Title

Ballasted Railroad Track Geometry and Deformation Monitoring: An Objective Comparison of Established and Emerging Automated Instrumentation & Monitoring Techniques

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Abstract

The advent of automated monitoring for track, utility, tunnel, bridge, and general railroad infrastructure occurred a couple of decades ago; automated methods are becoming more reliable and economical than manual methods. In recent years, the marketplace has become flooded with new technologies, making it confusing for practitioners to decide what automated technique, if any, is best for each application.

This paper will focus on long-term monitoring of ballasted railroad track and the authors' best attempt to form a concise, objective comparison of established and emerging automated techniques using both a theoretical framework and project case studies. These methods generally fall into two categories: optical measurement of relative displacements and measurement of inclination or "rotation" of various components of the rail-track structure. While optical measurements are typically taken by manual survey, or if site conditions allow, their automated counterpart, Automated Motorized Total Station (AMTS), there are a wide variety of inclination/rotation-based systems that usually incorporate microelectromechanical systems (MEMS). Examples include horizontal inclinometers, horizontal in-place-inclinometers (IPI), horizontal shape arrays (SAAX), tiltmeters attached to tilt beams parallel to the track, and at times, tiltmeters attached to individual crossties.

Each method has advantages and disadvantages depending on the type of installation method, amount of maintenance, achievable reading frequency, engineering unit measured, the ease of data reduction / analysis / evaluation, and overall risk levels associated with a particular project. This paper will share lessons learned from past projects and sketch out the major practical and theoretical considerations associated with proper selection of automated railroad track monitoring systems.

Introduction

The authors of this paper have implemented a variety of automated instrumentation and monitoring techniques that furnish long-term, continuous monitoring of railroad tracks, particularly in high-risk geotechnical construction projects involving underground or adjacent construction that poses the risk of ground loss, ground settlement/heave, or other geotechnical problems that could in turn lead to track geometry problems. As such, it is sometimes preferable to deploy an automated system of measurement that confers a fast response time to project stakeholders in the event of excessive or sudden movement that could indicate a developing issue with the track geometry, which may or may not demand immediate remedial action, and in which the mode of movement of the rail could conceivably have been caused by construction activities.

Automated track monitoring methods generally fall into two categories: optical measurements of relative displacement on the one hand, and on the other hand, measurements of rotation or “tilt” of the various components of the rail-crosstie track structure. Optical measurements of relative displacement are typically taken either by manual surveyors or a qualified firm capable of deploying their automated counterpart, the Automated Motorized Total Station (AMTS). Rotation-based devices are also being used more frequently and include horizontal shape arrays (SAAX) and tiltmeters.

Part 1 of this paper will provide a sketch of what the ideal track monitoring system consists of and then spell out practical constraints around this theoretical approach.

Part 2 will provide a summary of the traditional track monitoring methods and the three automated track monitoring techniques most familiar to the authors (AMTS, shape arrays, and tiltmeters) both in terms of their working principles of measurement, instrument capabilities, and physical differences.

Part 3 will compare each method through the lens of the advantages and disadvantages listed in the abstract, which include the type of installation method, amount of maintenance, achievable reading frequency, engineering unit measured, the ease of data reduction / analysis / evaluation, and the overall risk levels with a particular project. The conclusion of the paper will derive key lessons learned from the discussion to help practitioners make more informed decisions in the selection of track monitoring systems.

Part 1: The Ideal Theoretical Track Monitoring System

Part 1 begins with a thought experiment of what capabilities an ideal track surface monitoring system would have for tangent track. It is the authors' hope that this understanding will be of assistance in the selection of real solutions. Two logical precepts guide this effort, namely, that 1) nothing incomplete can truly measure anything, and that 2) even the complete truth may not be useful if it is not known in time. The first precept begs the question as to what a complete set of track geometry data would consist of in theory. Fortunately, there is no need to venture further than the track surface maintenance standards set forth in § 49 CFR 213.63 and reproduced in Table 1 below.

Table 1. § 49 CFR 213.63 – Track surface[1]

Track surface (inches)	Class of track				
	1	2	3	4	5
The runoff in any 31 feet of rail at the end of a raise may not be more than	3 1/2	3	2	1 1/2	1
The deviation from uniform profile on either rail at the mid-ordinate of a 62-foot chord may not be more than	3	2 3/4	2 1/4	2	1 1/4
The deviation from zero crosslevel at any point on tangent or reverse crosslevel elevation on curves may not be more than	3	2	1 3/4	1 1/4	1
The difference in crosslevel between any two points less than 62 feet apart may not be more than * [1] [2]	3	2 1/4	2	1 3/4	1 1/2
*Where determined by engineering decision prior to June 22, 1998, due to physical restrictions on spiral length and operating practices and experience, the variation in crosslevel on spirals per 31 feet may not be more than	2	1 3/4	1 1/4	1	3/4

For readers unfamiliar with the terminology in Table 1, a further explanation of each of the three quantitative limiting criteria dealt with in the paper (runoff is excluded) for tangent track surface maintenance follows:

First, the "deviation from uniform profile" is a measurement of the vertical surface uniformity (straightness) of the rails. It is also commonly called the "vertical alignment." In terms of hand measurements, this means that for tangent track, with a level line between the rail 62 feet in length, the elevation of the rail at the mid-ordinate cannot deviate more than 2 inches from the level line. In this manner, each rail is measured individually in 62 ft chord lengths to determine whether the "deviation from uniform track profile" is beyond safe working limits as set forth in Table 1. For example, for a Class 4 track, the vertical alignment (deviation from uniform profile) should not exceed 2 inches at the center of a 62-ft chord length without triggering track maintenance.

Second, the “deviation from zero crosslevel” is the measurement of the unintended difference in elevation between the top surface of the two rails. For tangent track, the cross level would be zero by design, whereas for curved track there is a built-in ‘cant’ / ‘superelevation’ by design to increase working speeds. Cross level is measured as a deviation from the intended superelevation (which could be zero in the case of a flat track). Figure 1 illustrates the meaning of crosslevel in the case of a tangent track.

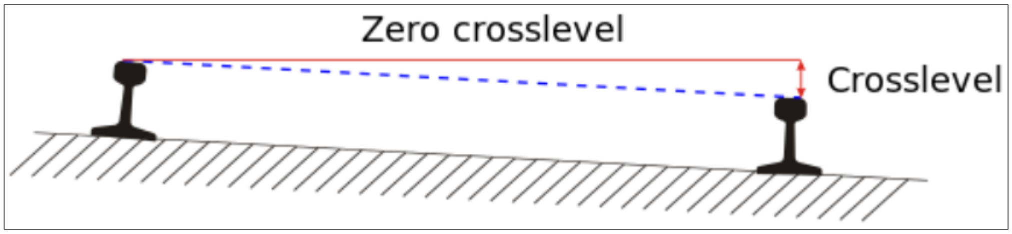


Figure 1. Schematic of the deviation from uniform crosslevel of tangent track.

Third, the “difference in crosslevel between any two points less than 62 feet” is best explained through an example, such as the case of Class 4 track, in which the difference in crosslevel between any two points within 62 feet along the rail cannot exceed 1.75 inches. In other words, track maintenance is triggered when the difference in elevation (height) of the top of the two rails at two separate locations within 62 feet of each other exceeds 1.75 inches.

The data collected from the ideal track monitoring system would provide the complete time history of the deviation from uniform track profile (vertical alignment), crosslevel, and difference in crosslevel under full wheel loading. This would theoretically satisfy Precept 1 for the purposes of this paper. To satisfy Precept 2 of the ideal track monitoring system, we would add the requirement that collection, transmission, post-processing, and comparison with track geometry thresholds set forth in Table 1 occur quickly enough to allow project stakeholders to take corrective action as quickly as possible for an emergent track geometry problem. The ideal system also would not produce any false alarms that point towards the presence of a potential defect in the track geometry that does not exist. For the purposes of argument, we will say that collection of monitoring data is sufficiently fast if the information is made available every 0.5 to 1 hour, only in the event of movements that surpass limits set forth in Table 1. To summarize, the ideal track monitoring system would provide:

- Complete time histories of parameters in Table 1 under full wheel load.
- Alarms would be configured to indicate real track geometry issues and not an arbitrary amount of relative movement.
- Data would be made available to project stakeholders quickly enough to take remedial action, if needed.

- The system would not produce false alarms that could both slow down work and create unnecessary mental stress to the project team.

Ideal monitoring solutions are difficult to implement. Real world solutions face complications, such as:

- Measurements of vertical movement by automated systems are taken periodically, whether or not trains are running or are parked, so the majority of the measurements from automated systems are taken when the rail is unloaded.
- Most track monitoring systems are limited to quantifying the impact of geotechnical construction itself, and as such are limited to measurements of relative movement alone and not actual track geometry.
- Collection, transmission, and comparison to alarm thresholds is not an instantaneous process. It is more likely that a "best case" is this data reaching project stakeholders every 0.5 to 1 hour, not instantly.
- Since an arbitrary amount of relative movement is measured, alarms based on an arbitrary amount of relative movement may be triggered even if there is not a track geometry issue.
- Relative horizontal movements parallel to the railroad are dominated by thermal effects in instances where monitoring points are attached to the actual rail and not the crossties; this thermal movement makes horizontal displacement measurements that are in line with the track noisy.
- Measurements of horizontal movements perpendicular to the railroad, while less noisy compared to those parallel to the track, are not measurable using MEMS technologies, but are measurable using optical methods.

Given the limitations above, the focus of this paper is on track geometry parameters and track monitoring systems that relate to vertical movements, not horizontal movements, such as the spreading gauge or other phenomena that can contribute to speed reductions and derailment risk. These limitations are imposed purposefully, due to the scale of geotechnical construction which lends itself to global movements and the fact that the quantitative parameters detailed in Table 1 also all relate to vertical movements, not horizontal movements.

Part 2: Comparison of AMTS, SAAX, and Tiltmeters as Automated Track Monitoring Methods

Part 2a: Traditional Methods

The discussion will begin with a brief treatment of traditional rail monitoring techniques. To be consistent with the remainder of this paper, the focus will be on measurements of track/rail settlement/heave (vertical movement). Other types of rail movement will not be considered. To the knowledge of the authors, most rail settlement monitoring during construction that are close to the rail is performed by manual surveyors that periodically track changes in the absolute elevation of discrete points spaced out along the rail. Reading frequencies of a manual survey may be taken daily or weekly in most cases, but they are unlikely to furnish more than one reading per day. Additionally, most manual surveying efforts related to rail settlement still are focused on determining relative movement of the rail from the initial position, and attempts are generally not made to calculate parameters in Table 1 using the absolute position data.

Horizontal inclinometers also are used in both the manual and automated methods to monitor track movement. Similar to the use of manual readings taken by a surveyor, use of a manual horizontal inclinometer may not be advisable in high-risk projects due to the larger intervals taken for measurements, which are typically daily or weekly, not hourly.

Automated In-Place-Inclinometers ("IPI") are sometimes permanently installed and operate with MEMS technology, but they do have a reduced spatial resolution compared to emerging methods such as shape arrays (discussed later). Typically, automated IPI's come in modular segments that are each 10 feet long and installed end to end.

To the knowledge of the authors, the post-processing is generally more time-consuming than with a single SAA device or AMTS. However, the spatial resolution of automated IPI's is approximately the same as what could be accomplished using optical measurements (manual surveyor or AMTS), and their modularity is useful in that custom lengths can be accommodated more easily than with SAA devices. Also, since the system is modular, if one ten-foot segment is damaged, the other ten-foot segments still function, and most of the deformation profile is still measured. Over long distances, the use of automated horizontal IPI's may be cost-prohibitive.

It should also be pointed out that, from the standpoint of the instrumentation solutions provider, the post-processed output from any inclination device is more "complicated" because the degrees have to be converted into displacements, whereas the optical approach, whether by manual survey or AMTS, provides displacement data "more directly". Many customers prefer a measurement with an output in the same dimensional units as the parameter of interest that alarms are based on, which is typically a magnitude of relative settlement in inches.

Since the traditional methods mentioned are well-established, and their benefits and drawbacks well known, further treatment of them will not be given in this paper. To summarize, in applications where the amount of track to be monitored is relatively short (50-100 feet), these traditional approaches may not provide adequate temporal and/or spatial resolution as compared to emerging technologies such as the SAAX. On the other hand, in applications where the total length of monitored track is long (500+ feet) the use of manual surveyors or inclination-based measurements of settlement may be cost-prohibitive. As a consequence, the reader is prepared to learn about why the Automated Motorized Total Station (AMTS) is heavily used.

Part 2b: Automated Motorized Total Station (AMTS)

Before introducing AMTS, a detailed explanation of the difference between absolute and relative measurements is warranted, because track geometry issues arise due to irregularities in overall track structure and not necessarily relative displacement, despite the fact that most monitoring techniques rely on relative measurements. Data provided within an absolute coordinate system place all points in the same reference system in the form of elevations and geospatial coordinates. On the other hand, data provided via relative measurements typically involve zeroing the first reading and from there evaluating deviations from that initial reading. It is productive to note that most automated instrumentation systems aimed at measuring changes in track geometry report data in a relative coordinate system and not an absolute coordinate system, despite the assertions made earlier in connection with Precept 1, which requires all information from Table 1 to be reported. With relative measurements, it is of utmost importance to establish a point of fixity in the monitoring system to allow for the relative measurements to match up with relative changes in absolute position.

The use of relative measurements rather than absolute measurements is usually justified on projects in which the concern is not actual track geometry, but rather the *relative changes in the track geometry caused by construction.* This is based on the claim that any existing track geometry issues prior to construction are not the contractor's fault.

In other words, if the relative movement data were used, and deviations were reported from the initial zero reading, there is an implicit assumption that the geometry of the track is starting from a point of perfection. Due to this constraint, it is advisable to have manual surveyors to initially measure the absolute positions along the rail in the same locations as the monitoring points used for the long-term monitoring effort relying on relative measurements. (Alternatively, an SAAX or a horizontal IPI could be used to determine the initial track geometry although in the experience of the authors this is rarely done in practice.) In this manner, if a relative movement is detected with the automated system, manual readings can be taken to confirm the magnitude of the movements.

The use of automated systems and dealing with the resulting measurements of relative movement is further justified in situations where it is clearly advantageous to have rapid and reliable post-processing that allows alerts to reach project stakeholders quickly if relative changes occur in the track geometry as a result of construction.

Since AMTS takes relative measurements between the control points and monitoring points prisms, it is not technically necessary that the AMTS itself is installed at a point of translational fixity, although it is still advisable. In theory, if the total station moves down, and the rail also moves down the same amount, the relative distance between them is the same, but relative to a stable control point network, the monitoring points will show relative movement.

As such, the stability of the "control point network" is essential, because it provides points of reference and confidence in the relative measurements collected. Control point stability must pass a 95% confidence margin relative to the initial position of the control points at the zero reading. If the control points move outside the 95% confidence margin, the relative coordinate system can be re-baselined to the altered control point network. However, if the total station itself moves but the control points do not, then the reported magnitudes will still be the true relative movements.

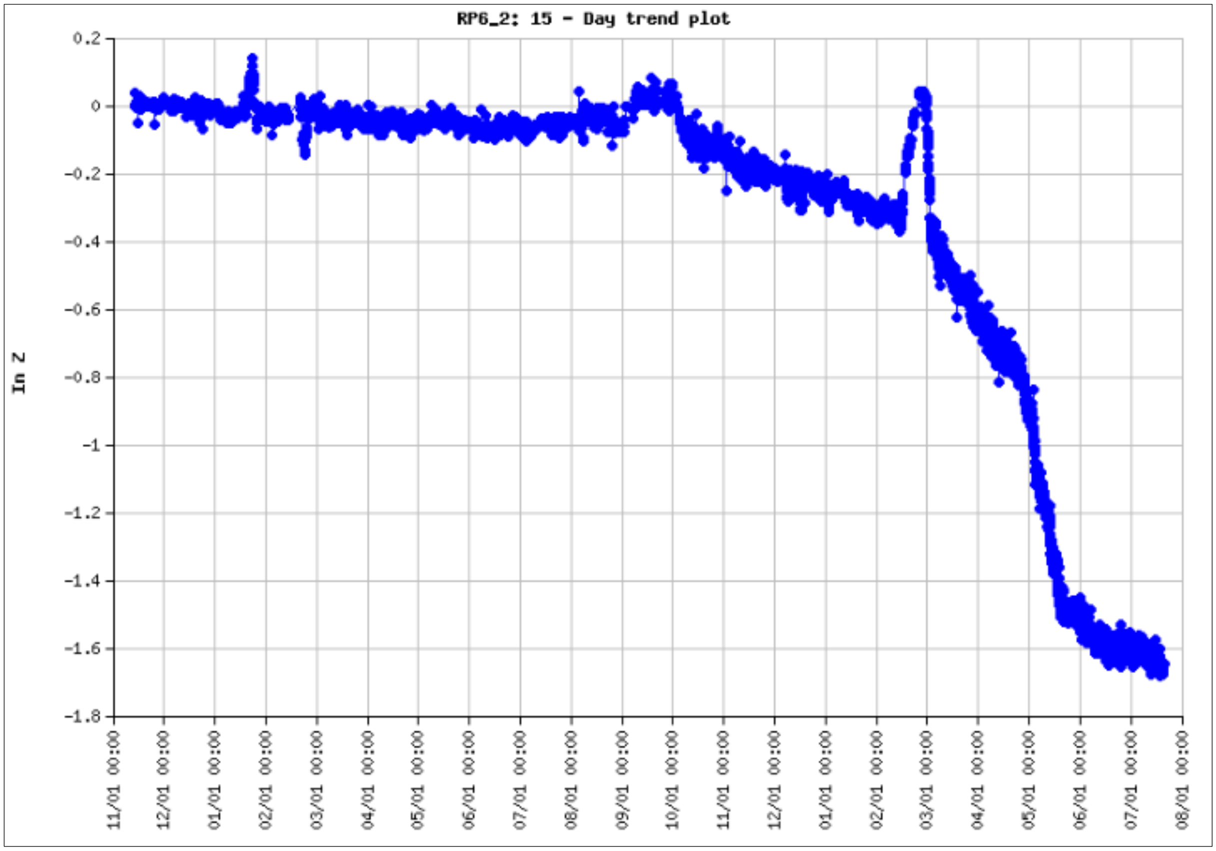
It is still typical to install the AMTS at point of vertical and horizontal fixity mainly because it ensures the total station will not rotate and go out level, and not because translational movements of the total station would prevent the relative movements from being valid.

Use of AMTS systems requires a suitable site layout/topography, a rotational point of fixity for the total station, a stable control point network, and line of sight to all monitoring points and control points. On projects in which the work moves constantly, or establishment of a stable control point network is not feasible, or in cases where line of sight to control points and monitoring points is difficult (such as in a rail yard with many parallel rails), electing to use inclination-based methods may be the better option. Please refer to Figures 2 and 3 (below) for images of typical AMTS track monitoring systems and their monitoring points, in the form of Rail Clip Prisms.

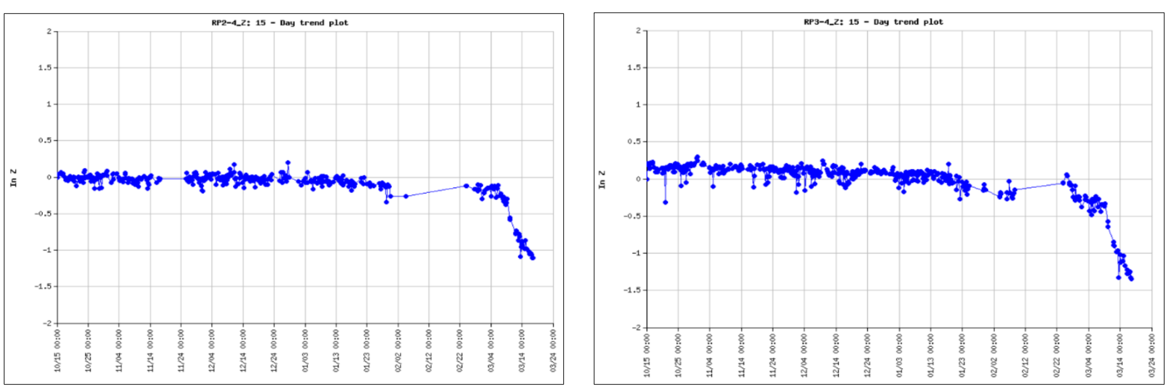
Figure 2. Various AMTS Track Monitoring mounting options.

Figure 3: Image of Rail Clip Prisms attached to rails with timber crossties.

Figure 4 (below) shows an example of project data from November 2019 through the end of monitoring in July 2021. As shown in the data plot, over the duration of the project, the rail settled approximately 1.6 inches. The project involved a support of excavation (“SOE”) approximately 15 feet away from the edge of rail for excavation that reached approximately 30 feet in depth. Due to deflection of the SOE, settlement of the rail was measured. Figure 5 (also below) shows an example of a project data involving a jack bore underneath a railroad embankment in which approximately 1.5 inches of relative settlement occurred above the tunnel-rail intersection due to ground loss.



<u>Figure 4</u>: Track settlement (in inches) developed because of cantilever deflection of the support of excavation.



<u>Figure 5</u>: Track settlement (in inches) measured on twin tracks on a Chicago rail embankment, at the rail-tunnel intersection, during jack boring activities involving a bore with a high tunnel-diameter to tunnel-depth ratio.

Figures 4 and 5 (above) illustrate that most monitoring projects involve measuring flat lines (in this case, minimal rail settlement). However, dramatic movements occasionally occur. These movements (rail settlement) are particularly interesting in that they represent movement of the *unloaded* rail, because most of the AMTS measurements are taken when trains are not parked or even less likely, when they are passing by and subjecting the rail to dynamic loading.

Furthermore, a case could be made that measurements of settlement of the unloaded rail are indeed the best way to capture movement due to construction, because by their nature, they remove the noise of variable loading scenarios and better capture the global, static settlement of the tie-ballast structure due to construction. In both project graphs shown above, the captured settlement data led directly to a conversation between the general contractor and the railroad owner regarding the *potential* need for track maintenance.

The meaning of “continuous monitoring” should be defined explicitly in terms of a reading frequency. Take, for example, the project involving the jack bore (Figure 5). Due to heavy snowfall and lack of safe site access, the AMTS system almost missed the key movement for which the system was deployed. This is because the prisms were buried in snow, blocking line of sight between the total station and the rail clips. This condition persisted for about 20 days. When the freezing conditions abated, the ice and snow were removed from the rail clips and the system was up and running before the jack bore resumed. Within days of resuming monitoring, the approximately 1.5 inches of rail settlement began. As discussed in the next section, line of sight issues can be avoided altogether using inclination-based methods, but at a high cost.

Although the focus of this paper is on vertical movements, it should be noted that optical methods such as AMTS have the capability of measuring horizontal displacements in addition to vertical displacements. While horizontal movements parallel to the rail are dominated by thermal strains, horizontal movements perpendicular to the rail are useful in quantifying the effect of geotechnical construction on the rail. For example, if a sheet pile wall is driven parallel to the rail, excessive cantilever deflection of the wall will presumably cause both settlement and some amount of horizontal displacement perpendicular to the track towards the cut. This is one of the key advantages of optical methods in that unlike inclination-based measurements, optical methods such as AMTS can also give indication of relative horizontal movements.

Part 2c: Shape Arrays (SAAX)

Horizontal shape arrays (SAAX) also have been deployed successfully to a less frequent extent to measure changes in track geometry. Typically, the “change in track geometry” is referred to as “track deformation” by users of the device, which is useful in a variety of deformation monitoring applications, such as slope stability, settlement beneath embankment fills, and lateral pile load tests, among many others. A shape array consists of a chain of rigid segments connected by flexible joints in which each joint contains three orthogonally oriented tiltmeter sensors. The joints between the segments cannot twist relative to each other, but they can bend freely in the X and Y axes. Each segment is instrumented with three orthogonally oriented tilt sensors. With the aid of a microprocessor, the overall shape of the array can be calculated using a chain of "L*sine(theta)" calculations.

Initial readings of shape arrays can be dealt with in two ways:

> Option 1: The entire chain is zeroed out, then subsequent changes in shape of the array are measured, meaning that its shape as represented on the graph is not the same as the actual deformed shape. This situation is similar to what happens at the beginning of an AMTS monitoring period, in which all monitoring points are forced into a zero reading. As mentioned previously, "zeroing" the initial readings is the same as saying that at the beginning of monitoring, the track geometry is "perfect." This relative data is in contrast with the "absolute" data output described in Option 2.
>
> Option 2: Only the fixed end is zeroed out, so the initial profile (and subsequent ones) is the existing vertical alignment. As a result, its shape as represented on the graph is the actual deformed shape. Therefore, with the right type of post-processing, real track geometry thresholds could be inputted as limiting values directly from Table 1, or derivative values (say ¾ or ½ to a limiting value) could be used.

Unlike Rail Clip Prisms, it is necessary to run the SAAX through protective conduit, which is then anchored to crossties using either wood screws (for timber ties) or concrete anchors (for concrete ties) or other rigid attachment methods.

Under load, it is inevitable that the rail will first deflect down to the crosstie before the crosstie starts to move down. As a result, it could be argued that the SAAX provides a better estimate of the 'true' track geometry under wheel load, because it tracks a shape closer to where the rail would bottom out under support of the engaged ballast support beneath the crosstie.

Due to the high up-front cost of shape arrays, they are typically only used in projects in which the length of monitored track is not more than ~100 feet. Typically, these projects involve a site with a layout and topography that do not have adequate locations for the AMTS to be installed at point of fixity, but there is a region of the rail outside the zone of influence of the construction efforts that is considered fixed. Shape arrays are more desirable on sites that lack stable control point locations, or where the installation of control points may not be practical (such as in a tunnel), or in rail yards where one parked train could compromise line of sight to the majority of AMTS monitoring points.

In order to capture crosslevel (and difference in crosslevel) information, two parallel shape arrays would need to be deployed on opposite sides of the same crossties. As a result, measuring crosslevel with shape arrays can be cost-prohibitive, especially for longer lengths of monitored railroad. It is important that both devices are installed with the exact same position parallel to the track for both of the fixed ends. To the knowledge of the authors, twin shape arrays only have been used in research settings due to their high up-front cost. There is added risk of damage if track maintenance operations are undertaken without first removing the shape array. It is far easier to replace a row of Rail Clip Prisms than it is to deploy an entirely new shape array device. Shape arrays may not be the ideal option in scenarios involving high-traffic and frequent track maintenance. However, for short duration jobs and/or low-traffic railroads, shape arrays may be the best option.

Shape arrays remain a compelling option because they allow for the absolute unloaded settlement/deformation profile of the crossties to be quantified. In contexts where the location of expected movement is known and a known point of relative fixity is fairly close to the expected point of maximum movement, shape arrays are ideal. Examples of this include projects in which tunneling operations are performed underneath the rail and the expected location of maximum settlement of the rail is directly above the tunnel-rail intersection.

When shape arrays need to be excessively long, or in projects near tracks that require frequent maintenance (tamping, undercutting, *etc*.) shape arrays are likely not a good option due to the high cost of the instruments and the elevated likelihood of damage if, for example, a tamping operation is performed on the track monitored by the SAAX. Importantly, if the entire array settles uniformly (*i.e.,* no relative movement between the segments in the shape array), then the shape array will show zero movement. Thus, having a point of fixity at one end of the SAA is essential. Horizontal shape arrays can capture only the vertical deformation profile, because MEM sensors operate via inclination relative to the gravity vector and produce information related to the vertical alignment.

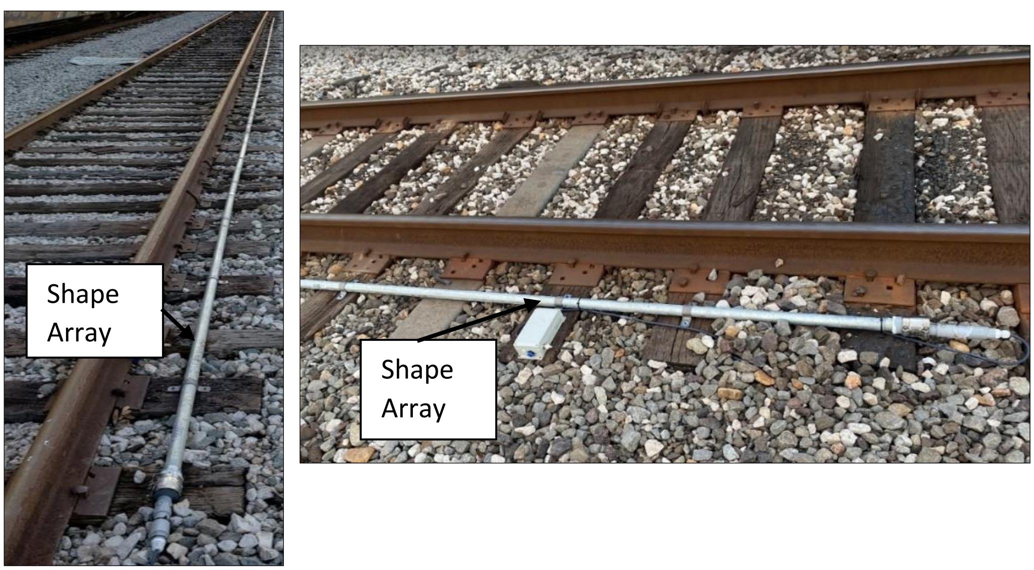


Figure 6: Photographs of field applications involving a horizontal shape arrays and timber crossties.

In connection with the “ideal” track monitoring system, shape arrays may be preferable because they are capable of providing the absolute track geometry, given a truly fixed end, and a post-installation data configuration that only zeroes out the far end, but preserves the initial deformed shape of the array. In this manner, the actual unloaded deviation from uniform track profile can be monitored with one shape array, while two shape arrays are necessary to monitor unloaded deviation from uniform track profile, in additional to crosslevel, and difference in crosslevel. With the appropriate post-processing (zero only the fixed end of the array) and configuration of track geometry limits based on Table 1, the shape arrays solution furnishes absolute track geometry based on the absolute deformed shape. The main drawbacks of shape arrays are the high up-front cost of the sensor itself, and the elevated risk of costly damages if track maintenance is performed without notification to project stakeholders. SAAX sensors also have a higher precision/accuracy compared to optical methods.

Part 2d: Tiltmeters

Wireless tiltmeter systems also have been deployed in some applications in the continental United States to monitor the rotation of crossties. Tiltmeters are typically installed using either concrete anchors or adhesive to the top surface of the crossties at a regular spacing (10-50 feet). Tiltmeters mounted in either manner are useful to monitor relative changes in crosslevel of individual crossties. Because each tiltmeter lacks a shared point of fixity perpendicular to the track, however, calculation of the difference in crosslevel is not possible. For similar reasons, along the axis parallel to the rail, the array of single-point tiltmeters also lacks a point of fixity on the axis parallel to the track. As a result, rotations along the axis parallel to the track cannot be cumulated in the same manner used for shape arrays and horizontal in-place-inclinometers (IPI's) to provide a measurement of relative settlement of the unloaded rail.

It is possible to circumvent the point of fixity problem parallel to the track via the use of a chain of tilt beams that run parallel to the track and which meet up end to end. After all, a tilt-beam assembly is, essentially, a rudimentary form of a horizontal shape array (or IPI), in that it provides a point of fixity in the direction parallel to the track. In a similar vein, a chain of tilt beams and wireless tiltmeters could be deployed to provide information about track geometry relevant to the deviation from uniform profile, but tilt beams are rarely actually deployed.

Tiltmeters can provide faster warning of movements compared to manual and other automated alternatives, and this is one of their main benefits. Fifteen-minute readings are easily achievable with tiltmeters and SAAX, but for AMTS, hourly readings are more realistic. However, developing meaningful alarm limits based on displacement (and not relative rotation) are not possible because the system lacks points of fixity parallel and perpendicular to the rail.

Tiltmeters are most useful for the monitoring of rotation of rigid bodies, such as concrete bridge abutments, diaphragm walls, cantilever walls, tilt of structures, *etc*. But, in "flexible" systems that lack a natural point of fixity, such as a ballasted railroad track, it is essential that the device itself furnishes a point of fixity as part of its design. Each of the other systems has a tangible answer to this issue of point of fixity:

1) The AMTS system achieves this through the confidence interval related to control point network stability, rendering the relative movement data valid.

2) The SAAX achieves this through having one end of the SAA physically outside the construction zone of influence, giving real meaning to the measurements it takes relative to that fixed point.
3) Tiltmeters, if unassisted by a constructed point of fixity such as a chain of tilt beams, is unable to render meaningful data related to total vertical movement of the rail, because translational movements are not detectible with inclination-based devices that lack a point of fixity.

In conclusion, the utility of relative rotation data of individual crossties furnished by wireless tiltmeters is of limited utility given that the main goal of a rail monitoring program is detecting the development of global and vertical displacement, which carries consequences in connection with the parameters in Table 1. In projects with ballasted track, stand-alone tiltmeters will likely produce confusing data, on which it is difficult to base any remedial action.

Part 3: Advantages and Disadvantages

As listed in the abstract, the considerations will include the type of fully automated method, amount of maintenance, achievable reading frequency, engineering unit measured, the ease of data reduction / analysis / evaluation, and the overall risk levels with a particular project.

Part 3a: Installation Method

The installation for the AMTS system involves the attachment of prisms using rail clips to the rail element, the installation of the AMTS unit itself in a suitably fixed location, and the installation of control points that also can be considered points of fixity.

The installation of the SAAX involves laying out the device on the crossties and sliding protective conduit over the device. The “X” orientation is faced vertically, and the set screws are tightened to prevent the assembly from rotating within the conduit. The end is then attached to a point of fixity along the rail outside of the construction zone of influence, and the communication cable is run to the logger.

The installation of tiltmeters typically involves attaching each individual tiltmeter to tilt beams, or less commonly, to crossties at regular spacings without tilt beams, and data is usually collected by wireless cellular gateways.

Part 3b: Amount of Maintenance Required

The AMTS system may require maintenance if there are issues related to the stability of the total station and the control points. When this occurs, it is necessary to relevel and/or to re-baseline the total station to the new control point orientation relative to the new position of the total station. Site maintenance also can be required if the prisms become dirty or if a passing train or other activity on the track damages some of the rail clip prisms; they can be individually replaced.

The SAAX system is likely to require less site maintenance compared than an AMTS system, because its measurement does not depend on the presence of a stable control network, or the total station being level, or line of sight. It also does not depend on the cleanliness of the system. In fact, the SAAX could be buried in snow and still function normally, as previously noted, and the main risk of deploying an SAAX is that track maintenance efforts destroy the sensor if it is not removed prior to maintenance. In connection with Figure 5, it would not have been necessary to make a return trip to the site because the system would have functioned even if buried in snow. As a result, barring destruction of the device and the need to install a new one, the odds of regular site maintenance using SAAX's are lower compared to AMTS.

The tiltmeter system requires maintenance if any of the tiltmeters loses communication to its gateway, and/or if tiltmeters are damaged, they will need to be replaced at higher cost compared to a Rail Clip Prism. The site maintenance demands for wireless tiltmeters are generally more onerous compared to AMTS and SAAX applications. Also, if a large relative rotation is measured without tilt beams deployed, a visual inspection of the rail is sometimes needed because there is not an easy way to evaluate the relative rotation mathematically in connection with relative settlement *nor* the parameters in Table 1, and this contributes to the maintenance effort.

Part 3d: Engineering Unit Measured

As discussed previously, the bulk of monitoring projects utilizing AMTS involve the collection of relative position data between the control points and the monitoring points (and not absolute locations in space). The device takes measurements in the form of horizontal angles, vertical angles, and site distances, which are post-processed into relative displacements in the X, Y, and Z directions. Units rendered are in inches.

Projects involving SAAX typically report changes in shape of the array in units of inches. The calculation involves a chain of "L*sine(theta)" calculations that are made possible by the assumed point of fixity on one end of the SAA. The data output (in degrees) must be converted into relative vertical displacement in inches.

Tiltmeters involve the collection of relative changes in rotation (and not absolute orientation). The engineering units associated with tiltmeters must remain in degrees and not inches, because the device does not have a point of fixity in lieu of tilt beams, and therefore it must report a magnitude of relative rotation, not translation, in most cases.

Part 3e: Ease of Data Reduction

For the purposes of measuring relative settlement, the traditional output of the AMTS system is easily used. The units are in inches, which is the same unit as typical alarm thresholds.

For the purposes of monitoring relative or absolute vertical track deformation parallel to the rail, SAAX system can be used. The output units are in inches, which is the same unit as the alarm thresholds.

In the experience of the authors, the relative rotation data provided by tiltmeters without tilt beams is only useful insofar as it is interpreted as an indication of relative change in crosslevel, and not crosslevel itself (because it is not an absolute measurement), or the difference in cross level. Similarly, given that individual tiltmeters lack a point of fixity, the rotation data cannot provide an indication of uniform translation (*i.e.*, neither absolute nor relative settlement).

Part 3f: Overall Risk Levels of the Project

This section includes considerations that describe prudent measures for higher risk projects involving adjacent or underground construction near railroads.

When projects require a high level of temporal resolution to quickly alert project stakeholders of changes in track geometry, an automated system of measurement may be more practical than using a rail profile vehicle, LIDAR scans, and manual measurements that are too slow.

If measurements of the actual track geometry are needed for the purposes of requesting track maintenance throughout construction, some form of absolute measurement should be taken. From the options that are fully automated, this would include SAAX and horizontal IPI's.

However, despite the above considerations, on projects with a long length of track needing to be monitored (500+ feet), AMTS may be the only cost-effective option.

If site access is difficult, and line of sight is likely to cause problems (such as in rail yards), SAAX may be the only solution that can reliably produce data at the desired intervals, and it should be used despite the higher up-front cost and elevated risk of damage.

On high-risk projects in which it is essential to measure relative displacement not relative changes in crosslevel of individual crossties, it is necessary to implement a solution that can measure translation via an established point of fixity such as the AMTS itself or a fixed end of an inclination-based device.

Conclusion

In the preparation of this paper, and the project experience leading up to its writing, the authors have been immersed in various types of track monitoring techniques and were driven towards this effort to narrow down what truly are the best automated track monitoring methods. The answer to that question is not simple, because it depends on many project-specific factors. It is the authors' hope that the reader will have come to appreciate the complexity and challenge of delivering truly useful track monitoring data that first and foremost, provides data that easily lends itself to mathematical evaluation related to potential track geometry issues, and secondly, that meets both the temporal and spatial resolution of the project. With the track monitoring system properly selected, geotechnical project stakeholders are empowered to inform railroad owners of potential track geometry issues and thereby mitigate geotechnical risk to track geometry. The authors believe that the ongoing evolution of automated track monitoring systems will tend towards identifying *actual* track geometry issues in addition to relative movements of the rail, which today serve as indicators of *potential* track geometry issues but do not furnish information directly related to the track surface maintenance criteria set forth in 49 CFR 213.63.

Sources

1. **https://www.law.cornell.edu/cfr/text/49/213.63**