Impact Effects on Pipelines Beneath Railroads

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Design methods being developed for uncased crossings of high-pressure gas pipelines use impact factors to account for the increase in live load response due to the effects of vehicle speed, track stiffness, vehicle suspension characteristics, or irregularities in the running surface. Field experiments to measure impact effects were conducted on an instrumented pipeline 36 in. (914 mm) in diameter buried 5.75 ft (1.75 m) below the Facility for Accelerated Service Testing track at the Transportation Test Center in Pueblo, Colorado. Ranges of vehicle speeds and surface geometry conditions were investigated, and impact factors based on measured pipeline strains were determined. The results indicated that train speeds of 5 to 40 mph (8 to 64 km/hr) had a relatively minor influence on impact response, whereas changes in surface geometry resulted in a range of dynamic pipeline strains, with the maximum values nearly 1.6 times larger than previously recorded under baseline operating conditions.

When high-pressure gas pipelines cross beneath railroads, the owner of the railroad generally requires that the carrier pipeline be installed within a metallic casing. The main design criterion for the cased carrier is that the circumferential (hoop) stress due to internal pressurization be less than some percentage of the specified minimum yield strength. The allowable percentage is based on the population density in the vicinity of the pipeline, the type of pipeline welds, and the operating temperature. Because the casing is designed to carry the earth and live loads, the carrier design for cased pipelines is unaffected by additional live load effects due to impacts at the surface.

Research focused on the development of design procedures for uncased gas pipelines is under way. Uncased pipelines must be designed to withstand live load stresses imposed by vehicular traffic as well as stresses due to internal pressure and earth load. Rational methods to account for impact forces are an important part of design procedures.

Two instrumented high-pressure steel pipelines were installed without casings, using auger boring methods, at the Transportation Test Center (TTC) in Pueblo, Colorado. Field experiments were conducted to measure pipeline response to train loading. The effects of vehicle speed, internal pressure, and time since pipeline installation were investigated during a 2-year period. Figure 1 shows profiles of the two pipelines. The pipeline 12 in. (305 mm) in diameter has a wall thickness of 0.25 in. (6.4 mm) and a specified minimum yield strength of 42,000 psi (290 MPa). The pipeline 36 in. (914 mm) in diameter has a wall thickness of 0.61 in. (15.5 mm) and a specified minimum yield strength of 60,000 psi (414 MPa). The depth from the top of the railroad crossties to the crown of both pipes at the track centerline is 5.75 ft (1.75 m).

Both pipelines were instrumented before field installation. Instrumentation consisted of strain gauges, both internal and external, on the pipes, accelerometers, pressure transducers, and temperature sensors. Strain gauges also were mounted on the rails directly above the pipes to measure the applied wheel loads. The strain gauges on the pipes were oriented to measure both circumferential and longitudinal strains at the inside and outside crown, springlines, and invert. The locations of the instrument stations are shown in Figure 1 as solid circles. The gauge locations correspond to locations on the pipelines directly beneath the outside rail, track centerline, inside rail, and other locations along the pipe's long axis sufficient to measure the distribution of strains along the pipeline.

Testing of the pipelines began in July 1988. Measurements were made at 4- to 6-month intervals through the spring of 1990. Although measurements of live load response were recorded for both pipes, special impact testing was conducted only with the 36-in. (914-mm) pipeline. The remaining discussion focuses on the 36-in. (914-mm) pipeline data.

BASELINE TESTING

Field data were measured for a range of train speeds and internal pressures from the summer of 1988 through the spring of 1990. After the installation of the 36-in. (914-mm) pipeline, the annulus left by the 1.5-in. (38-mm) auger overbore remained partially open and did not collapse fully. The resulting pipeline strains were small, because contact between the pipe and the soil was limited. To replicate long-term loading conditions, the remaining annulus around the pipe was injected with a slurry of native sand and water in May 1989. Field data indicated that the annulus had collapsed partially between July 1988 and May 1989, and strains had been increasing. The decision to fill the annulus and increase live load transfer was necessary, because long-term response was desired and the field testing program had a duration of 2 years. There is little doubt that, given several years, the annulus would have collapsed fully because of repeated traffic. Between May and June 1989, the field measurements increased and stabilized at a consistent level. Measurements in July 1989 confirmed that the annulus around the pipeline was in a steady-state condition.

Figure 2 shows the longitudinal pipeline strains at the crown and invert of the 36-in. pipe measured in May 1989 before the annulus was filled, in May 1989 just after the annulus was

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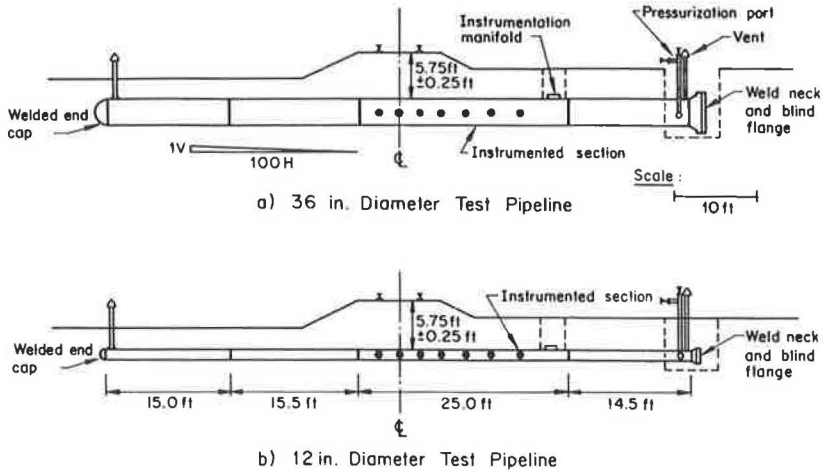

FIGURE 1 Profile views of test pipelines (looking west).

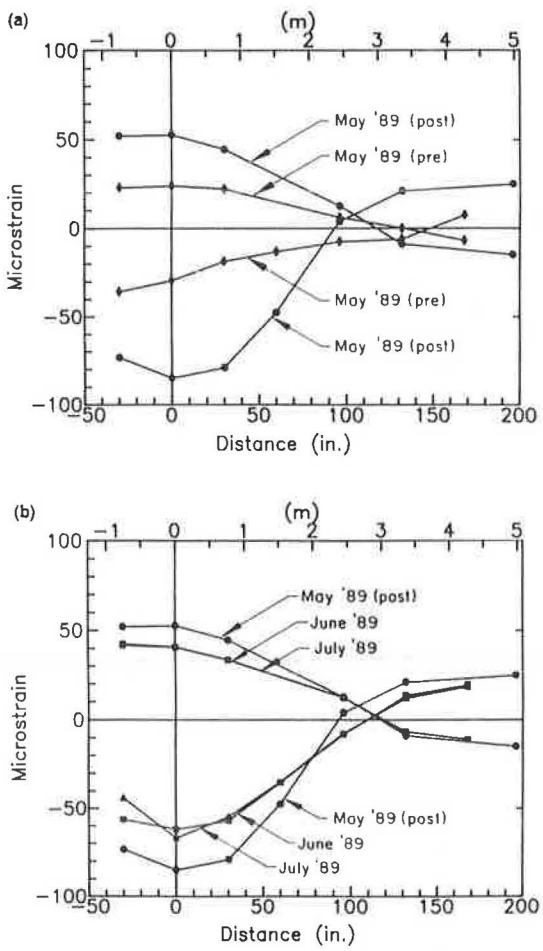

FIGURE 2 Changes in longitudinal strains at crown and invert over time.

injected with the native sand and water slurry, in June 1989, and in July 1989. (Distance 0 corresponds to the track centerline.) The rail surface at this time was level, without irregularities. Train loading was generated by slowly rolling loaded freight cars weighing 315,000 lb (1400 kN), producing 39.4-kip (175-kN) wheel loads. The freight cars are referred to as 125-ton cars and are representative of the heavy loadings anticipated in the near future on U.S. revenue lines. As shown in Figure 2, the strains before the annulus was filled were substantially smaller than those after the annulus was filled in May 1989. Strain decreased from May 1989 to June 1989, as any locked-in injection pressures dissipated. The June 1989 and July 1989 data indicate that the contact conditions between the pipe and soil had stabilized and were taken to represent the long-term condition. The relative changes in pipe strain from May 1989 to July 1989 shown in Figure 2 are representative of the changes of circumferential strain at the pipe crown, invert, and springline over time.

Train speeds above the instrumented pipeline were varied from a slow roll of roughly 5 mph (8 km/hr) to 40 mph (64 km/hr). The upper limit was based on the maximum speed that the train could achieve through the test section. Figure 3 shows dynamic longitudinal strains at the crown and invert of the 36-in. (914-mm) pipe, at the gauge station directly below the centerline of the track. The data indicate that at the pipeline depth of 5.75 ft (1.75 m), there was no measurable effect of train speed for the baseline field condition, without surface irregularities. Thus, for the normal track conditions at the Facility for Accelerated Service Testing (FAST) track at TTC, impacts were not measured.

Figure 4 shows the dynamic wheel loads measured using the strain gauge instrumentation installed on the rails directly

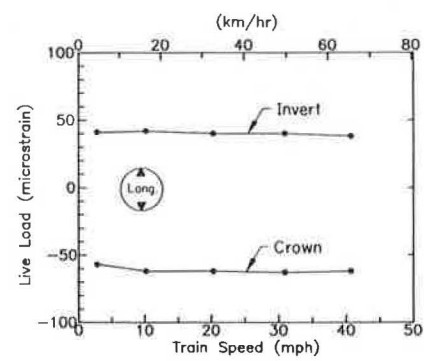

FIGURE 3 Longitudinal strains at crown and invert versus speed, July 1989.

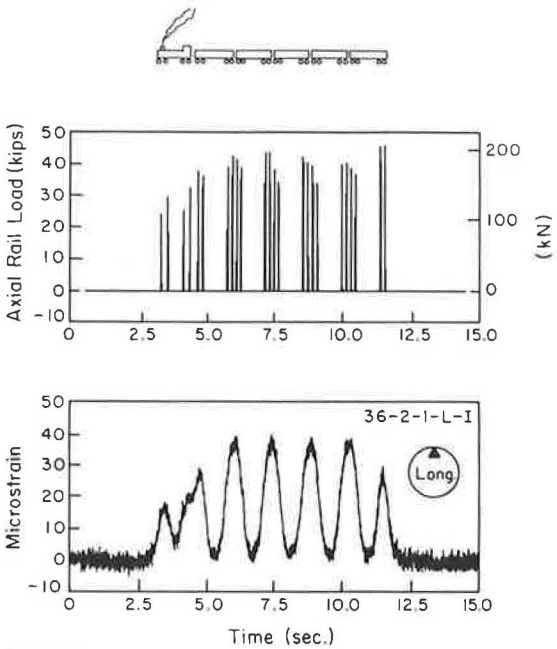

FIGURE 4 Dynamic wheel loads and longitudinal strains at invert for train speed of 30 mph.

above the pipeline for a train speed of 30 mph (48 km/hr) and the corresponding longitudinal strains at the pipe invert beneath the track centerline. The train used for this data run consisted of one locomotive and five freight cars. There is some variation in the dynamic wheel loads from the freight cars. The dynamic loads are approximately 40 ± 4 kips (178 ± 18 kN). The nominal static wheel load for the freight cars was 39.4 kips (175 kN). This indicates that at 30 mph (48 km/hr), the surface impact factor is 1.0 ± 0.1. Figure 4 also shows that four axles result in a single stress pulse at the pipeline depth.

IMPACT FACTORS

Design methods for pipelines subjected to traffic loads generally use some factor to account for the increase in live loading effects due to vehicle dynamics and the quality of the running surface. For railroad loadings on buried pipelines, two approaches are often used. The first is to use an impact factor as a multiplier of the static wheel load and calculate pipe response on the basis of the increased surface loading. This approach is also used for conventional track design, and several methods are available for estimating the surface impact factor. Typical methods are based on a combination of vehicle speed, wheel diameter, track stiffness, track quality, and unsprung mass of the wheel sets (*1–6*). In general, these methods predict surface impact factors on the order of 1.3 to 1.6 for track in good condition at vehicle speeds from 5 to 40 mph (8 to 64 km/hr). Impact factors based on these methods increase to approximately 2.0 to 2.5 at high train speeds for track in poor condition.

The second approach for impact loadings, which is more common for pipeline design, is to predict stresses within the soil mass that are based on a nominal design wheel load and then to increase the predicted stresses by a factor that is greater than unity at the surface and that decreases with depth. This method accounts for the attenuation of dynamic stresses with increasing depth. The two most common formulations for this variable depth impact factor are those recommended by the American Society of Civil Engineers (ASCE) (*7*) and the American Petroleum Institute (API) (*8*). The impact factor recommended in the ASCE method equals 1.5 between 0 and 5 ft (0 and 1.5 m), decreases linearly to 1.0 at a depth of 22 ft (6.7 m), and remains constant below that depth. The API impact factor is 1.75 between 0 and 5 ft (0 and 1.5 m) and decreases linearly by 0.03/ft (0.01/m) between 5 and 30 ft (1.5 and 9.1 m). Below 30 ft (9.1 m), the API method uses an impact factor of 1.0.

IMPACT TESTING

The observation that negligible speed-induced impacts occurred through the test section is consistent with wheel load data reported previously for FAST (*9*), in that only a small percentage of wheel loads at the well-maintained FAST track were significantly larger than the nominal static values.

Because the primary purpose of the field experiments was to provide data to substantiate a pipeline design procedure, it was important to replicate typical field conditions and to generate realistic upper bound loading conditions. Project advisors from the gas and railroad industries, the Association of American Railroads, and the American Railway Engineering Association also were concerned that the loading conditions at FAST might not represent those of revenue lines, because the track maintenance standards are high, and irregular train wheels are removed when they are detected. Thus, a series of impact tests intended to cause increased dynamic loadings representative of lesser-quality track was initiated. In addition, impact loading measurements could be used to substantiate current impact formulations used commonly in pipeline design.

Impact testing consisted of progressively degrading the track quality above the pipeline and operating the train at a range of speeds. The degradation procedure included installing a rail joint directly above the pipeline. The installation of the joint required removal of the wheel load detection circuits. Wood shims were placed between the top of the ties and tie plates at both rails over a distance of roughly 80 ft (24.4 m), so that a uniform rail raise of 3 in. (76 mm) was achieved over the central 30 ft (9.1 m). The wood shims over the central portion of the elevated track were removed in stages beneath the inside rail to produce a dip in one rail and a cross-level variance of up to 3 in. (76.2 mm) between the inside and outside rail. The joint at the rail above the pipeline also could be adjusted to produce either a tight joint or a pulled joint. The gap caused by the pulled joint was approximately 0.8 in. (20.3 mm). In addition, the end of the upstream rail at the joint was progressively ground to simulate a battered joint. The mismatch ranged from 0 to approximately 0.3 in. (7.6 mm) and was increased with increasing cross-level variances. The test conditions were selected to correlate with track class designations specified by the Federal Railroad Administration (FRA) (*10*) so that the track irregularities could be related to revenue track conditions at other sites.

Eight test steps were investigated, for FRA Class 6+ standards down to FRA Class 1 standards. For each test step, train speeds were varied from a slow roll to the maximum permissible or safe train speed, with both a tight and a pulled rail joint. Table 1 summarizes the impact test conditions along with the associated FRA class limits for cross-level and rail mismatch. The maximum joint gaps are also given in Table 1. The joints for the tight joint conditions were made as close as possible, not exceeding 1/16 in. (1.6 mm).

Figure 5 shows the measured cross-level variances between the outside and inside rail variances versus tie number for the test steps given in Table 1. Shims were removed from the inside rail, which caused the dip in the rail profile shown. The test pipeline was located beneath Tie 53, corresponding to the center of the rail dip and maximum cross-level variance.

Test Step 1 represents the nominally smooth track that had been shimmed to provide a uniform 3-in. (76-mm) raise through the test section. A slow roll of the train through the test section indicated that the installation of the shims and rail joint did not cause a change in the strains measured in the 36-in. (914-mm) pipeline from those recorded during the baseline measurements. Thus, the slow roll at Test Step 1 was representative of the baseline test conditions. Impact testing proceeded for each test step by increasing the train speeds from 5 mph (8 km/hr) up to the maximum attainable speeds given in Table 1 with the rail joint tight, and then repeating the speed sequence with a pulled joint. After the completion of a test step, the shims were removed as necessary, and the rail was ground to the rail mismatches given in Table 1.

Figure 6 shows the variation in dynamic strains in the pipe beneath the track from Test Step 5b for several important pipeline locations. Figure 6 indicates that strain increases only slightly as speeds increase from 5 to 40 mph (8 to 64 km/hr). There is a slight subpeak in the dynamic strains near 20 mph (32 km/hr), which corresponds to a resonant effect that frequently has been observed in other testing at TTC using 39-ft (11.8-m) jointed rail sections and trains traveling at 18 mph (29 km/hr). Also, the longitudinal strains are not symmetrical about the unrestrained pipe's neutral axis. This trend is also shown in Figure 2. The circumferential strains at the springline have a greater absolute magnitude than at invert. This trend was observed consistently in all of the experimental data.

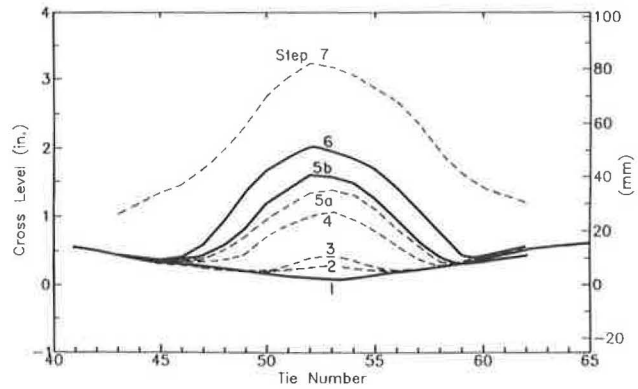

FIGURE 5 Cross-level variances for impact tests.

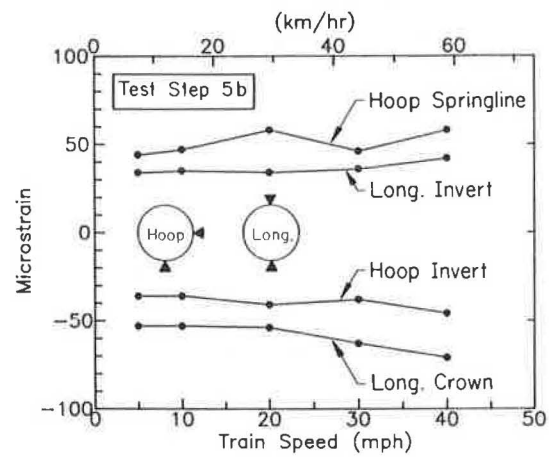

FIGURE 6 Variation of live load strain with train speed, Impact Test Step 5b.

Impact factors for the field tests were defined as the ratio of pipeline strain under impact conditions to the strain measured at the same gauge location from the baseline tests. Table 2 gives the measured impact factors at three critical pipeline locations, determined for the worst surface geometry case and maximum attainable train speed. The impact factors

TABLE 1 SUMMARY OF IMPACT TEST CONDITIONS

Test Step	FRA Class	Speeds (mph)	Cross Level (in.) Test	Cross Level (in.) FRA Max.	Rail Mismatch (in.) Test	Rail Mismatch (in.) FRA Max.	Maximum Joint Gap (in.)
1	6+	0 - 40[a]	0.07	0.00	0.00	0.00	0.88
2	6	0 - 40[a]	0.29	0.50	0.12	0.12	0.81
3	6	0 - 40[a]	0.42	0.50	0.12	0.12	0.94
4	5	0 - 40[a]	1.00	1.00	0.12	0.12	0.75
5a	4	0 - 40[a]	1.38	1.25	0.12	0.12	0.81
5b	3	0 - 40[a]	1.58	1.75	0.19	0.19	0.75
6	2	0 - 25[b]	1.96	2.00	0.25	0.25	0.80
7	1	0 - 10[b]	3.18	3.00	0.28	0.25	0.75

a - Maximum attainable at test section
b - Maximum allowable for FRA Class

TABLE 2 IMPACT FACTORS FOR PULLED JOINT TEST CONDITIONS

Test Step	Train Speed (mph)	Cross Level (in.)	Rail Mismatch (in.)	Joint Gap (in.)	Impact Factor at Station[a] Hoop, Invert	Hoop, Springline	Longitudinal, Invert
1	40	0.07	0.00	0.88	1.30 (2)	1.13 (3)	1.12 (2)
2	40	0.29	0.12	0.81	1.32 (1)	1.19 (3)	1.10 (1)
3	40	0.42	0.12	0.94	1.22 (2)	1.10 (3)	1.12 (1)
4	40	1.00	0.12	0.75	1.15 (2)	1.19 (3)	1.05 (2)
5a	40	1.38	0.12	0.81	1.41 (2)	1.17 (3)	1.12 (1)
5b	40	1.58	0.19	0.75	1.52 (2)	1.25 (3)	1.38 (1)
6	25	1.96	0.25	0.80	1.48 (3)	1.48 (3)	1.17 (1)
7	10	3.18	0.28	0.75	1.36 (1)	1.21 (3)	1.07 (1)

a - Numbers in parentheses refer to pipeline station: 1 = outside rail; 2 = centerline; 3 = inside rail

from Test Steps 1 through 5a did not show a clear trend of increasing with worsened track condition. Test Steps 5b through 7 had increased cross-level variance and rail mismatch, but the maximum allowable test train speeds decreased from 40 mph (64 km/hr) to 10 mph (16 km/hr). The data given in Table 2 suggest that larger impact factors would have been achieved for Test Steps 6 and 7 if the train speeds had been higher.

In general, Test Steps 5b and 6 resulted in the highest measured impact factors. Figure 7 shows comparisons of the pipeline strain from the impact tests with the strain from the initial condition or baseline cases at the same gauge location. Figure 7a shows data from Test Step 5b, and Figure 7b shows data from Test Step 6. The strains at the inside invert, outside crown, and outside springline are shown, using data taken from all instrumented sections along the pipe, as shown in Figure 1. As indicated in Figures 7a and 7b, impact factors can be determined by the ratios of the impact strains to the initial condition strains. There is a distribution of impact factors from roughly 0.8 to 1.6 for both test steps. Impact factors of less than unity are possible due to wheel bounce, load transfer between inside and outside rails, and dynamic interaction effects of the trains passing through the irregular track section.

As described previously, both ASCE and API recommend design impact factors dependent on depth below the track. Figure 8 shows the design impact curves for ASCE and API, along with the maximum impact factor determined from the field testing. Although only one experimental pipeline depth was investigated, the datum shown in Figure 8 suggests that the ASCE recommendation may be unconservative. The field testing had limitations on the maximum train speeds, particularly for the most severe geometric irregularities. Thus, it is likely that greater impacts are possible with revenue train speeds of up to 80 mph (129 km/hr). The API design curve has an impact of 1.75 for the upper 5 ft (1.5 m), which is larger than the maximum field test value of 1.6. Given that higher impacts than measured during the field tests may be possible, the API curve would be preferred for uncased pipeline design.

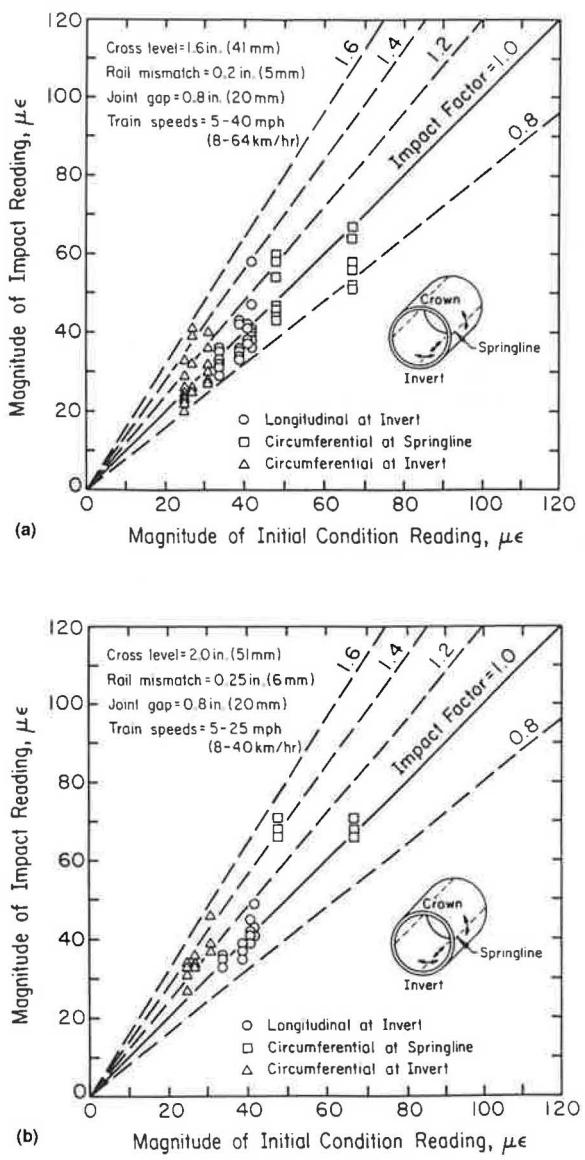

FIGURE 7 Measured impact factors from field tests.

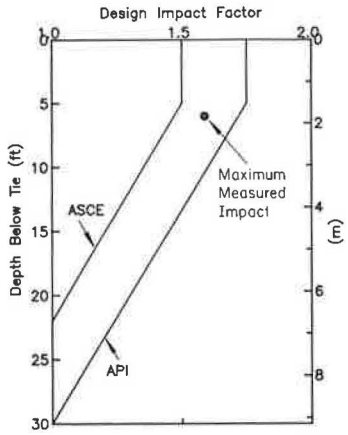

FIGURE 8 ASCE and API design impact factors and maximum measured impact factor from field tests.

SUMMARY

Field testing of live load response on well-maintained track at TTC indicated that negligible dynamic impact effects occurred during baseline field testing. In response to concerns from the gas and railroad industries, and to replicate upper bound conditions to the extent practically possible, a series of special impact tests was conducted to investigate live load response for changes in track quality consistent with FRA class standards. Track quality was degraded progressively by increasing the cross-level variance between the inside and outside rails, producing a condition representative of a dipped joint. Rail mismatch on the order of 0.25 in. (6.4 mm) was included, along with a pulled joint producing a gap of approximately 0.8 in. (20.3 mm). Heavy-axle freight cars were operated over an instrumented steel pipeline 36 in. (914 mm) in diameter buried 5.75 ft (1.75 m) below the top of the tie. Impact factors increased slightly with speed for each of the test configurations. Impact factors based on pipeline strain were measured and ranged from 0.8 to 1.6. On the basis of the maximum measured impact factor of 1.6, and the consideration that higher impacts might have been developed had higher test speeds been possible, the impact formulation given by API is recommended for the design of uncased gas pipelines crossing beneath railroads.

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