Estimating Dent Strain Using Multiple Low-Resolution Caliper Inspections

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Abstract

Over the past decade operators have used curvature-based strain assessments to assess the likelihood of cracking associated with dent formation in natural gas pipelines. Accurate curvature-based dent strain assessments require that the dent shape is captured with a high-resolution caliper tool, where high-resolution is defined by the number of sensors around the circumference of the pipe. However, the use of a high-resolution caliper tool can be infeasible due to restrictions such as multi-diameter passages, internal obstructions or small diameter. This paper presents a case study where multiple inspections were performed in an 8-inch line using low-resolution caliper tools. The initial conservative estimates of the dent strain identified a significant number of dents with exceptionally high strains. A multi-step process was developed to improve the dent strain assessment. First, methodologies to estimate upper and lower bound strains based on a single data set are presented. Next, a methodology is developed and presented to combine the low-resolution data sets from multiple inspections. Finally, the paper compares these results from the first two steps with the results of optical scans performed on excavated dents and the results of numerical analysis. This paper will be helpful for operators who have inspection scenarios that are limited to low-resolution caliper tools or may not have high-resolution data available.

Background

Caliper technologies were born from the need to inspect steel pipelines for geometric anomalies and mechanical damage that may be injurious to the pipeline. Caliper technology resolution is defined in both the axial and circumferential direction. Caliper tools used in the late 1990s and early 2000s may have had limitations in axial resolution due to on-board memory restrictions or sensor limitations. However, most caliper tools available today have an axial resolution that would classify as high-resolution with reporting intervals on the order of 0.05 to 0.1-inches (1.2 - 2.5 mm). This resolution is considered sufficient to capture the profile of a dent. However, the authors are aware of some technologies with longer reporting intervals of 0.25 to 0.5 inches (6.4 – 13 mm). These longer reporting intervals can limit the ability to perform advanced assessments and should not be considered as meeting the requirements of high-resolution.

The circumferential resolution of caliper tools is more critical because advanced assessments require a determination of whether a dent is reentrant or non-reentrant. Non-reentrant dents result in “flat” or “blunt” circumferential shapes where the radius of curvature is larger than the nominal pipe curvature. Reentrant dents have a concave profile where the nominal curvature of the pipe is reversed. From the perspective of dent strain, reentrant dents are universally more severe than non-reentrant dents. Unfortunately, the ability to accurately capture the circumferential profile is directly proportional to the number of sensors on the caliper tool. This is illustrated graphically in **Figure 1**. Two dents with similar depths are shown, but the dent on the left is non-reentrant while the dent on the right is reentrant. Both shapes are shown with 24 sensors where one sensor travels through the

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peak dent depth. In the image on the right, it would be difficult to identify the reentrant nature of the dent because the sensor resolution is insufficient to capture the circumferential shoulders necessary to identify the dent as reentrant.

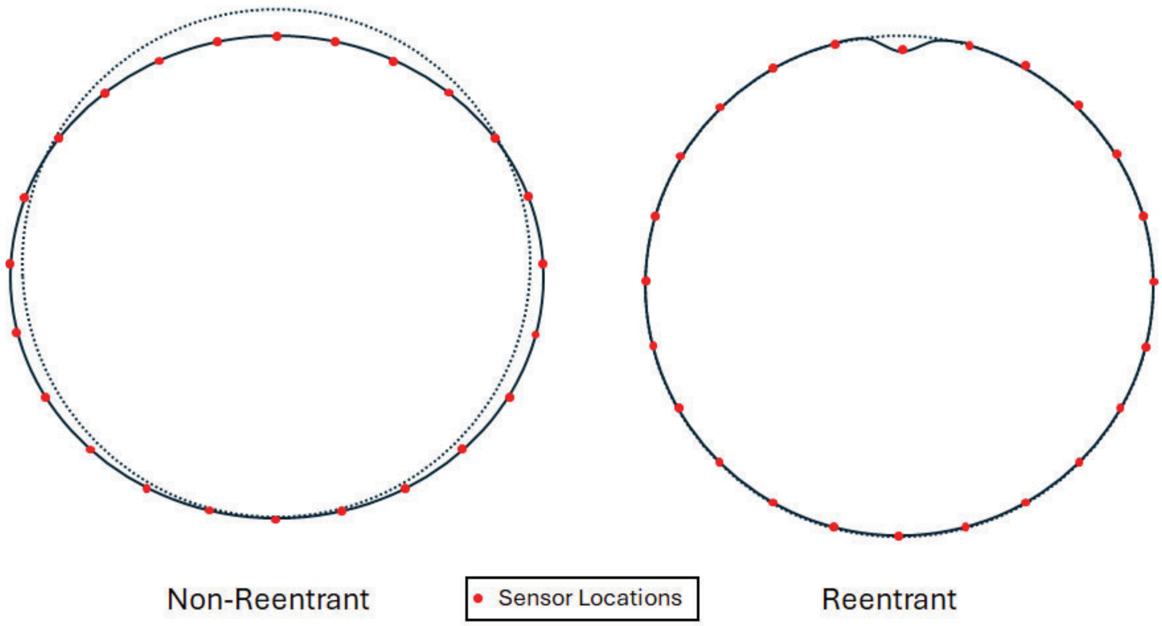

Figure 1: Impact of circumferential sensor resolution

Early caliper tools are generally low-resolution due to their limited sensor density. Many low-resolution caliper tools available today may have sensors grouped behind a deformable cup to help with detection. Low-resolution caliper tools can measure the depth and axial profile of a deformation anomaly but are limited in their ability to accurately measure the circumferential profile of an anomaly. In the past twenty years, high-resolution caliper tools are characterized by their ability to more accurately capture the circumferential profile of a deformation. Examples of low and high-resolution caliper tools are shown in
Figure *2*.

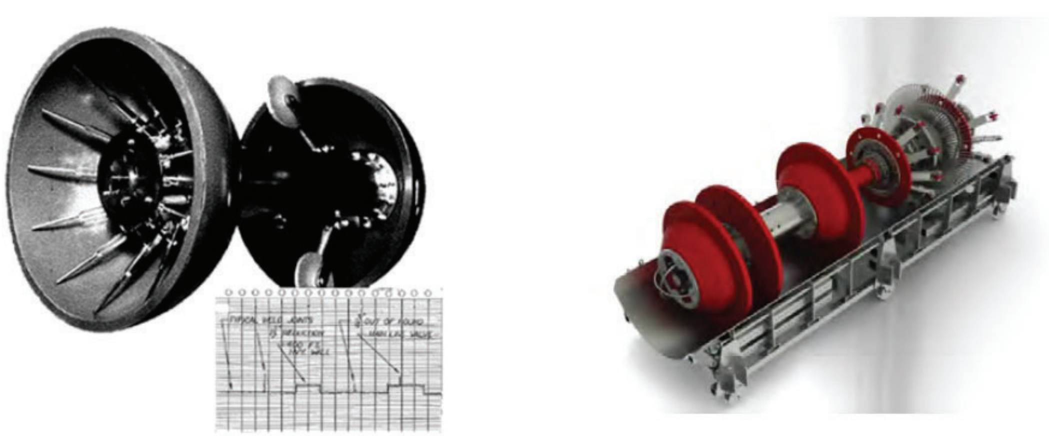

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Figure 2: Low-resolution caliper tool (left) and high-resolution caliper tool (right) *(1)*

Low-resolution caliper tools are still relevant in the industry today. Challenging pipeline conditions, such as small radii back-to-back bends, internal obstructions, multi diameter pipelines, or sufficiently small diameter pipelines are instances where a smaller or shorter low-resolution tool may provide the only option for inspecting the pipeline. If the cost to modify a pipeline to be inspected by a high-resolution tool is too great, an operator may elect to run a low-resolution tool.

The authors recognize that high-resolution is a marketing term with no industry accepted definition. However, practical application of high-resolution tools typically requires a spacing between sensors that is no greater than 1.5 inches with sensors spread out between a single or multiple rings of sensors on the body of the tool. It is important to note that high-resolution is not determined solely by the number of sensors or their circumferential spacing. A larger diameter tool (i.e., greater than 16 inches) should be capable of meeting the requirements of a high-resolution tool, and they are commonly available today with 40 or more sensors. However, it is difficult to achieve a similar number of sensors in a 4-inch pipeline, and this is why most small diameter tools do not meet a high-resolution requirement.

The authors in (2) examined the influence of the number of circumferential sensors in an inspection tool on the ability to calculate the circumferential strains using B-splines. The study investigated 8, 16, 32, and 64 sensor configurations in a 12-inch pipeline. The study found that the 16 and 32-sensor configurations showed less than a 2% error in predicting the strains while the 8-sensor solution was described by the authors as having “relatively” high errors. It is important to note that this study assumed the sensors would travel through the deepest part of the dent, and did not examine the influence of the sensor not capturing the peak of the dent.

Case Study

In 2019 and 2022, TC Energy (TCE) performed two low-resolution caliper inspections in an 8” natural gas pipeline. The pipeline is not configured in a way that would allow passage for high-resolution caliper tools. The inspections were performed by the same ILI vendor and used the same configuration low-resolution caliper tool in 2019 and 2022. The low-resolution tool considered in this study has twelve caliper arms, with a circumferential sensor spacing of 2.25”.

TCE requested D2Integrity (D2I) review fifty-five deformation anomalies reported by the ILI vendor in the 2022 inspection due to these features having abnormally high strain values (i.e., > 10%). Of the 55 dents TCE requested D2I analyze, 48 of them were reported by the ILI vendor with strain values greater than 10%, and the maximum strain value was 37.2%. The magnitude and number of reported strains greater than 10% is atypical for any pipeline. It was recognized that the tool would

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be limited in its ability to capture the circumferential curvature, and the purpose of this evaluation was to identify the dents that are most likely to have strains greater than 10%.

Bounding Scenarios for a Single Data Set

D2I began the analysis by confirming the strain calculation method used by the ILI vendor and reviewing the reported strains. Due to the limited circumferential resolution of the ILI tool, the vendor used the axial radius of curvature (R2) measurement taken at the deepest part of the dent, shown in Figure 3, and set the circumferential curvature (R1) of the dent, shown in
Figure *4*, to equal R2. This practice assumes a hemispherical dent shape and is common for low-resolution tools. This methodology will typically produce conservative estimates of the dent strain for non-reentrant dents or cases where the axial curvature is sharper than the circumferential curvature. Unconservative results can occur when the circumferential curvature is smaller than the axial curvature such as might occur with a long indenter aligned with the axis of the pipe. D2I designated this R1=R2 as Scenario 1.

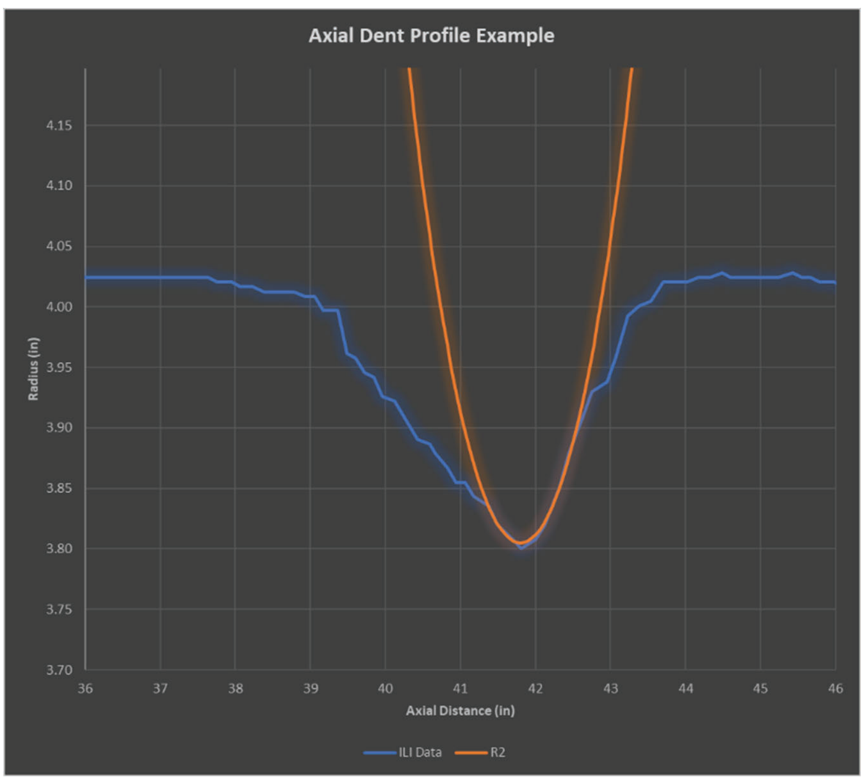

Figure 3: Axial radius of curvature (R2)

D2I investigated a second method, Scenario 2, where the circumferential radius of curvature, R1, was set to 100 inches, simulating a “flat” or “blunt” dent that is not-reentrant, shown in

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Figure 5. The axial radius of curvature, R2, was measured at the tightest location of the axial dent profile as shown in Figure 3 for Scenario 1. Scenario 2 represents a lower-bound estimate of the strain where a large radius of curvature is assumed, and the dent is not-reentrant. Scenario 2 demonstrated that if the combined strain for a dent was greater than 10% assuming a blunt shape, then the strain is controlled by the axial radius of curvature and will exceed 10% regardless of how the circumferential curvature is calculated or whether the circumferential profile was accurately captured by the ILI tool.

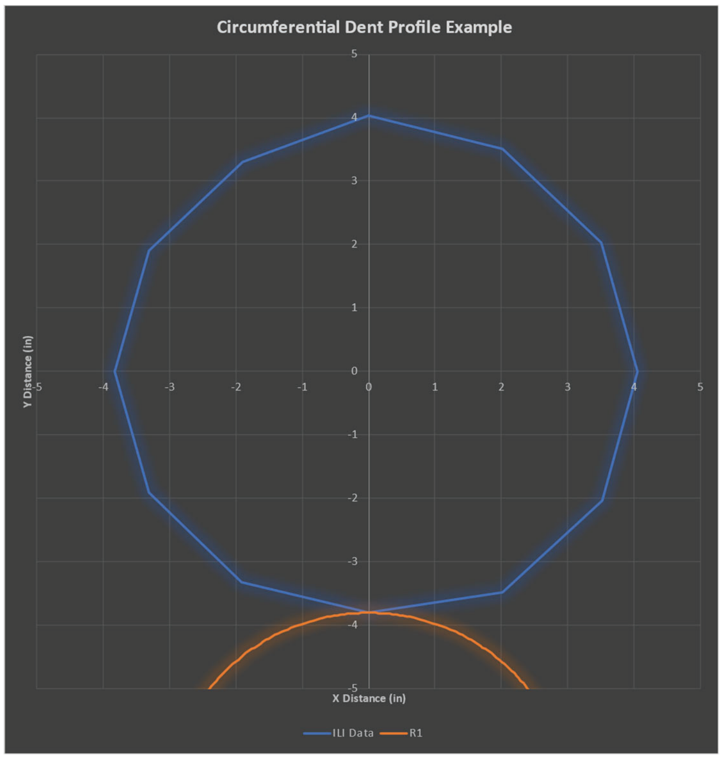

Figure 4: Circumferential radius of curvature (R1), when R1=R2 for Scenario 1

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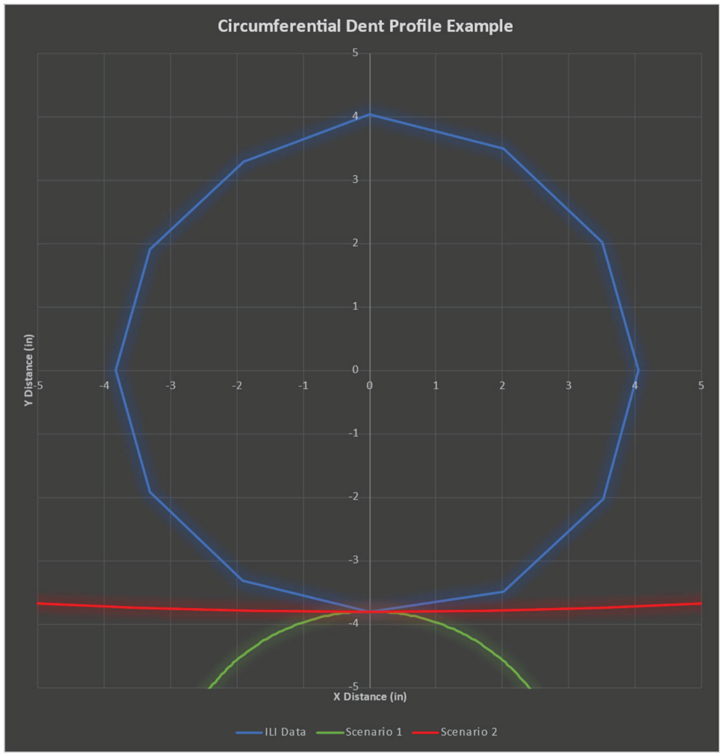

Figure 5: Circumferential radius of curvature (R1), when R1=100 for Scenario 2

A third method, Scenario 3, was designed to estimate strains that fall between Scenario 1 and Scenario 2. In Scenario 3, the axial radius curvature was measured at the tightest location of the axial dent profile, as shown in Figure 3, and was the same value as Scenarios 1 and 2. However, the circumferential radius of curvature, R1, for Scenario 3 was selected based on visually fitting a curvature that captures the majority of the axial profile rather than through the location of sharpest curvature. An example from Scenario 3 is shown in Figure 6. This "average" axial curvature was then assumed to be the reentrant circumferential curvature. By design, this value will fall between the curvatures from Scenarios 1 and 2, as shown in

Figure 7, which can be compared to the curvatures shown in

Figure *4* and

Figure 5. Scenario 3 attempts to hypothesize a less severe hemispherical shaped dent by capture a more average representation of the axial curvature rather than a sharper local curvature. For dents that do not have a sharp local axial curvature, the difference between Scenario 1 and Scenario 3 will be minimal.

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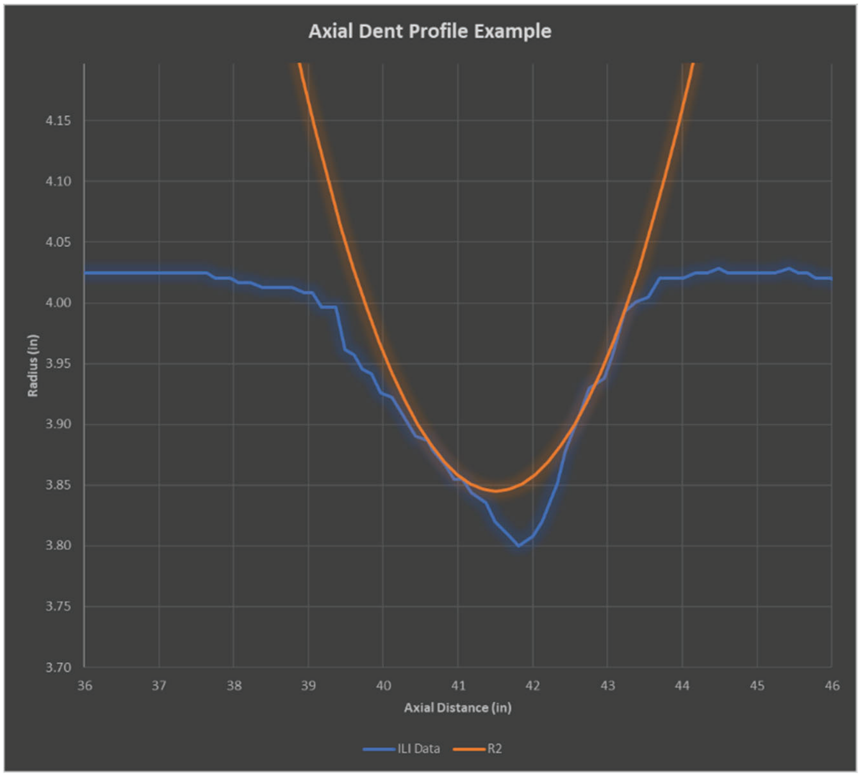

Figure 6: Wider R2 value used for calculating R1 in Scenario 3

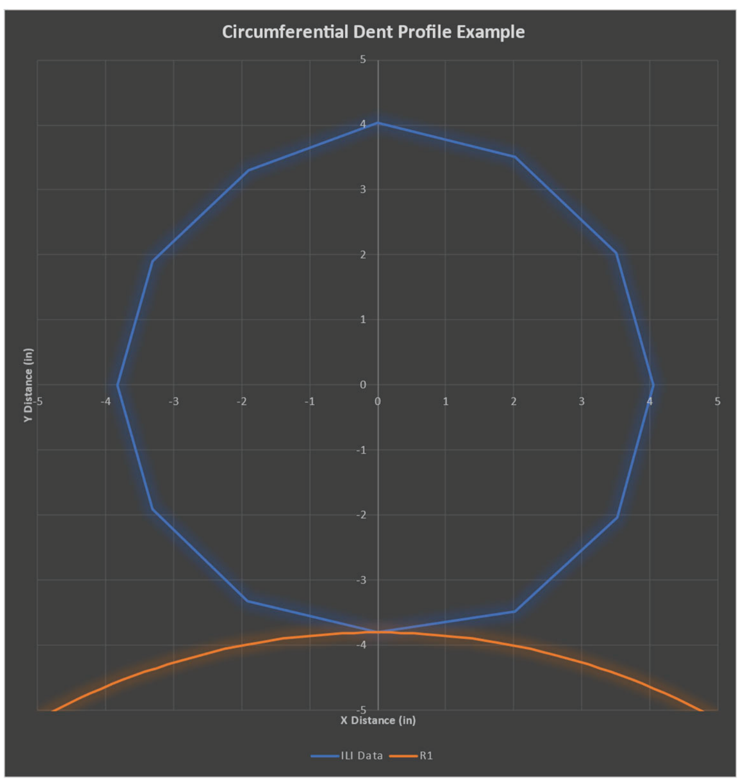

Figure 7: Circumferential radius of curvature (R1) for Scenario 3

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Results of Bounding Scenarios

Figure 8 shows a unity plot comparing Scenario 1 to the 2022 ILI results. Scenario 1 showed general agreement in strain calculations when compared to the results of the 2022 ILI inspection. One outlier exists showing a scenario in which D2 felt that the vendor overcalled the axial radius of the dent, leading to higher strains than the measurement generated in scenario 1.

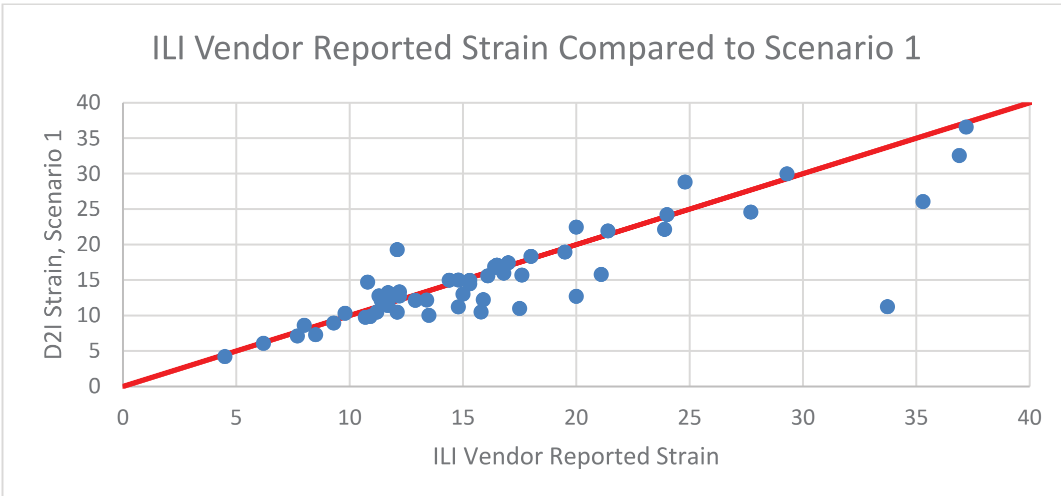

Figure 8: Strain comparison between 2022 ILI results and scenario 1

The results of the dent strain assessment are summarized in **Table 1** for all three scenarios. The number of features with a combined strain greater than or equal to 10% is greatest for Scenario 1 and lowest for Scenario 2, as expected. Scenario 3 falls between Scenarios 1 and 2, trending towards Scenario 1. These results show that many of the dents' strain values are driven by their axial profiles. Based on Scenario 2 showing 18 dents with strains greater or equal to 10%, it is likely that these 18 dents would be found in the field as having strains greater than 10%, regardless of the circumferential radius of curvature.

Table 1: Strain Results

	ILI Vendor	**Scenario 1**	**Scenario 2**	**Scenario 3**
Number of Analyzed Geometric Deformations	55	55	55	55
# Features with Strain < 6.0%	1	1	5	1
# Features with 6.0% <= Strain < 10%	6	7	32	16
# Features with Strain >= 10.0%	48	47	18	38
Maximum Dent Strain (%)	37.2%	36.5%	21.6%	27.1%

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Comparison to Laser Scan Data

D2I was provided with two laser scans collected in the field. Axial and circumferential profile comparisons were performed on the 2022 ILI data and laser scan data for both dents. The axial and circumferential profile comparisons between the ILI data and the laser scan for Dent ID 1 are shown in Figure 9 and Figure 10, respectively. The same comparisons are shown for Dent ID 2 in Figure 11 and Figure 12. Both dents show that the low-resolution tool did a good job capturing the axial profile of the dent. A detailed review shows that the ILI tool produced a slightly sharper axial curvature for both dents. Unfortunately, both dents showed a reentrant circumferential profile that was not adequately captured by the 2022 ILI survey alone.

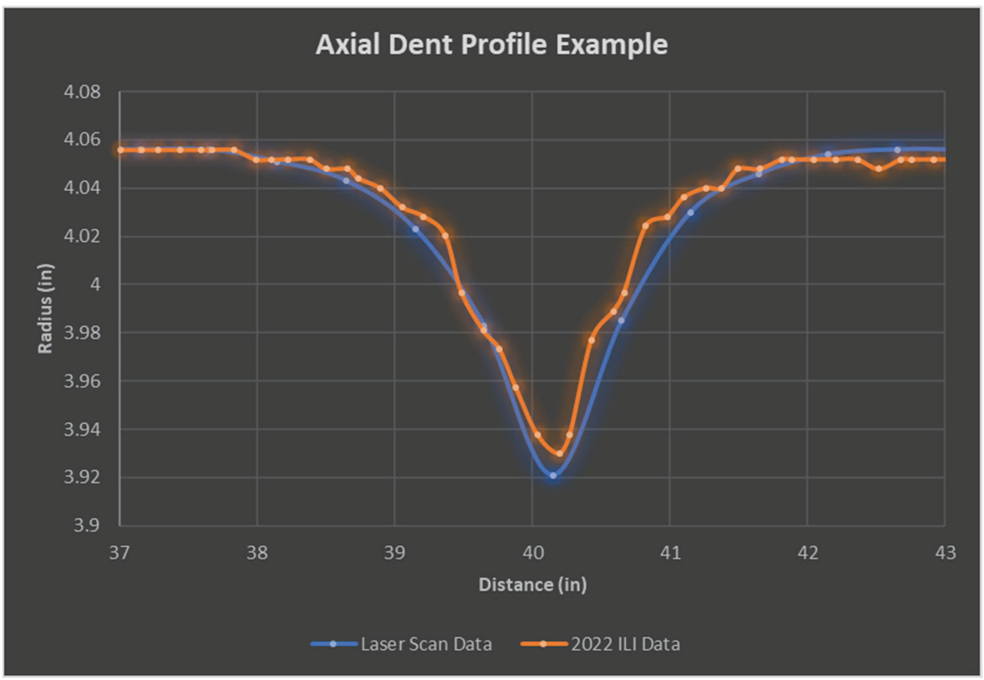

Figure 9: Axial profile comparison, laser scan data and 2022 ILI Data, Dent 1

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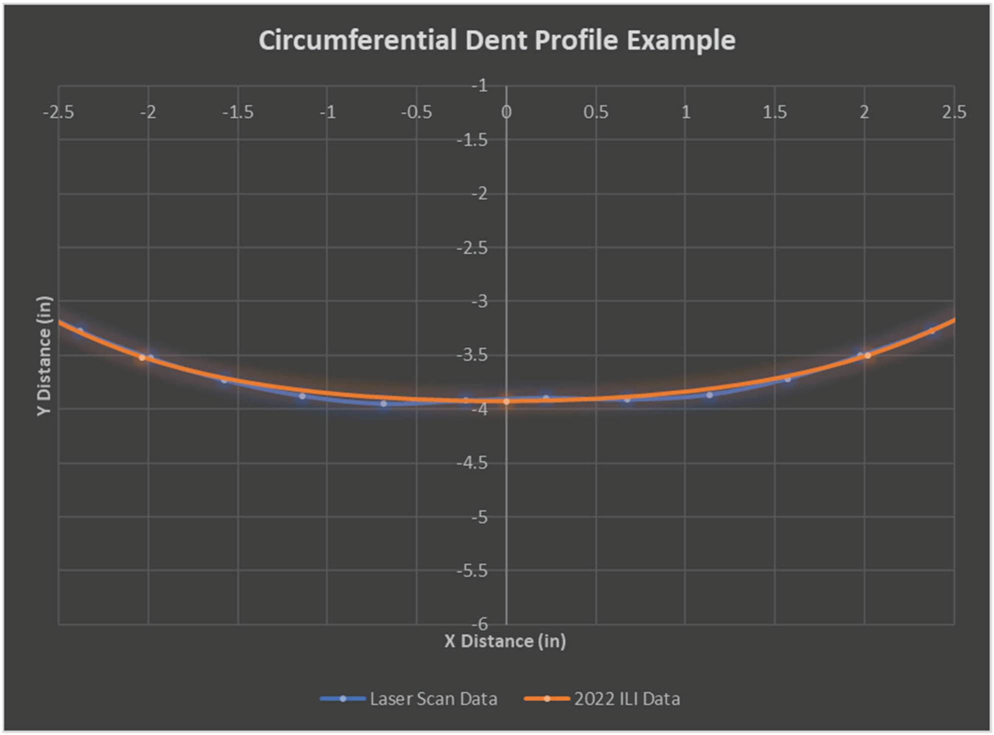

Figure 10: Circumferential profile comparison, laser scan data and 2022 ILI data, Dent 1

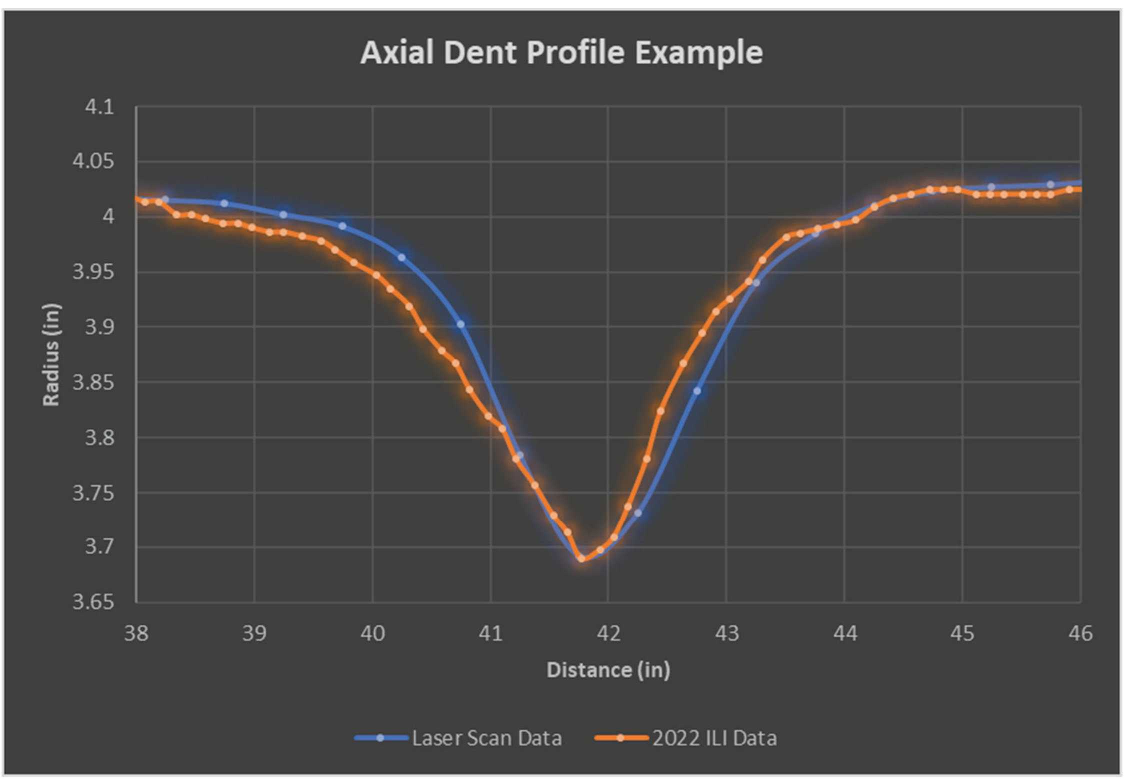

Figure 11: Axial profile comparison, laser scan data and 2022 ILI data, Dent **2**

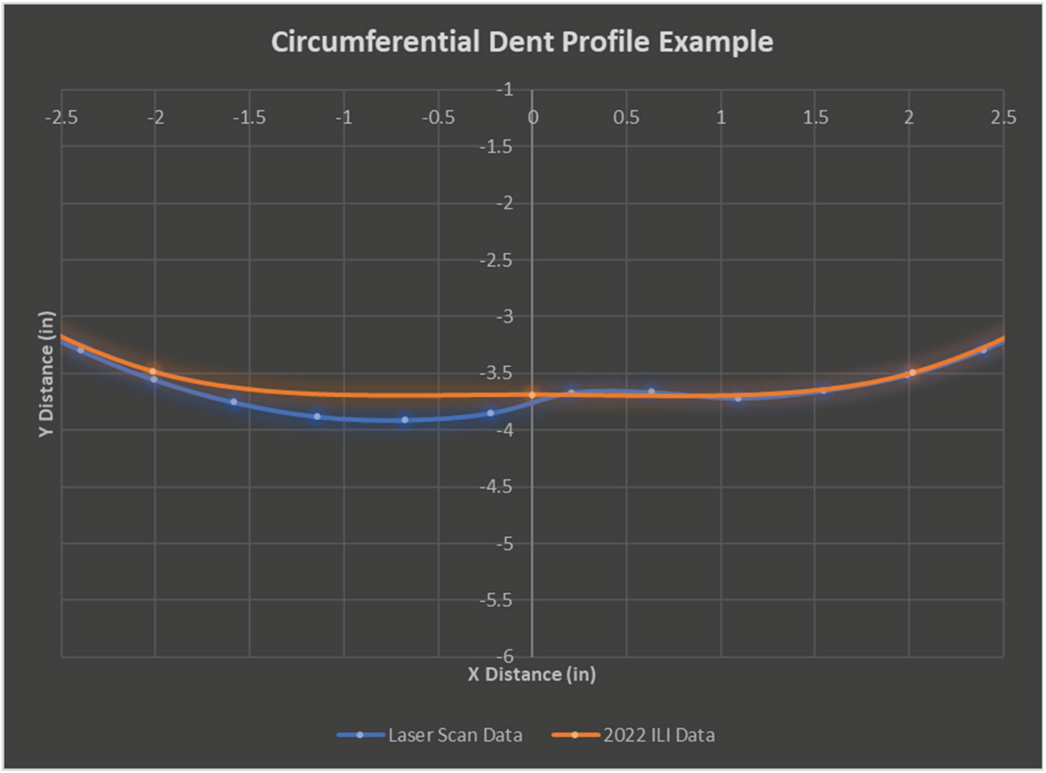

Figure 12: Circumferential profile comparison, laser scan data and 2022 ILI data, Dent 2

A comparison of the strains from the ILI tool and the laser profile is provided in Table 2. As expected, the laser scan data confirmed the strains calculated in Scenario 1 were overly conservative for both cases. In both cases, the strains based on the laser scan were closer to Scenario 1 or Scenario 2. Ultimately, it is difficult to draw any conclusions from only two data points. However, the results do tend to suggest there is some use in understanding the level of conservatism in Scenario 1 by investigating other scenarios.

Table 2: Strain Results for Dents with Laser Scan Data

Dent ID	Scenario 1 Strain	Scenario 2 Strain	Scenario 3 Strain	Laser Scan Strain
1	30%	17.6%	22.0%	15.7%
2	28.8%	17%	24.1%	19%

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Combining Low Resolution Data Sets

After calculating the three above scenarios, D2I developed a fourth scenario using an additional set of radii files from the previous ILI inspection in 2019. D2I developed a methodology to align the profiles from the 2019 and 2022 inspections and produce an estimate of the circumferential shape at the deepest location within the dent. The radii files provided by ILI vendor for both the 2019 and 2022 inspections contained a field labelled "Orient (First Column Spider channel)(radians)." This field denoted the orientation of the first measurement arm on the tool. By using this field, the circumferential positions of the remaining arms were determined.

This combined profile analysis, Scenario 4, was only performed on features that had strain values less than 10% in Scenario 2 and had not been previously excavated by TCE. 23 dents were selected for analysis using Scenario 4. The 2019 and 2022 radii files were scanned to find the deepest axial location, or odometer distance, for each file. The radius data for each arm at that odometer position were then read into a tool that would align each sensor position using the "Orient (First Column Spider channel)(radians)" value. From here, each following radius arm was plotted based on the sensor arms being equidistant from each other. The resulting profile, containing both 2019 and 2022 radius points, was then checked to see if the circumferential offset between the two datasets were sufficient to improve the circumferential profile of the dent.

Figure 13 shows an example of a dent where the circumferential profile could be more accurately measured due to the ILI tools navigating the dent at different orientations. Of the 23 dents that were evaluated using combined profiles, 17 were deemed to have sufficient sensor offset to improve the circumferential strain calculations. **Figure 14** shows an instance where the ILI data was insufficiently offset to improve the circumferential profile of the dent. In the six cases where the combined ILI data was not offset to a degree that would increase the accuracy of the circumferential profile, D2I did not provide a strain value for Scenario 4.

Table 3 shows the results of the seventeen dents that received combined profile analysis in Scenario 4 when compared to the results of the other Scenarios. None of the 17 profiles analyzed for scenario 4 had strains greater than 10%. These results confirm that the assumptions in Scenario 1 are indeed conservative for most of the dents. Additionally, the results demonstrate that combining the results from two low-resolution inspections can help refine and improve the strain calculations.

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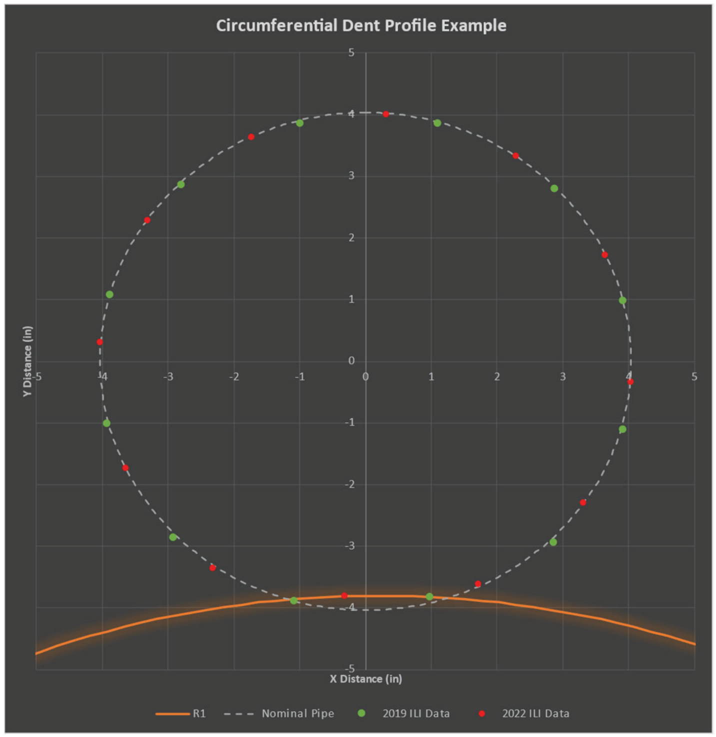

Figure 13: Combined circumferential profile based on sensor orientation

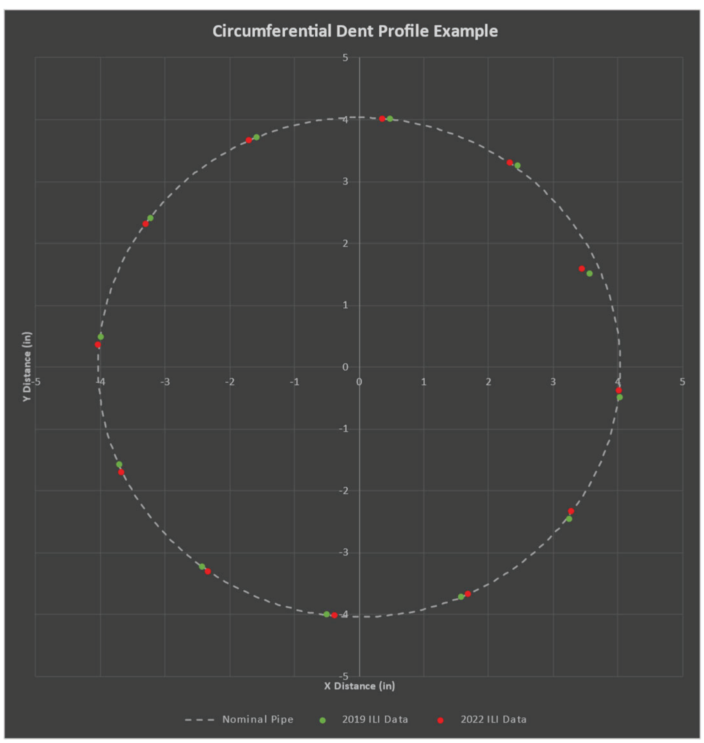

Figure 14: Unsuccessful combination of ILI data due to insufficient sensor offset

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Table 3: Strain Results for Dents Receiving Scenario 4 Analysis

	ILI Vendor	Scenario 1	Scenario 2	Scenario 3	Scenario 4
# Features with Strain < 6.0%	0	0	2	0	3
# Features with 6.0% <= Strain < 10%	4	5	15	11	14
# Features with Strain >= 10.0%	13	12	0	6	0
Maximum Dent Strain (%)	33.7%	13.3%	8.5%	12.1%	9.0%

Conclusions

The use of low-resolution caliper tools will continue within the industry due to ILI tool passage threats, operation budgets, and tool availability. By combining multiple runs' datasets from the same ILI tool configuration, Operators may be able to improve circumferential resolution and strain measurement accuracy. Factors such as data quality concerns, caliper tool similarity, and caliper density should be considered before attempting to combine caliper tool data. Operators should also accept a level of chance is involved in this process, as caliper tools may travel over a feature in the same orientation as the previous inspection. Applying this method to high-resolution caliper tools will introduce diminishing returns, as high-resolution tools typically have sufficiently high sensor density to capture the circumferential profile of a feature.

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