds were used for liquid coupled ILI tools up to 1.5 m/s (3.3 mph). The testing at different speeds was used to evaluate the performance of the tool at different speeds and duplicate testing was completed to both minimize the risk of data loss or corruption from a single run and to provide multiple observations of each feature.

The general pipe string data collected from each trial run included:
- Tool speed measured by the tool odometer time history for each test,
- A pipe tally listing the position of each pipe segment based on the Upstream (U/S) girth weld position, and
- A feature listing for each test in the direction of ILI travel defining the axial and clock position of:
  - Girth welds,
  - Long Seam,
  - Center hole of the 5-hole reference marker (see Figure 3),
  - Dent peak (deepest point),
  - Metal loss for both individual features and Metal Loss clusters,
  - Flanges,
  - Cracks (crack start, crack end, deepest position of crack), and
  - Pipe wall thickness for each pipe in the tally.

The metal loss feature data collected from each trial run included:
- Individual corrosion features (Length, Width, and Depth in percent WT) and position,
- The class of corrosion feature such as General, Pitting, Grooving, Slotting, etc. to be specified.
- Gouges are to be called out separately,
- Corrosion features that are interacting with dents are to be called out, and
- Corrosion features to be differentiated as external or internal.

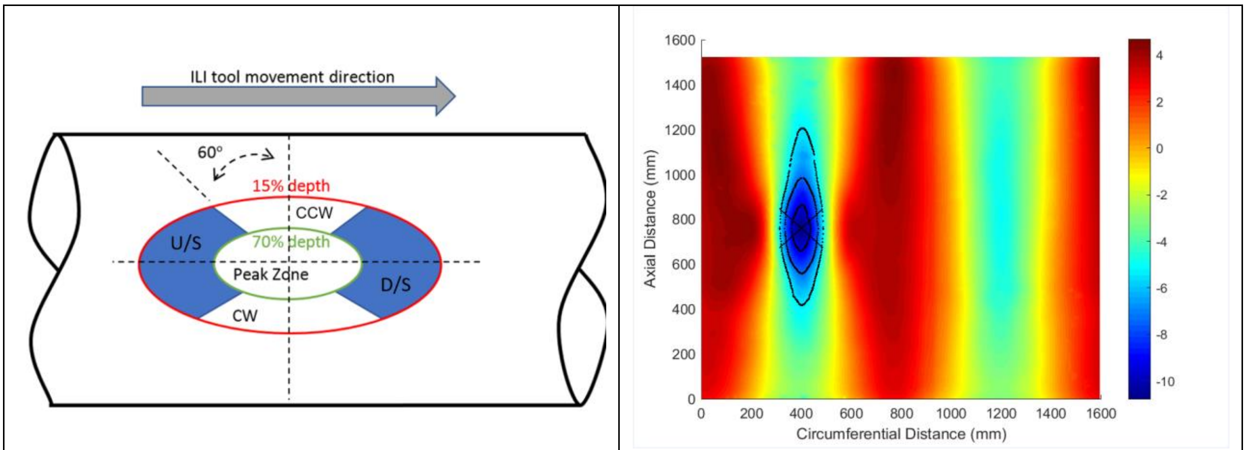
The dent feature data collected from each trial run included:
- Dents interacting with corrosion features (dent interacting with metal loss, dents interacting with gouges),
- Multi-apex dent or double dents,
- All Dent geometric parameters as per API RP 1183 for Level 2 analysis are to be provided (i.e., characteristic lengths and areas),
- Two dent depths - The Maximum Dent Depths from Axial profile with respect to Upstream (U/S) shoulder and Downstream (D/S) shoulder. The U/S and D/S dent depths data were used to generate the dent geometric parameters and were therefore essential,
- All four Restraint parameters as calculated using the procedure presented in API RP 1183,
- The complete 360-degree pipe wall radial deformation ILI caliper data of each run without removing ovality, and
- The complete 360-degree pipe wall radial deformation ILI Caliper Data for each individual pipe segments in each joint. These data were used to extract dent geometric parameters as per API RP 1183. BMT used this data to compare ILI profile with laser scan profile as well as use it to extract dent geometric parameters.

The crack feature data collected from each trial run included:
- Cracks are to be identified as individual cracks, crack colonies, multiple cracks, etc.,
- OD crack, ID crack,
- Axial, circumferential, angle,

- Interacting with dent, corrosion, weld,
- The position of the crack, dent peak, dent shoulder (U/S, D/S, transverse shoulder),
- Crack length, crack width,
- Crack position-, axial start, axial end, and
- Position of the maximum crack depth.

The ILI Service Providers that participated in the trials were requested to submit small samples of their data to confirm the format and content of the data being provided. This small data set was reviewed by BMT and discussed independently with each ILI Service Provider to ensure that both parties held the same interpretation of the data and calculated parameters to avoid communication/data reduction instruction errors from affecting ILI system performance evaluation. After these review meetings, the remainder of the data was processed and delivered by the ILI Service Providers.

The collected data was used to evaluate the performance of ILI systems by comparing the ILI system reported data with the project Truth data. It is noted that statistics reported in this project may be based on relatively small data sets and thus may not be representative of the performance of the ILI system over a larger population of features that may be used by the ILI Service Provider to develop their performance specification. In addition, the performance of the ILI systems was evaluated with respect to coincident feature combinations and the effects of speed that may not be explicitly considered in the ILI system specification. For this investigation, the coincidence of features with the dent were identified based on their location within the five zones defined in Figure 6. Based on these definitions of the coincidence zones, the coincident feature location was identified by the following characteristics:
- ID and OD,
- U/S shoulder,
- D/S shoulder,
- Sides of the dent (clock position),
- Center of dent, and
- Plain pipe (outside of the dent feature).



a) Pictorial definition of dent coincidence zones | b) Pipe surface illustration of coincidence zones

Figure 6: Dent Coincident Feature Locations

Each feature in the truth data was defined to be one of seven specific types for the sake of performance evaluation:

1. Crack in corrosion
2. Crack in corrosion in dent
3. Crack in dent
4. Corrosion in dent

5. Corrosion
6. Gouge in dent
7. Dent

The corrosion features were sub-characterized using the corrosion feature type definitions (e.g., pitting, grooving, general corrosion) in API 1163. Corrosion features with depths of less than 10 percent of the pipe wall thickness were not considered in the ILI system performance evaluation reporting process. In comparing the ILI system reported corrosion features with the Truth data, no metal loss interaction or clustering criteria were applied to the Truth data and the two data sets were aligned by aligning the five-hole reference marker (Figure 3) in the two data sets. Individual features were matched by minimizing the distance between the features in the two data sets as shown in a sample laser scan (Truth data black box outline) and ILI system reported (features in the blue box outline) in Figure 7. The laser scan Truth data shown with black outline boxes may intersect with multiple ILI reported features as show in the magnified area of Figure 7. In this instance all of the intersecting ILI reported features will contribute positively to the probability of detection (POD) but will diminish the probability of identification (POI) because the feature may represent the wrong metal loss class.

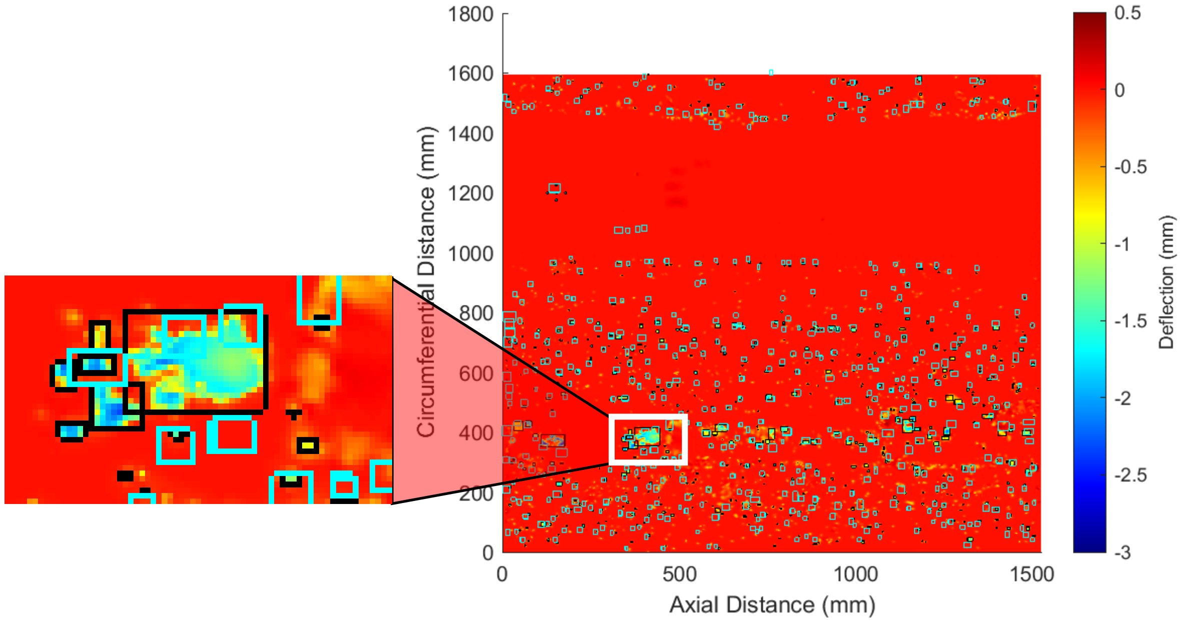
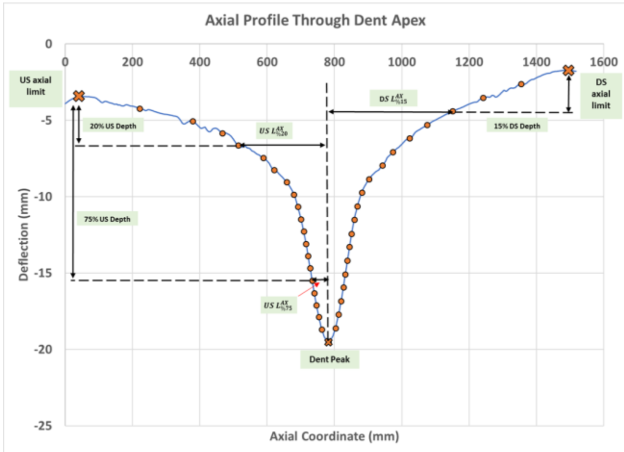


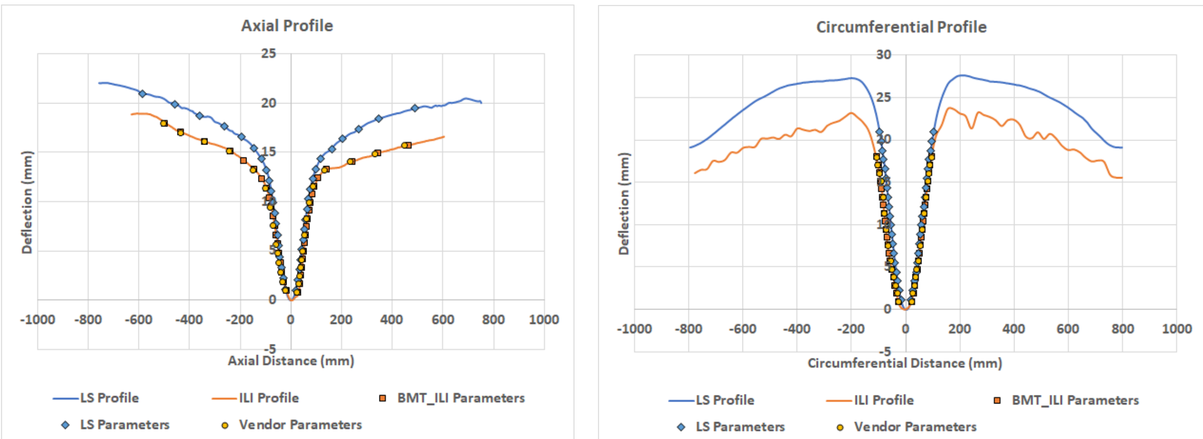
Figure 7: Sample Truth Data (Laser Scan Black Outline Box) to ILI System Reported (Blue Box) Features

The corrosion analysis process involved processing of the laser scan reference data followed by the ILI metal loss boxes. The first step undertaken was to process the laser scan data to detect wall thickness reductions on the pipe surface. These data points were isolated and grouped together to form distinct metal loss regions. Regions of wall thickness reductions less than 10 percentWT were not considered, as this value is lower than the detection thresholds of most ILI tools. The distinct metal loss regions were boxed and the depth of the deepest point within the regions were assigned as the depth of the metal loss boxes. The boxed laser scan features were then tested for dent interaction based on the dent interaction scheme presented in Figure 6(a). Coincidence with these zones resulted in characterizing of the laser scan metal loss features as interacting. After the completion of these steps, the ILI provided metal loss boxes were processed. The first step involved the overlapping of the laser scan and ILI boxes representing the 5-hole reference marker. Further, optimization was performed to maximize the overlap of laser scan and ILI boxes based on minimizing the distance between the centroids of the laser scan and ILI boxes. After the overlap was completed the coincidence between laser scan and ILI boxes was established. Overlap of the boxes or having vertices within 25 mm of each other, established the correspondence between the laser scan and ILI features. Matching of a single laser scan feature with multiple ILI boxes and vice versa was possible and these multiple correspondences were considered. After the matching process was complete various statistics like probability of detection, probability of identification and box dimension measurement errors were calculated.

The performance in characterizing dent features was completed by comparing the API RP 1183 characteristic lengths and areas derived from ILI caliper tools to those derived from laser surface scan data. Figure 8 illustrates the API RP 1183 characteristic lengths derived from an axial profile of a dent taken at the clock position such that the profile traverses the deepest point of the dent. Figure 8 also includes a sample illustration of the overlay of the ILI, surface scan and the points used to characteristic lengths for the API RP 1183 dent shape definition process. The illustrations in this figure demonstrate that the U/S and D/S dent depths can be different if the dent is not symmetric because the U/S and D/S dent shapes are different.

a) Illustration of the dent axial profile characteristic length definition





b) Sample comparison of ILI and Truth data

Figure 8: Dent Profile Shape Characteristic Length Definition and Truth Data to ILI System Comparison

The POD and POI in the performance evaluations were completed as defined in API RP 1163, noting that the sample sizes may be small. The formulae for evaluating POD and POI, considering the ILI system specification thresholds used in this program were as follows:

$$POD = \frac{True\ Positives\ (within\ specification\ )}{(True\ Positives\ (within\ specification) + False\ Negatives\ (within\ specification)}$$

$$POI = \frac{Correct\ Identifications\ \ (A\ )}{(Correct\ Identifications\ (A) + Incorrect\ Identifications\ (A)}$$

The measurement performance evaluation involved comparing the feature sizes reported by the ILI system and those in the Truth data. The POD, POI and sizing performance was evaluated three times as follows:

1. All features of a given type (e.g., all corrosion features)
2. All features of a given type without dent coincidence (e.g., corrosion in plain pipe)
3. All features of a given type with dent coincidence (e.g., corrosion in a dent)

The POD, POI and sizing were further evaluated separately for each feature type, coincidence condition, trial speed, corrosion metal loss depth in 5 percent depth increments, corrosion feature type, crack orientation and feature pipe surface location.

The feature sizing performance was presented both in unity plots and statistical descriptions of the ILI system performance with respect to ILI tool speed by characterizing the trends in mean sizing error and standard deviation for each trial speed.

4. STAGE 3 - BLIND TRIAL EXECUTION

The objective of this stage in the project was to execute the trials for each ILI system such that the ILI Service Providers could evaluate the trial measurements and submit data for assessment. The trials were completed at the PRCI TDC over a three- to five-day private trial execution period for each ILI Service Provider. Trials were completed cooperatively with seven ILI Service Providers and considered four ILI technologies. Both dry test string pull through trials and liquid-coupled (water) pump through trials were completed.

Figure 9 illustrates the ILI performance trial winch and pull string assembly for the program. The pull strings were roughly 152 m (500 feet) long and contained more than 65 dent features with and without corrosion, cracks and gouges). The test setup also included pipe samples with just corrosion features that were used as a reference samples for the performance evaluation.

Figure 9: ILI Trial Setup and Pull Through Winch

Both trial day data testing conditions and processed data were collected as outlined in the previous section. The trials were completed as blind trials, in that the ILI Service Providers were only informed of the types of features that would be present in the trial strings prior to testing. During the trials, the ILI system data, trial conditions, attendees and any issues related to the trial were recorded for future reference. For example, the pull speed was recorded based on the winch wire speed to demonstrate the uniformity of the pull speed as shown in Figure 10. This data was compared with tool speed data provided by the ILI service Provider and no significant difference was observed.

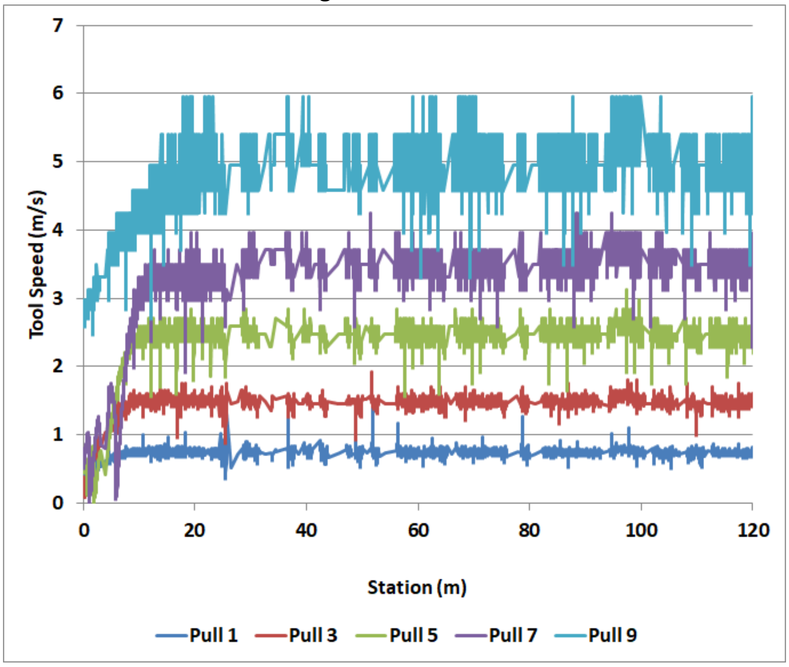


Figure 10: Reported ILI Trial Pull Speeds

5. STAGE 4 - ANALYSIS OF THE ILI TRIAL RESULTS

The objective of this stage in the project was to compare the ILI system reported data with the Truth data to report on the performance of the ILI systems in detecting, identifying and sizing dents and coincident features. The results in this section are not presented in their entirety; but are a sample of typical results derived from specific ILI systems and trial conditions to illustrate the types of data and results generated in this project. More complete project results will be available in the PRCI project report (NDE-4-18). In this project, the trial results were delivered and discussed with the ILI Service Providers for their information and use and the analysis results will be accumulated in the final project report with the ILI systems presented in an anonymized fashion.

The trial protocol performance evaluation process and means of presenting the data employed in this project are summarized in Table 1. The performance trial assessment process and definitions were reviewed with the ILI Service Providers. It was noted that some of analysis approaches were different form their expected practice.

Evaluation Stage - Parameter of Interest	Evaluation Method / Presentation
1.0 Detection 1.1 Anomaly call 1.2 Location of anomaly (Boxed Feature) ▪ Circumferential ▪ Axial	Probability of Detection (POD) by feature type - Demonstrate effect of: ▪ Coincidence ▪ Orientation ▪ Feature Size Unity Plots (consider agreement trend and bias) - Location
2.0 Identification 2.1 Feature Type (Dent, Corrosion, Weld, Crack Gouge) 2.2 Surface (ID/OD) [for metal loss and planar features] 2.3 Orientation (Degrees from axial . . . for planar features (i.e., cracks) 2.4 Location (Feature deepest point) ▪ Circumferential ▪ Axial 2.5 Coincident features	Probability of Identification (POI) by feature type - Demonstrate effect of: ▪ Coincidence ▪ Orientation ▪ Feature size and shape - Unity Plots (consider agreement trend and bias) ▪ Location
3.0 Sizing 3.1 Dent ▪ Maximum depth[1] ▪ Characteristic lengths and areas[1] ▪ 3 dimensional shape 3.2 Metal Loss ▪ Maximum depth ▪ Length ▪ Width 3.3 Planar Feature (Crack) ▪ Maximum depth ▪ Maximum length	Sizing performance by feature type and level of accuracy - Demonstrate effect of: ▪ Coincidence ▪ Orientation ▪ Feature size and shape - Unity Plots (consider agreement trend and bias) ▪ All sizing parameters (left table column) ▪ Confirm calculation of characteristic lengths and areas from 3 dimensional shape

[1] Definitions as outlined in API RP 1183 (PRCI MD-4-9 program)

Table 1: ILI Performance Trial Protocol Data and Evaluation Summary

The sections that follow provide illustrations of the ILI system performance results. The data presented includes samples of trial results for single ILI systems and groups of up to six ILI systems to demonstrate the performance across a range of systems.

5.1. ILI Performance Trial Results for Dents

The ability of the ILI tools to detect and identify features as dents was high, resulting in nearly perfect performance, as illustrated in Table 2. The instances where the POD values were not 100 percent related to the characterization of adjacent or multi-peak dent features. The POD and POI performance for dent features was shown to be independent of the tool speeds tested.

A unity plot for the ILI system reported dent depth, for one ILI system, is shown in Figure 11. This data for a single ILI system and all of the pull trials completed shows a good ability to report dent depth, relative to the Truth Data. There is a minor bias to over reporting depth which appears to be greater for the dent depth reported for the upstream shoulder. A similar unity plot is presented in Figure 12 for six mechanical caliper tools which includes 6,360 observations (i.e., 6 ILI systems X 5 trial speeds X 2 pulls X 53 dent features x 2 depths (U/S and D/S). These results illustrate that while there are a few outlier measurements, the performance of the ILI systems is similar in measuring dent depth.

Pull #	Tool Speed (m/s (mph))	True Positive	True Positive + False Negatives	POD
1	0.74 (1.65)	70	70	1.00
2	0.74 (1.64)	70	70	1.00
3	1.46 (3.26)	69	70	0.99
4	1.44 (3.23)	69	70	0.99
5	2.40 (5.36)	69	70	0.99
6	2.37 (5.30)	69	70	0.99
7	3.28 (7.34)	69	70	0.99
8	3.21 (7.18)	69	70	0.99
9	4.81 10.76)	70	70	1.00
10	4.64 (10.39)	69	70	0.99

Table 2: Dent POD Performance

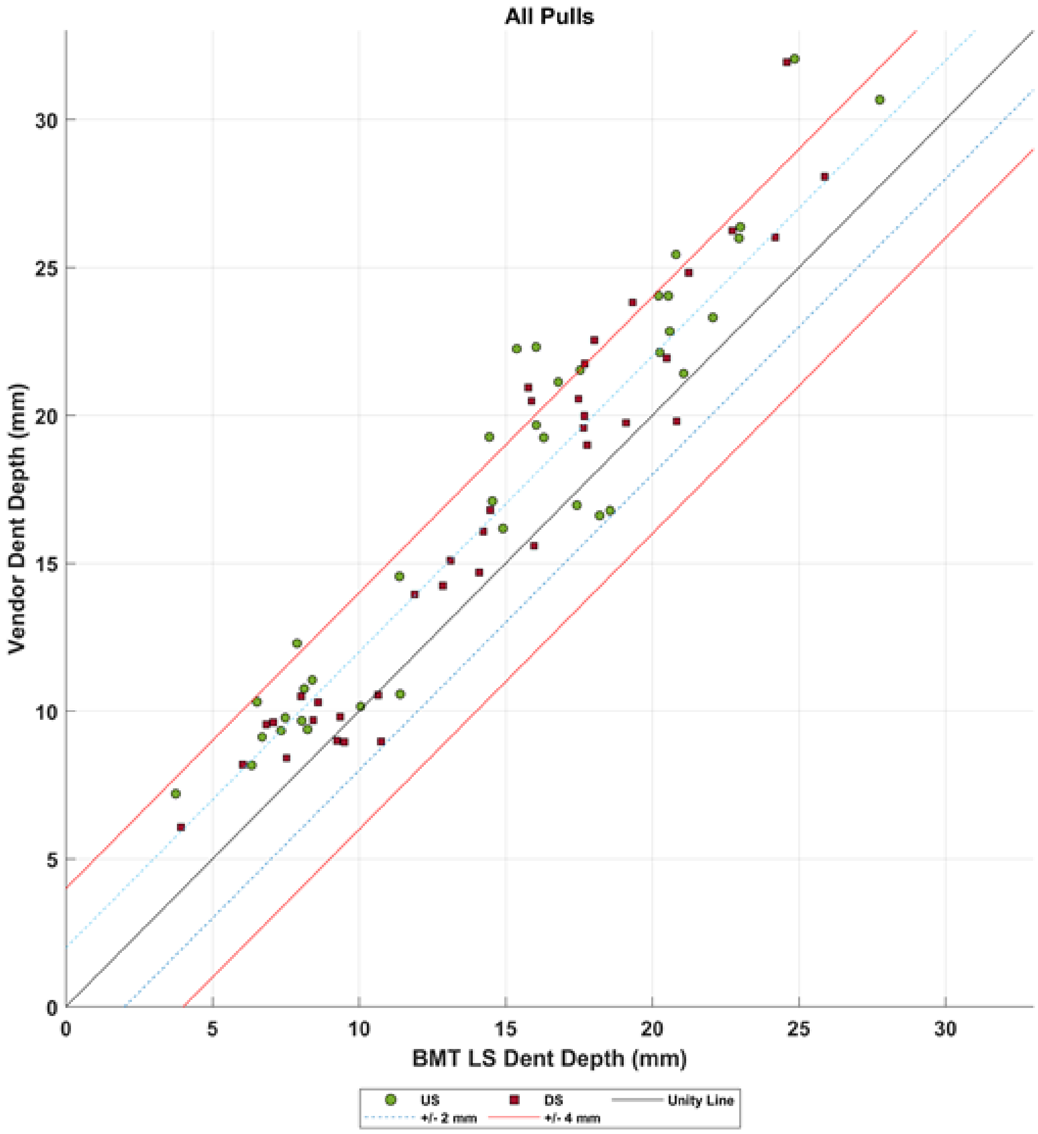


Figure 11: Sample Dent Depth Unity Plot – One Mechnical Caliper ILI System

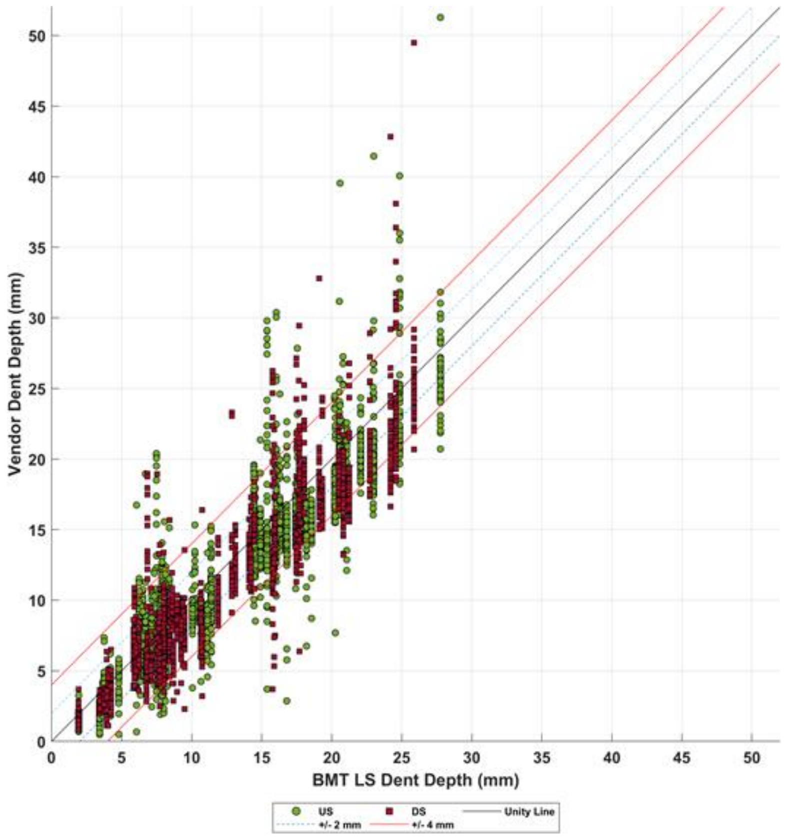


Figure 12: Sample Dent Depth Unity Plot – Six Mechanical Caliper ILI Systems

Since the ILI system performance evaluation for dents is based on the calculated API RP 1183 characteristic lengths, a first check of the data was completed to compare the ILI Service Provider interpretation of the characteristic lengths to those developed by BMT from the same ILI system reported three-dimensional dent shape. This check was completed to ensure that the reported ILI system performance was not degraded due to communication or comprehension of the API RP 1183 dent characteristic length and area concepts. The dent characteristic lengths measure the distance between the deepest point in the dent to points on the dent profile that are a specific fraction of the dent depth. The identification of these reference points includes some interpretation of the dent profile and depends on the characterization of the maximum dent depth. As such, there is expected to always be some variability in these parameters. A sample of the average and standard deviation of the percentage difference between an ILI Service Provider and the BMT (Truth data) interpretation of the dent characteristic lengths are presented in Table 3. The data presents the average differences in measurements for the dent profiles for all pull tests (e.g., all speeds) with the data shown for the U/S and D/S axial profiles as well as the clockwise (CW) and counterclockwise (CCW) directions. These results indicate that for this specific ILI system the percentage difference increases as the characteristic length measurement points are located away from the dent center and that the differences are higher at the center of the dent for the axial dent profile. It is also noted that the upstream difference is greater than the downstream difference. These observations are made for a specific tool and averaged across all test speeds for a specific ILI system and are provided as an example of the results generated in the study.

Mean Percent Difference						Standard Deviation of Percent Difference				
Depth Percent OD	US_L_AX	DS_L_AX	CW_L_TR	CCW_L_TR		Depth Percent OD	US_L_AX	DS_L_AX	CW_L_TR	CCW_L_TR
10	-8.58	-2.89	-0.17	-1.44		10	16.33	17.14	14.19	17.85
15	-8.19	-1.18	0.18	-0.81		15	15.18	20.32	14.54	18.22
20	-6.96	-2.27	1.45	-0.77		20	14.53	13.82	17.33	16.07
30	-4.02	-1.23	1.50	-1.02		30	11.99	12.66	15.61	13.45
40	-1.90	-0.91	1.93	-0.76		40	11.99	12.09	17.52	15.11
50	-0.04	-0.69	1.95	-0.22		50	12.90	13.29	20.19	19.17
60	1.17	-1.03	2.51	-0.44		60	14.99	16.14	24.36	21.40
70	2.77	-0.90	3.56	0.13		70	18.80	18.26	31.11	26.72
75	3.98	-0.34	4.55	0.69		75	21.63	23.27	36.58	31.56
80	5.29	1.07	6.19	1.31		80	26.32	28.77	45.01	36.59
85	7.82	0.50	8.83	1.91		85	37.01	27.55	59.81	46.28
90	13.02	1.63	14.93	3.92		90	56.39	32.38	89.59	64.54
95	28.63	6.70	29.45	10.26		95	120.55	48.91	174.43	117.47

Table 3: Sample Percent Difference Between ILI Service Provider to BMT Truth Data Characteristic Lengths, for one ILI Service Provider

Unity plots for the absolute measurement performance were generated to explore ILI system performance relative to the laser surface scan ILI Truth data. Sample unity plots comparing the ILI system reported characteristic lengths to the Truth data are presented in Figure 13, for a specific ILI tool and these results include data from all of the pull tests. These results are presented for characteristic lengths from the dent deepest point to points that are 85, 50 and 10 percent of the dent depth. The graphs are repeated for the axial (U/S and D/S) and circumferential (CW and CCW) directions from the dent depths. The graphs include reference lines for perfect agreement, ±25 and ±50 mm. The reference lines are not selected based on any standard or specification but are included for reference. The same trends can be derived from the unity plots as were derived from the difference data presented in Table 3. This presentation of the data suggests that for this ILI technology, there is a tendency to underpredict dent characteristic lengths in the axial direction and overpredict axial lengths in the circumferential direction. These results are presented here for the performance of a single mechanical caliper ILI system.

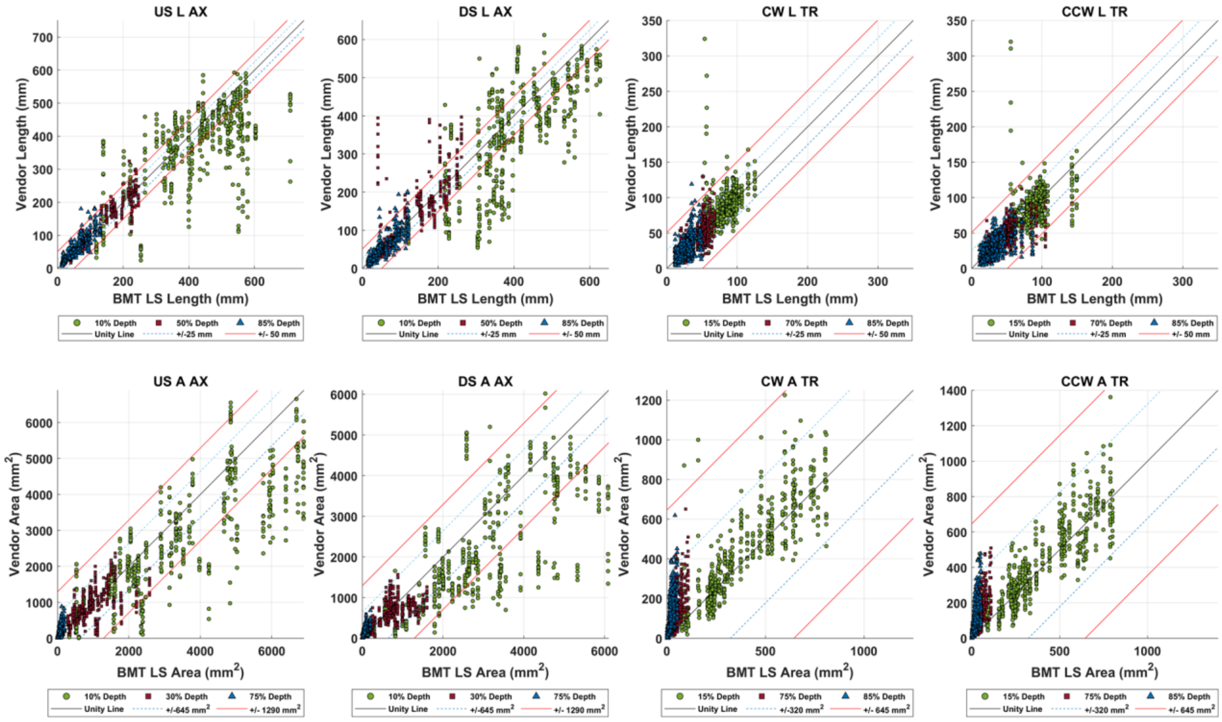


Figure 13: Sample Dent Characteristic Length Unity Plots – One Mechnical Caliper ILI System

The statistics for the ILI trials of the presented ILI system indicated that the trend in measurement error (mean error) as a function of ILI trial speed is as expected, with higher variability at the shallow portions of the dent away from the deepest point of the dent. Measurement of the deep portions of the dent with depths greater than 50 percent of the dent depths show no trend or bias in the variability of dent characteristic length measurement. These results are presented in Figure 14 for a single mechanical caliper ILI system.

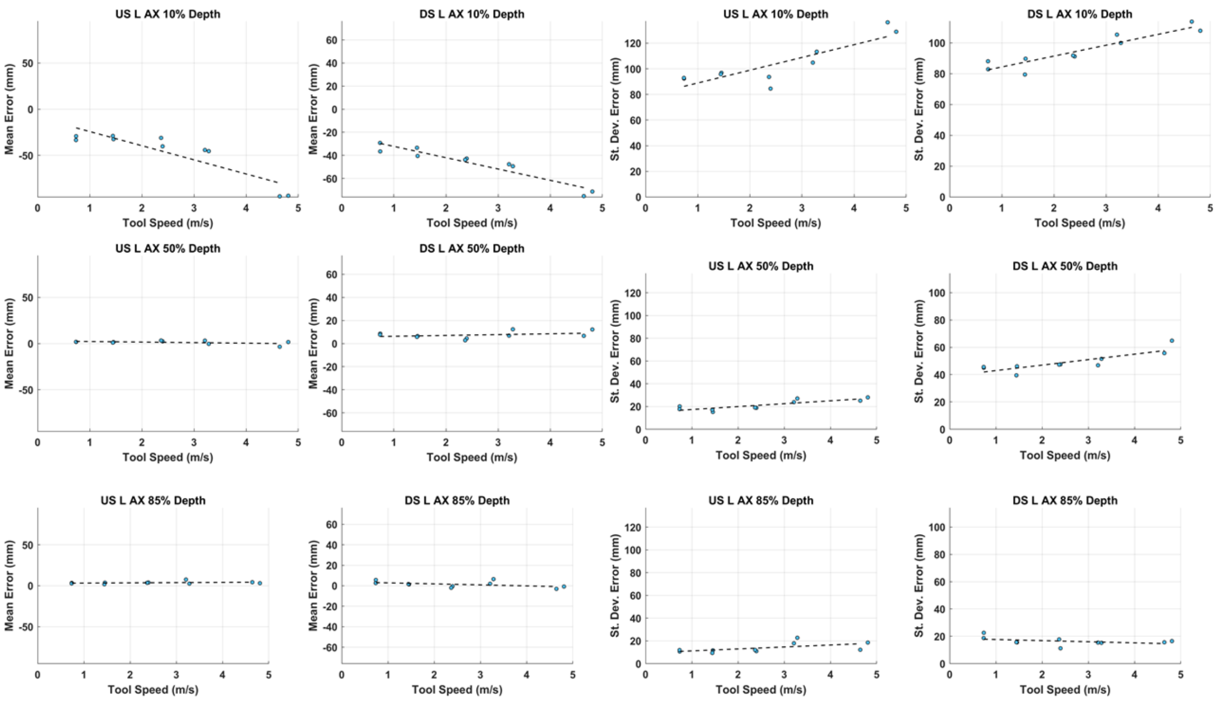
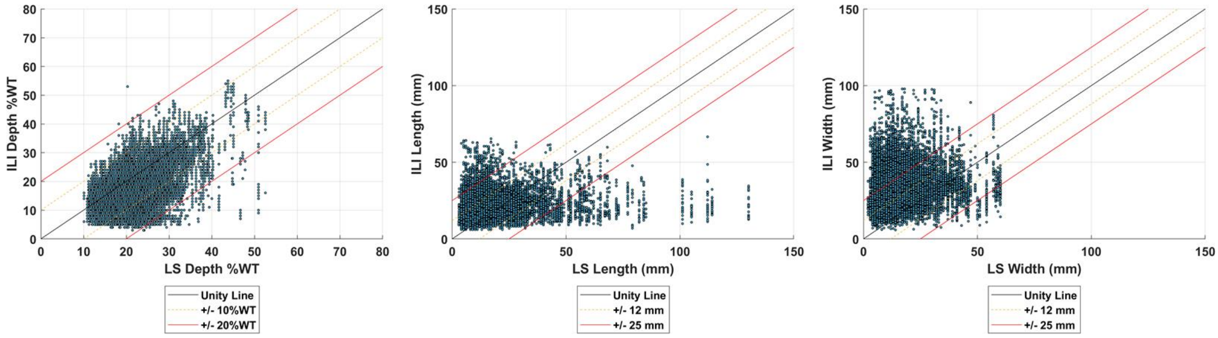


Figure 14: Dent Characteristic Length Measurement Error for a single Mechanical Caliper ILI System

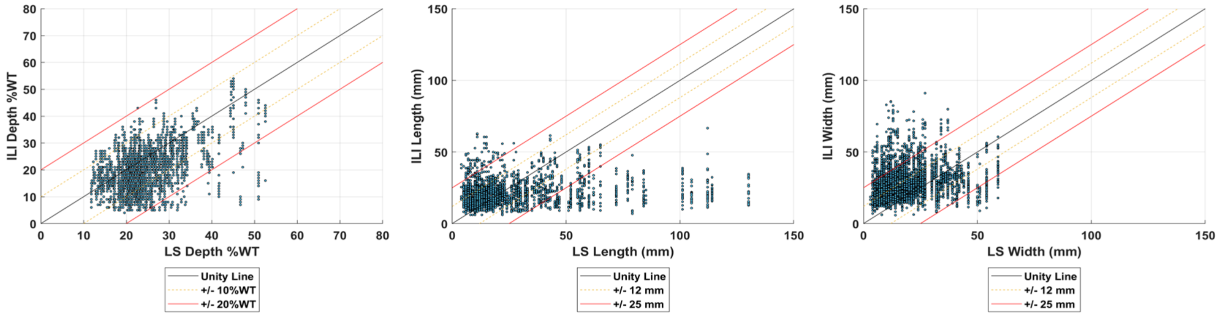
5.2. ILI Performance Trial Results for Corrosion

In the assessment of ILI system performance for corrosion, both corrosion features coincident with dents and those in round pipe were considered. The ability of the ILI systems to identify detected metal loss features as corrosion was very good. In the discussion that follows, the ability of the ILI tools to detect and identify corrosion features by API 1163 metal loss classes was considered. The ability to properly classify features was hampered by the fact that the ILI Service Provider reported data did not apply feature interaction or boxing rules which may have combined multiple features to report an elongated class of feature. This tended to result in under estimation of the corrosion feature size and is due to the approach taken by the trial performance evaluation which is non-standard for the MFL tools. The interaction or boxing rules were seen as non-standard and can vary depending on the ILI Service Provider or the pipeline operating company involved in ILI reporting of corrosion features. As feedback from the ILI Service Providers, in future, a standard 6t x 6t box or interaction area will be established and applied across all ILI Service Providers. Regardless of this “non-standard” method for defining corrosion feature size, the performance of the ILI systems was good. The net result of this matter is observed in the unity plots as the ILI under estimation of the feature length or width.

Both statistical summaries of performance (average and standard deviation of difference between the Truth (reference) data and ILI system measurements) and unity plots were developed. This description will focus on the unity plots considering corrosion features that are coincident or not coincident with dent features in Figure 15. The graphs include reference lines for perfect agreement, ±10 percent and ±20 percent wall thickness, as well as ±0.5 inches (12.7 mm) and ±1.0 inches (25.4 mm) in feature size (i.e., length or width). The feature size performance may have been affected by not applying feature interaction or boxing rules as illustrated by the underestimation of the feature length in the unity plots. These unity plots, for this specific ILI tool, illustrate that while the performance of the ILI system in reporting corrosion feature depth tested is affected by the presence of the dent, there is only a limited reduction in performance. As shown in Table 4, for a specific ILI system, the POD for all metal loss (ML) features drops on average 1% when the corrosion feature is coincident with a dent. The POD is lowest for features in the dent peak zone, as defined in Figure 6a.



a) Unity plots for all metal loss features



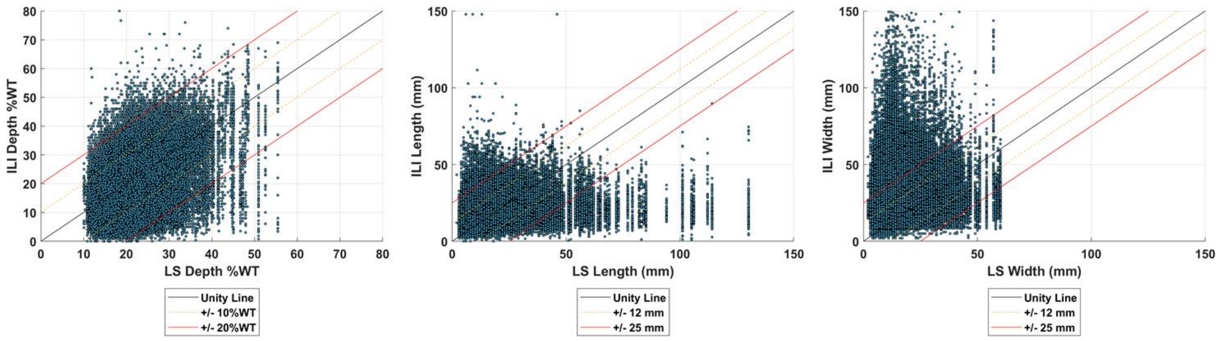
b) Unity plots for all metal loss features coincident with dents

Figure 15: Corrosion Metal Loss Feature Sample Unity Plots for a Single MFL ILI System

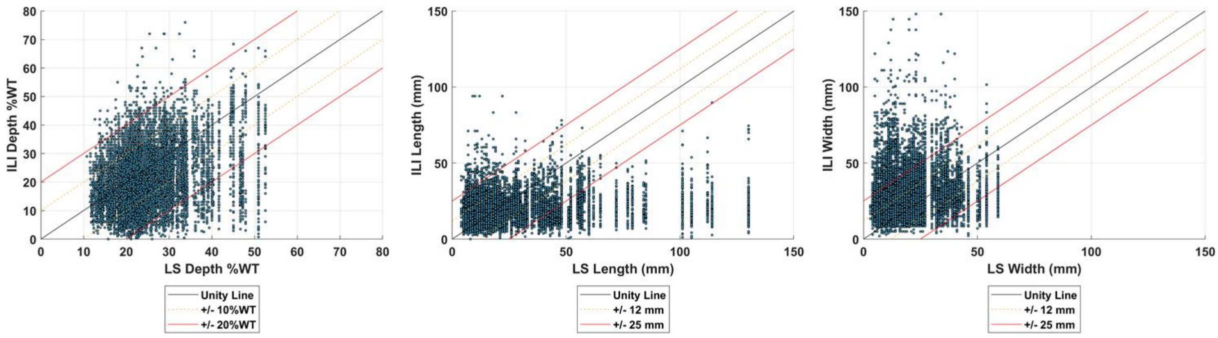
The performance of MFL based ILI systems in characterizing corrosion features, considering six ILI systems, is presented in Figure 16. These observations represent approximately 194,000 corrosion feature measurements form the ILI performance trials. These unity plots are comparable to those presented in Figure 15. The performance of the group of ILI systems is similar to that of the individual ILI system with a slightly higher standard deviation (spread) of the observations. This additional spread is due in part to the differences in measurement bias and reporting characteristics of each tool. The measurements include a small bias for underestimating feature depth and due to the clustering rules not being applied and ILI system performance long features are underestimated and feature widths are over estimated.

		Category	POD (Within Tool Specification)	POI (Based on ML Class)	Difference in ILI vs LS Depth Data (Percent WT)
Corrosion Features Coincident with a Dent	By corrosion Feature depth	All ML	0.81	0.46	-3.20
		10-15 Percent WT	0.90	0.80	2.78
		15-20 Percent WT	0.85	0.52	0.05
		20-25 Percent WT	0.79	0.37	-3.31
		25-30 Percent WT	0.77	0.49	-4.37
		30-35 Percent WT	0.85	0.56	-5.89
		35-40 Percent WT	0.79	0.45	-5.60
		40-45 Percent WT	0.82	0.44	-9.32
		45-50 Percent WT	0.82	0.16	-9.96
		50-55 Percent WT	0.95	0.08	-9.25
	Dent Interaction	Peak Zone	0.76	0.47	-4.13
		US	0.79	0.46	-3.26
		DS	0.88	0.49	-2.38
		CCW	0.81	0.45	-3.05
		CW	0.88	0.28	-2.40
Corrosion Features Not Coincident with a Dent		All ML	0.82	0.42	-4.49
		10-15 %WT	0.87	0.67	0.69
		15-20 %WT	0.89	0.71	-0.47
		20-25 %WT	0.81	0.25	-6.05
		25-30 %WT	0.73	0.32	-7.32
		30-35 %WT	0.79	0.50	-6.29
		35-40 %WT	0.92	0.62	-4.51
		40-45 %WT	0.80	0.63	-5.41
		45-50 %WT	0.73	0.91	-7.52
		50-55 %WT			

Table 4: Sample Corrosion Feature POD, POI and Depth Performance Data



a) All corrosion features

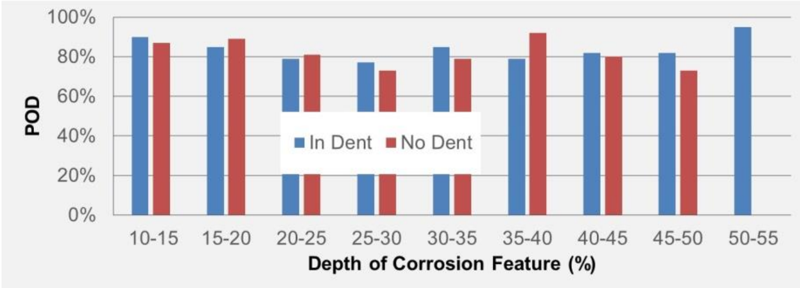


b) Corrosion features coincident with dents

Figure 16: Corrosion Metal Loss Feature Unity Plots For Six ILI Systems

The effect of the dent feature on corrosion metal loss detection and sizing are illustrated in Figure 17. The probability of detection for corrosion features in a dent and in the pipe away from the dent are compared in Figure 17a, whereas the corrosion feature depth sizing performance is illustrated in Figure 17b. These results suggest for the ILI tool considered the performance of the ILI system is very similar for detecting and sizing corrosion features in dents and in plain pipe. While results across all ILI systems are not identical, good performance is observed for all of the ILI systems tested.

a) Effect of dent on corrosion feature detection



b) Effect of dent on corrosion feature depth sizing

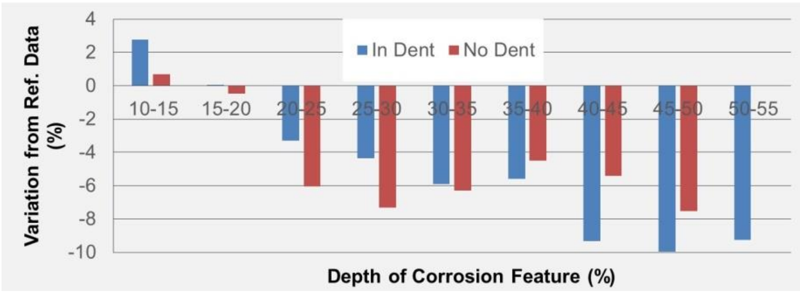
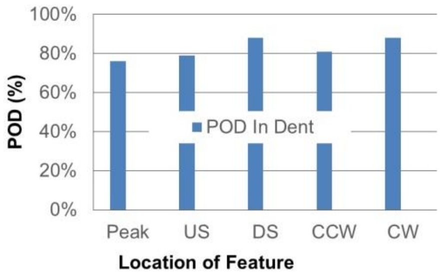
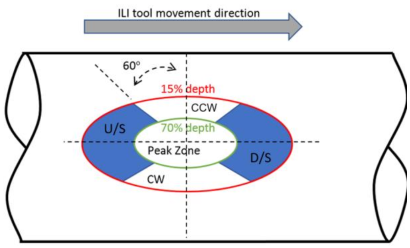


Figure 17: Effect of Dent on Corrosion Feature Detection and Sizing

Figure 18 illustrates the effect of corrosion feature location within the dent for a specific ILI system on probability of detection. This result indicates that while performance is good, the ILI system has the most difficulty in detecting and sizing features at the peak of the dent. The dent coincidence zones from Figure 6a are repeated in this figure for reference.

a) Effect of corrosion feature location within a dent on probability of detection





b) Effect of corrosion feature location within a dent on depth sizing

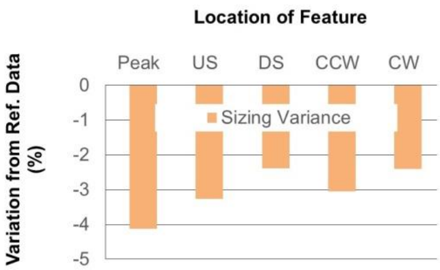


Figure 18: Effect of Corrosion Feature Location Within a Dent on Detection and Sizing

The trial results indicated that the performance of the MFL ILI tools in characterizing corrosion features was insensitive to tool speed for the speeds tested.

5.3. ILI Performance Trial Results for Gouges

In the assessment of ILI system performance for gouges, the performance in detecting and identifying gouges varied significantly across ILI systems. Both machined gouge features and those created with an excavator tooth during the dent formation process were considered. The gouge features were provided by EPRG project 217, including those features simulated using a pipe aggression rig and those machined after indentation. While the number of gouge features was small, some ILI systems achieved a POD as high as 90 percent and a POI as high as 80 percent for these features. Other ILI systems performance was significantly lower. Magnetic tools tended to have a lower POI for the machined gouge features (e.g., 67 percent). The ability of the ILI systems to report feature gouge depth and length is considered in Figure 19. These results indicate that the ILI system was better able to size the simulated features (developed in the pipe aggression rig) than those machined after indentation. The ILI systems demonstrated relatively large errors in characterizing the feature length, as shown for this ILI system example.

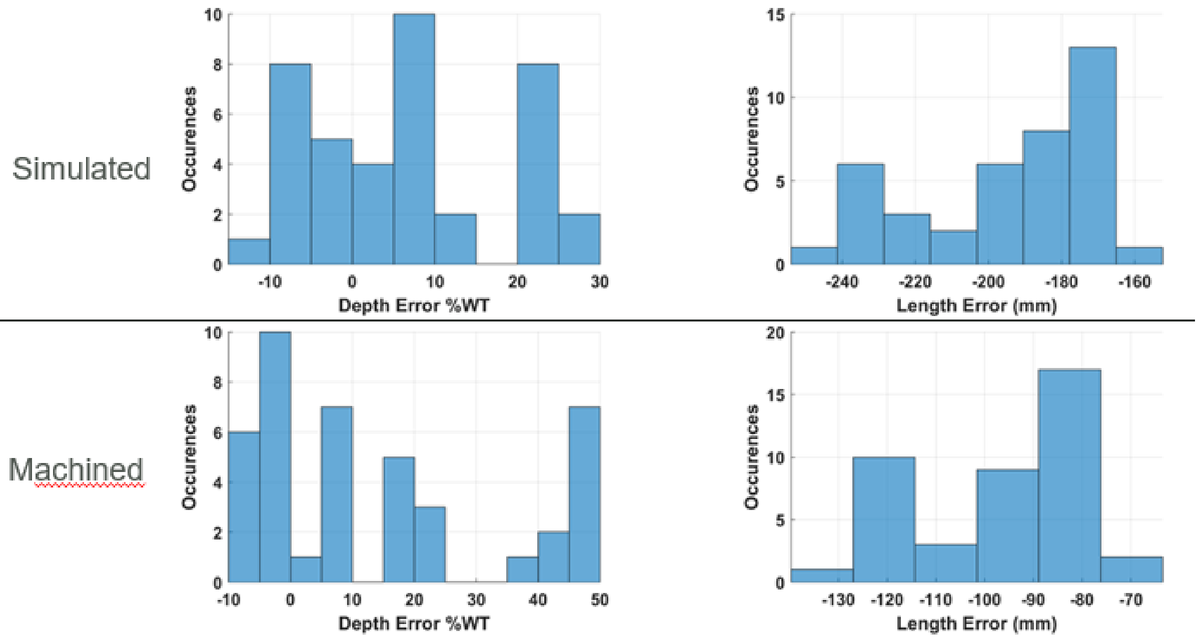


Figure 19: Sizing Performance for Gouges in Dent Features for One ILI System

It was noted that inspection speed only tended to impact gouge POD, POI and sizing for the highest inspection speeds.

5.4. ILI Performance Trial Results for Cracks

The trials included one ultrasonic inspection tool that was successful in detecting crack features coincident with dents and corrosion. It is noted that the cracks in the trial specimens included a range of crack orientation (e.g., circumferential, axial), initiation surfaces (e.g., ID and OD), crack depths from 10 percent of the wall thickness to through wall cracks, and a range of crack types (e.g., isolated cracks and crack colonies). It is noted that all of the cracks involved in this performance trial were fatigue cracks which are very tight cracks making them more difficult to detect.

The performance of the ILI system in detecting and identifying the cracks is shown in Figure 20 considering the probability of detection and probability of identification. The crack included in this performance trial result are in plain dents and in dents with coincident corrosion. The probability of identification involved correctly identifying the crack initiation surface and the orientation of the crack (i.e., angle of the crack with respect to the pipe axis). These results illustrate that there is a small effect of tool speed and the POD and POI are on the order of 80 percent. There were a significant number of false positives in the ILI system reported crack data.

Some of the pipes included in this trial had ERW weld seams that were noted to potentially have weld seam features. None of these seams interacted with the dent, however, the ILI system identified approximately a dozen features within 0.5 in (12 mm) of the weld seam. No truth data is available to confirm that these identifications aligned with ERW weld seam features.

a) Crack probability of detection

b) Crack probability of identification

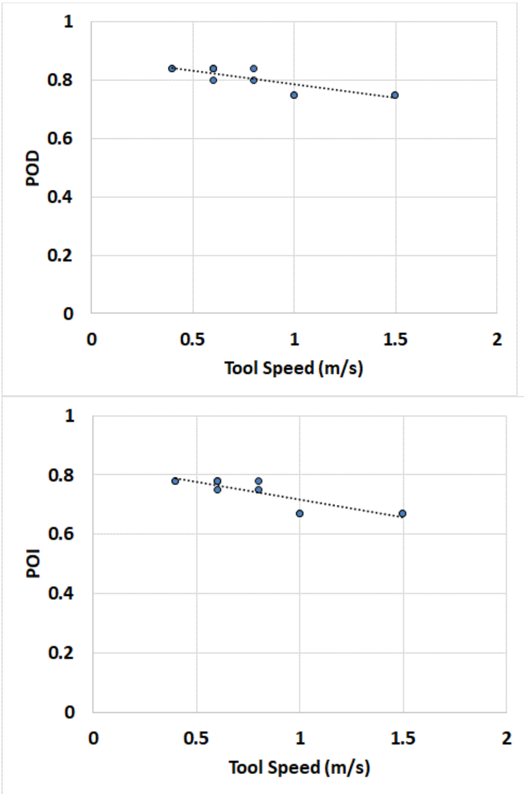


Figure 20: Ultrasonic Inspection System Performance for Cracks

The performance of the ultrasonic tool in sizing the crack features is shown in Figure 21. These results illustrate good performance in reporting crack lengths in plain dents and dents with corrosion. There is a bias that overestimates the crack length; however, most cracks are sized within ± 2 inches (50 mm).

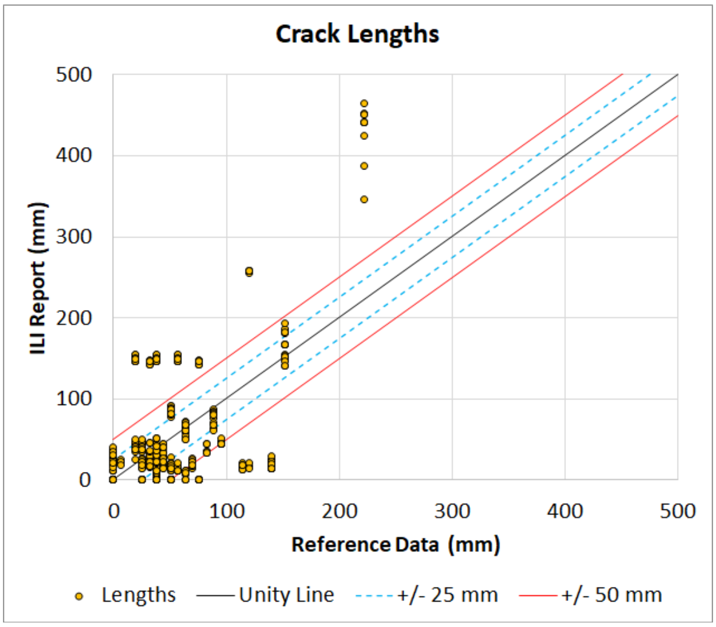


Figure 21: Ultrasonic Inspection System Crack Sizing Performance

6. CONCLUDING REMARKS

To support enhancement of pipeline integrity management programs, the project reported in this paper, sponsored by PRCI, has focused on the improvement of the industry understanding of ILI system inspection performance for mechanical damage features including coincident features. ILI performance trials considering a range of ILI systems based on Magnetic, Ultrasonic and Caliper technologies were completed using pump through and pull test processes. These trials developed data describing the performance of individual ILI systems from seven ILI Service Providers. This paper described the ILI system performance trial research based on the five primary stages involved in the project, including:

1. Production, characterization and deployment of a set of pipe samples with a range of dent and coincident features to demonstrate inspection performance of ILI systems for dent/deformation features,
2. Development of a trial protocol drawing on the definitions in API 1163 [2] and API RP 1183 [3], but reaching beyond to specifically consider the requirements of mechanical damage,
3. Completion of blind trials considering the effects of tool speed on ILI system performance to detect, identify and size the dent and coincident features,
4. Analysis of the ILI trial data using techniques specifically developed for mechanical damage with coincident features and provide feedback to the ILI Service Providers and Pipeline Operators, and
5. Recommendation for the direction of future trials and development of mechanical damage integrity management tools and programs.

The results presented in this paper include performance data for individual and groups of ILI technologies and they provide insights on the value derived from this work. At the highest level, they demonstrate that existing ILI systems can detect, identify and size dents and their coincident features. These results demonstrate that ILI reported feature sizes can be used to support dent feature engineering critical assessment. These results will support the pipeline industry in making a case that assessment is viable because ILI systems can reliably detect, identify and size the features.

The project team, PRCI and the industry are grateful for the participation of members of the ILI Service community in these trials. It is believed that the understanding derived from these trials and the truth

or reference data shared with the participating ILI Service providers will be used to support enhancements in the ILI system performance and perhaps their specifications.

It is also believed that the ILI trial protocol with enhancements from lessons learned in this trial program will be useful in future testing programs. The ILI system performance evaluation and metrics employed in this program may also be of interest for updates of ILI system performance demonstration or measurement standards.

The next steps for this type of ILI system performance trial will be carried out in a project supported by PRCI and the US Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA). These trails will include more than 160 test samples including combinations of dents, cracks, corrosion, gouges and welds. These trials are scheduled for execution in 2022, with the first two ILI systems having already tested.

7. REFERENCES

[1] NTSB recommendation P-17-01 in Pipeline Accident Brief (PAB)-17/01, dated June 05, 2017.
[2] American Petroleum Institute, "In-line Inspection Systems Qualification", API 1163, 2021.
[3] American Petroleum Institute, "Assessment and Management of Pipeline Dents", API RP 1183, 2020.