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PERFORMANCE AND TESTING REQUIREMENTS FOR PORTABLE TRACK GEOMETRY INSPECTION SYSTEMS

This digest summarizes the results of TCRP Project D-7/Task 13, "Performance and Testing Requirements for Portable Track Geometry Inspection Systems." The digest was prepared by Transportation Technology Center, Inc. (TTCI), Pueblo, Colorado. Jerry Malone served as principal author.

SUMMARY

This project investigated portable track geometry measurement systems and their applicability to transit operations and developed performance guidelines and testing requirements for use by transit agencies in evaluating and selecting a portable track geometry system. The research was conducted under TCRP Project D-7 and included the following tasks:

- A review of portable geometry systems currently available,
- Discussions with transit agencies to determine industry needs,
- Development of performance guidelines that can be used by transit agencies to evaluate and validate system performance, and
- Development of test procedures and requirements that can be used by transit agencies to evaluate and validate system performance.

For purposes of this study, a portable track geometry measurement system is considered to be any track geometry measurement system that is not permanently affixed to a conventional rail vehicle. In practice, this means that the geometry system is either mounted to a hi-rail vehicle, or it is a self-contained pushcart-based system.

To review the portable geometry measurement systems currently available, vendors of portable track geometry systems were identified. A 13-page survey was developed and sent to the vendors. The survey focused on the general characteristics of each portable geometry measurement system, as well as those aspects of portable geometry systems most likely to be of special interest to transit agencies or to require special attention in typical transit territory. Measurement accuracy, calibration, data reporting, and exception reporting were also covered. Of the vendors contacted, five completed and returned their surveys.

Data from the manufactures' surveys indicate that the characteristics, features, methods of measurement, and price of their systems vary considerably. All of the systems examined had particular characteristics making them suitable for use by transit agencies. Examples of these characteristics include system performance on paved-in track and girder rail, performance on very tight curves common to transit territory, and the ability to quickly customize the system for use on different lines. A few of the systems offered features of interest only to rail transit agencies, such as the ability to measure third-rail geometry or the flangeway width on girder rail.

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To assess the needs of rail transit agencies in selecting and operating a portable track geometry system, an 11-page survey was developed and sent to North American rail transit agencies. The survey covered the following areas: (a) characteristics of each transit system, (b) how track geometry is currently tested and used, (c) requirements and desired features of a portable geometry system, (d) potential safety issues in using a portable track geometry system, and (e) additional issues or comments concerning portable geometry systems on rail transit systems. Eleven North American rail transit agencies completed and returned the survey. Where more detailed information was needed, rail transit agencies were contacted for additional discussion.

The survey results indicate that transit agencies are currently using a variety of geometry systems, practices, standards, and procedures to gather and process track geometry data. There was general agreement on the importance of particular track parameter data channels as well as general agreement on how a portable geometry measurement system should perform in territory and track designs common to rail transit agencies. Results of this survey were used to determine the features in a portable geometry system that transit agencies need. These needs are discussed in Section 4.

Using information from the vendors and transit agencies, performance guidelines were developed for use by transit agencies in selecting a geometry system and evaluating system performance. These guidelines focus on two critical areas: (1) reproducibility of track geometry measurements and (2) verification of system performance against known standards. A search of the University of Illinois Champagne-Urbana railroad engineering collection yielded publications describing previous research and experience of some relevance to this task; where applicable, this information was used developing performance guidelines. The guidelines are presented in Section 5.

Finally, test procedures and requirements were developed based on the performance guidelines developed. The test procedures and requirements are presented in Section 6.

1 INTRODUCTION

Innovations in technology have led to better, more versatile, and more portable track geometry measurement systems. The research team has investigated various portable track geometry measurement systems and their applicability to transit use, and has developed performance guidelines and testing requirements for use by transit agencies in evaluating and selecting portable track geometry systems. This project included the following tasks:

- A review of portable geometry systems currently available,
- Discussions with transit agencies to determine industry needs,
- Development of performance guidelines that can be used by transit agencies to evaluate and validate system performance,
- Development of test procedures and requirements that can be used by transit agencies to evaluate and validate system performance,

2 PORTABLE SYSTEMS

For purposes of this study, a portable track geometry measuring system is defined as a track geometry measurement system that is not permanently mounted to or affixed to a conventional rail vehicle. In practice, this means that the geometry system is either mounted to a hi-rail vehicle, or it is a self-contained pushcart-based system. Although other portable configurations are certainly possible, hi-rail-mounted and pushcart systems are, at present, the only commercially available portable track geometry systems that produce the traditional track parameter measurement channels that conventional rail-vehicle-mounted track geometry systems produce.

2.1 Improvements in Track Geometry Measurement Technology

In the recent past, most track geometry measuring systems were severely restricted by the requirements of their inertial sensors. The gyroscopes, gyrometers, and inclinometers used had to be located in the passenger compartment of a typical full-sized rail vehicle. This necessitated compensation systems to remove the effects of the dynamics of the truck and suspension from the inertial measurement. Such systems added complexity to the measurement system and made maintenance and troubleshooting difficult.

Modern gyrometers, for example, are smaller and more rugged than their predecessors and can be mounted to the vehicle suspension rather than the car body, eliminating the need for compensation transducers and associated circuitry and thus greatly simplifying the system. These improvements in instrumentation have allowed inertial measurement equipment to be placed much closer to the wheel-rail interface, eliminating the need for compensation systems and increasing system reliability by reducing the number of moving parts. Some vendors are now offering systems equipped with analog or digital fiber-optic gyrometers, which offer improved accuracy over conventional mechanical gyros.

Advances in non-contact distance measurement have simplified the design and improved the reliability of track geometry measurement systems. Laser/sensor-based servo systems eliminated the need for contact gage and alignment measurement. Recently, machine-vision techniques based on line-scan video cameras have superseded even the servo system technologies, allowing measurement of all track parameters without moving parts.

A decade ago, conventional track geometry measurement systems suffered from limitations. They were subject to wear and tear of mechanical components and were initially tied to the suspension of the host rail vehicle, and therefore its characteristics. Today's systems typically have few or no moving parts and usually employ non-contact technology to measure gage and other track parameters (although some portable hi-rail and pushcart systems do use contact measurement systems for gage and other inputs). These improvements, combined with greatly improved processing power, have produced a generation of track geometry measurement systems that have reduced mechanical complexity, are more independent of the vehicle to which they are mounted, and offer greatly improved reliability. They are more compact than previous-generation systems, typically consisting of just a few modules and a computer workstation.

2.2 Improvements in Track Geometry Data Quality

Because of a reduced need for mechanical compensation, reduced dependence on vehicle systems, and greater computing resources, modern track geometry measurement systems deliver higher-quality, more reproducible data and have greater accuracy than could be achieved previously. Improved data quality allows geometry data to be used in such applications as rail-vehicle dynamic modeling with minimal processing.

2.3 Hi-Rail and Pushcart Systems

Improvements such as the elimination of mechanical compensation transducers, introduction of line-scan camera technology, improved gyroscopic measurement technology, and much greater computing resources have facilitated the development of modern portable track geometry measurement systems. Many systems originally designed for use on a conventional rail vehicle are now essentially self-contained and can be mounted on hi-rail vehicles with little or no modification. Other systems were designed *a priori* as portable pushcart-based systems. These systems usually employ mechanical contact measurement techniques. Over the years, pushcart systems have evolved considerably.

3 REVIEW OF CURRENTLY AVAILABLE PRODUCTS

To review the portable geometry measurement systems currently available, vendors of portable track geometry systems were identified. A 13-page survey was developed and sent to each of the vendors. Vendors were asked to fill out a separate survey for each portable product or service they sold or manufactured. The survey focused on the general characteristics of each portable geometry measurement system, as well as those aspects of portable geometry systems most likely to be of special interest to transit agencies or to require special attention in typical transit territory. The survey was divided into the following areas:

1. General information about the vendor,
2. General information about the system,
3. Applicability of the system to transit service,
4. Conclusion and other comments, and
5. Safety concerns.

Response to the survey was generally good. Of the vendors contacted, five completed and returned at least one survey.

3.1 Vendors

The survey was sent to the following vendors:

1. Abtus
2. Andian Technologies, Ltd.
3. Ensco, Inc.
4. ETSelig, Inc.

5. ImageMap, Inc.
6. KLD Labs, Inc.
7. Leica
8. Railcare Advanced Instruments, Inc.
9. Stanley, Inc.
10. Terra International, Ltd.
11. TrackTech, Inc.

These vendors were chosen specifically because they make portable track geometry measurement systems. Many of these vendors also make conventional rail-vehicle-mounted measurement systems or make one system that can be adapted to a variety of vehicles.

Other vendors, not listed above, were contacted, but were excluded from the survey when it was learned that they do not make portable systems.

Some of the vendors provided additional information such as sales literature, plots of data from track geometry test runs, operating instructions, safety certification documents, photos of the system, and other materials. Where appropriate, information and photographs taken from these materials are included in the system descriptions.

3.2 General Survey Results

Data from the manufactures' survey indicate that the characteristics, features, methods of measurement, and price of their systems vary considerably. All of the systems examined had particular characteristics making them suitable for use by transit agencies. Examples of these characteristics include system performance on paved-in track and girder rail, performance on very tight curves common to transit territory and the ability to quickly customize the system for use on different lines. A portable system can be found that meets the needs of practically any transit agency.

4 DISCUSSIONS WITH TRANSIT AGENCIES TO DETERMINE THEIR NEEDS

To assess the needs of transit agencies in selecting a portable track geometry system, an 11-page survey was developed and sent to North American rail transit agencies. The survey covered the following areas:

1. Basic characteristics of each transit system,
2. How track geometry is currently measured and how the data are used,
3. Requirements and desired features of a portable geometry system,
4. Potential safety issues in using a portable track geometry system, and
5. Additional issues or comments concerning a portable geometry system.

Of the North American transit agencies surveyed, 11 were completed and returned. In cases where clarification was required, the transit agency was contacted and issues discussed in greater detail.

Results of the survey are summarized in the sections that follow.

4.1 Track Geometry Measurement Systems in Use by Transit Agencies

The survey asked transit agencies to indicate (1) whether they owned a track geometry system or hired track testing services and (2) what type(s) of systems they used. Results are indicated as follows:

- Six of the 11 transit agencies surveyed own a track geometry measurement system. The vast majority of these transit agencies (five of the six) own a conventional rail-vehicle-mounted system.
- The transit agencies who do not own a track geometry system, all contract out their track geometry testing.
  - Two of the five hire testing services using conventional rail vehicle-based systems.
  - Three of the five hire hi-rail portable systems or pushcart systems or both.
  - One transit agency that owns a conventional system also contracts for hi-rail testing.

One transit agency explicitly indicated a desire to purchase a portable track geometry measurement system in the near future.

4.2 Calibration Practices, Test Practices, and Test Frequency

- The procedures used by transit agencies to calibrate track geometry systems were typically those recommended by the manufacturer, those developed in-house, or those of a third-party contractor. Those transit agencies that own their systems tended to follow the manufacturer's calibration procedure or a closely related in-house calibration procedure. These transit agencies usually calibrated their systems at specific intervals. The intervals given are: once each day, four times each year, twice each year, and once each year. As one would expect, those transit agencies who contracted for track testing services typically left calibration and geometry system maintenance to the contractor.

- Test frequency varied quite considerably. Some transit agencies tested their track once every 5 years, while others tested 26 times per year (every 2 weeks). Those operating heavy rail systems or a combination of heavy, light, and commuter-rail systems tended to test most frequently.
- Transit agencies that owned their own conventional geometry systems tend to test their track far more often (8.5 times more often, on average) than those that contract out their track testing services.
- Like U.S. freight railroads, the majority of transit agencies measure track gage 5/8-in. below the top-of-rail. However, many transit agencies (five of 11) use other gage points or multiple gage points to accommodate differing standards found on different lines. Gage points given in the survey were 1/4, 3/8, 1/2, and 5/8 in., and 10 mm.
- Many of the transit agencies surveyed indicated that they desire mid-chord offset (versine) data for string lining curves and for verifying geometry exceptions.
- Ten of 11 transit agencies survey respondents indicated that they rely heavily on a trained operator to edit exceptions and screen out false exceptions.
- Six of 11 survey respondents indicated that they normally require local supervision or a local track maintainer to ride the geometry car during testing. Most of those not following this practice preferred that a representative from the system engineering department ride the car.

4.3 Track Safety Standards and How Geometry Data Is Used

The transit agencies surveyed typically test track against Federal Railroad Administration (FRA), American Public Transportation Association (APTA), or internal track safety standards. Many test against all three. In addition to track testing, all of the transit agencies surveyed use geometry data for long-range maintenance planning and renewal. Surprisingly, many of the transit agency survey respondents expressed an interest in rail-vehicle dynamic modeling.

- Nine of 11 survey respondents test track to FRA standards.
- Five of 11 survey respondents test to APTA standards.
- Ten of 11 survey respondents test to internal standards.
- All survey respondents use track geometry data for track maintenance planning and renewal.
- Seven of the 11 survey respondents indicated that they use track geometry data for rail vehicle dynamic modeling or would like to do so.

4.4 Location and Exception Identification

- Six of 11 survey respondents indicated their track geometry system used GPS data to determine location and to locate track exceptions. Interestingly, the transit agencies that contracted for testing were most likely to use GPS in addition to manual landmark entry.
- Nine of 11 survey respondents indicated that they use input from a human landmark observer to mark wayside landmarks. (In two cases, the locations of passenger stations were most critical.)
- None of the survey respondents used transponder tags to mark track locations.
- Only one of the survey respondents used paint to mark geometry exceptions. This transit agency is in the processes of phasing out this practice.

4.5 Sampling and Track Parameters

Sampling refers to how often the track parameters are sampled in distance. Typically, this is done once each foot on U.S. freight railroads. While five of 11 transit agency survey respondents use this interval, surprisingly, the rest use quite a range of sample distances; one sample every 2.5, 3, and 10 ft.

Table 1 shows the responses of each transit agency when asked to rate the importance of several common track geometry data channels on a scale of 1 to 10, with "1" being not important at all and "10" being critical to transit agency operations. Several respondents did not rate particular channels.

Table 1 Usefulness of track parameter channels as rated by survey respondents

Track Geometry Data Channel	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8	System 9	System 10	System 11
Gage	10	10	10	10	10	10	10	10	10	10	8
Cross level	10	10	10	10	10	10	10	10	10	10	10
Superelevation	10	10	10	10	10	10	10	10	10	10	10
Curvature	10	10	10		10	10	10			8	9
Alignment Space Curve	10	10			10	1	*			6	0
Alignment over a 62-ft chord	10	10	10		10	10	10		10	9	8
Alignment over a 31-ft chord		10	10	10	10	10	5			9	7
Alignment over another chord length	10				10	1	0		10	1	0
Surface Space Curve	10				10	1	*			6	0
Surface over a 62-ft chord	10	10	10		10	10	10		10	6	8
Surface over a 31-ft chord				10	10	10	10	9		1	7
Variation in Cross level over 62 ft	10	10	10		10	10	10		10	8	0
Variation in Cross level over 31 ft		10		10	10	10	10	8		6	0
Other: (see text)					10						

This was interpreted as indicating they were not familiar with that channel or felt it was of minimal importance. In one case (Transit System 7), the respondent explicitly indicated that they were unfamiliar with two of the channels (marked with asterisks in Table 1). Another of the respondents (System 5) indicated that other channels not listed in the survey were important to their operations; these are "124-ft chord alignment and 10-ft warp." The average rating of these channels is shown in Table 2. While these averages are obviously rough estimates (computed to one decimal place) they are, nevertheless, revealing.

Sampling and track parameter conclusions are as follows:

- The traditional track parameters (gage, superelevation, cross level, and 62-ft mid-chord offset [MCO] alignment) are used by many transit agency survey respondents in geometry testing and are considered most valuable. 62-ft MCO surface, variation in cross level, alignment over 31-ft chord, and curvature ranked lower, but are still relatively important to many transit agencies.
- Survey respondents tend to use *either* 62-ft MCO measurements or 31-ft MCO measurements. While using either chord length is in accordance with the requirements of APTA track safety standards, few transit agencies used both.
- A minority of transit agency survey respondents are using alignment over a different (nonstandard) chord length.

Table 2 Average ratings of track geometry channels

Track Geometry Data Channel	Ave Rating
Cross level	10.0
Superelevation	10.0
Gage	9.8
Alignment over a 62-ft chord	8.7
Surface over a 62-ft chord	7.6
Alignment over a 31-ft chord	7.1
Variation in Cross level over 62 ft	7.1
Curvature	7.0
Variation in Cross level over 31 ft	5.8
Surface over a 31-ft chord	5.2
Alignment Space Curve	3.7
Alignment over another chord length	3.2
Surface Space Curve	2.7

- Many transit agency survey respondents do not use alignment and surface space curves or are unfamiliar with space curve measurements.

4.6 Features of Portable Systems Ranked by Transit Agencies

Several operational and performance-related features of portable track geometry systems were selected as subjects for the survey. Transit agencies were asked to rate the desirability of these features for their operations. Table 3 shows the responses of each transit agency. A scale of 1-to-10 is used in Table 3, with 10 being most valuable and 1 being least valuable. Four of the transit agencies (Transit agencies 3, 4, 5, and 6) did not supply ratings; these transit agencies indicated that they do not currently use a portable geometry system and would not find such a system useful to their operations. These are marked "N/A" in the table. Two of the transit agencies, although they rated the features, indicated that while they do not currently use a portable geometry system, they *would* find such a system useful in their operations. (Note: A blank space indicates that a transit agency did not provide a rating.)

In Table 4, the features are listed in deceasing rank-order by average rating. In computing the averages, transit systems that did not participate in this portion of the survey (Transit agencies 3, 4, 5, and 6) were not counted, whereas a zero was counted for those transit agencies that did not rate a particular feature. A score of 9 was used for the rating of "8 to 10" given by Transit 1. Averages were rounded to a single decimal place.

Accuracy of measurements, accuracy of location data, and purchase price were the three most highly-ranked features. Interestingly, performance in the specific situations most troublesome to transit territory all ranked lower than the more general "accuracy of measurements" and even customer support features such as "ease of operator training." This indicates that good overall performance is more valuable than performance in a particular situation. Transit agencies, it appears, are willing to overlook quirky environmental performance in conditions such as snow or autumn leaves, provided that the measurements are accurate everywhere else.

4.7 Comments by Transit Agencies

Several of the survey respondents provided comments about the desirability, use, and features

Table 3 Importance of features in portable track geometry systems as rated by transit agencies

Feature	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8	System 9	System 10	System 11
Low Initial Purchase Price	8–10	7	N/A	N/A	N/A	N/A	10	9	10	8	10
Reasonable Maintenance Requirements	8–10	10	N/A	N/A	N/A	N/A	10	10		8	10
Availability of Replacement Parts	8–10	10	N/A	N/A	N/A	N/A	10			8	10
Price of Replacement Parts	8–10	10	N/A	N/A	N/A	N/A	10			8	10
Availability of Service	8–10	10	N/A	N/A	N/A	N/A	10	7		10	10
Good User Interface	8–10	10	N/A	N/A	N/A	N/A	10	8		10	10
Ease of Use	8–10	10	N/A	N/A	N/A	N/A	10	10		9	10
Ease of Operator Training	8–10	10	N/A	N/A	N/A	N/A	10	8		8	10
Performance on Tight Curves	8–10	9	N/A	N/A	N/A	N/A	10	7		8	10
Performance on Girder Rail	8–10	9	N/A	N/A	N/A	N/A	10	7		8	5
Performance in Stations	8–10	9	N/A	N/A	N/A	N/A	10			8	8
Performance in Switches	8–10	9	N/A	N/A	N/A	N/A	10	6		8	8
Performance on Embedded or Paved-in Track	8–10	9	N/A	N/A	N/A	N/A	10	7		8	5
Performance in Rain and Snow	8–10	5	N/A	N/A	N/A	N/A	5	6		5	1
Performance in Autumn Leaves	8–10	5	N/A	N/A	N/A	N/A	5	6		5	1
Accuracy of Measurements	8–10	10	N/A	N/A	N/A	N/A	10	10	10	8	10
Accuracy of Location Data	8–10	10	N/A	N/A	N/A	N/A	10	7	10	8	10
GPS Data	8–10	5	N/A	N/A	N/A	N/A	5		10	9	7
Good Curve/Spiral Limit Detection	8–10	10	N/A	N/A	N/A	N/A	10		10	7	9
Minimum Number of Moving Parts	8–10	8	N/A	N/A	N/A	N/A	10			5	7
Quality of Documentation	8–10	10	N/A	N/A	N/A	N/A	10			8	10
Ease of Changing the Gage Point	8–10	8	N/A	N/A	N/A	N/A	10			3	9
Ease of Changing the Chord Length	8–10		N/A	N/A	N/A	N/A	5			3	9
Other: (see text)							10	10		8	

Table 4 Features ranked by average importance

Average Rating	Feature
9.6	Accuracy of Measurements
9.1	Accuracy of Location Data
9.0	Low Initial Purchase Price
8.3	Ease of Use
8.1	Reasonable Maintenance Requirements
8.1	Good User Interface
8.0	Availability of Service
7.9	Ease of Operator Training
7.9	Good Curve/Spiral Limit Detection
7.6	Performance on Tight Curves
7.1	Performance in Switches
6.9	Performance on Girder Rail
6.9	Performance on Embedded or Paved-in Track
6.7	Availability of Replacement Parts
6.7	Price of Replacements Parts
6.7	Quality of Documentation
6.4	GPS Data
6.3	Performance in Stations
5.6	Minimum Number of Moving Parts
5.6	Ease of Changing the Gage Point
4.4	Performance in Rain and Snow
4.4	Performance in Autumn Leaves
3.7	Ease of Changing the Chord Length

of portable geometry systems. These comments are reproduced below.

- [Written in under "Other useful features:"] "Easy to use at night with poor light. Able to run through road crossings and switches." (Transit 7)
- "[A portable system would be helpful,] depending on ability to use." (Transit 2)
- "Any track geometry measurement system must be simple to use and reliable." (Transit 10)
- "[A portable geometry system] would allow for more frequent and/or specific inspections." (Transit 1)
- "Owning a [portable] system could provide some benefits provided initial costs and cost to operate/maintain such a system can be reduced to acceptable levels. Contracting [out this] service allows [us] to benefit from advances in technology and to have experienced operators and interpreters of data." (Transit 10)
- "We don't have the [portable hi-rail] system; we have a contractor supply the system. It is more cost-effective to contract this out." (Transit 9)
- "[We use our] data-logging trolley statically only to check track parameters and test the following: super elevation, distance, warp, gradient, 4.9-ft chord versine." (Transit 11)
- "It [a portable system] could be used to provide a measure of track condition. Repeat runs could be used to see changes over time. This information would be useful to plan future track maintenance." (Transit 7)
- "Repeatability of measurements to allow comparisons of scans taken several years apart." (Transit 10)
- "Portable systems must be of sufficient quality to ensure high repeatability. Ease of use and installation are critical to keep operators proficient. Track geometry is typically measured annually. On a small system with approximately 70 track miles it is unlikely that we can keep staff proficient on such complex equipment. The track geometry measurement system must be capable of recording rail profiles, even on embedded track and [on] curves with restraining rail." (Transit 10)

4.8 Safety Issues

Some of the geometry measurement systems have inherent safety issues that may be of concern to transit agencies. These safety issues were either addressed by the manufacturers or were raised by the transit agencies who participated in the survey. They include the following:

1. Lasers used in optical measurement systems. These are often invisible infrared lasers—typically Class IIIa or IIIb—requiring precaution during operation, troubleshooting, and maintenance. In addition, special protective goggles may be required during troubleshooting and maintenance. Laser safety training may be required for operators and maintainers.
2. The usual safety hazards of hi-rail vehicles: speed, stopping distance, inactive crossing gates, and the possibility of derailment.

3. The ability to remove a portable pushcart system from track quickly and safely especially in conditions of heavy and frequent traffic.
4. Electrical hazards associated with operating in third-rail territory.

Several of the transit agencies provided comments concerning safety. Two of these are:

- "Staying on track. Working near [the] third rail. [The] safety of employees using equipment." (System 2).
- "Times of trains are every 3 to 6 minutes during peak hour. Best time to use portable track geometry is after revenue service." (System 11).

4.9 Summary: What Transit Systems Need

The survey results indicate that transit agencies are currently using a variety of geometry systems, standards, and practices to gather and process track geometry data. There was good general agreement, however, on the importance of performance features and track parameter data channels. There was also good agreement on how a portable geometry measurement system should perform in situations common to rail transit agencies. This agreement was consistent even among those transit agencies not interested in obtaining a portable system. The features generally needed by transit agencies are summarized in the following subsections:

4.9.1 General Interest

- Those transit agencies that operate multiple modes—heavy, light, and commuter rail—typically prefer a conventional geometry system supplemented by a hi-rail-based portable geometry system. A portable system is typically used for situations where flexibility is advantageous.
- Many transit agencies, typically those with single-mode operation, would prefer a hi-rail-based portable geometry system for regular track geometry testing.
- Some transit agencies prefer pushcart-based geometry systems for quick on-the-spot testing of track geometry in territory of interest, typically to supplement regular geometry testing by a conventional or hi-rail-based geometry measurement system.
- Many pushcart systems can be used for right-of-way surveying in addition to track geometry measurement. Transit agencies that do extensive surveying of their rights-of-way, to obtain clearance data, for example, may be interested in pushcart-based portable systems for this reason.

4.9.2 Advantages of Portable Geometry Systems

- Ability to get on and off of track quickly, offering a very significant savings in time over conventional geometry testing
- Less interruption of traffic than conventional geometry testing
- Generally costs less to operate and maintain than a conventional geometry vehicle
- Easy and quick inspection of specific sites of interest
- Easier surveying of right-of-way and clearance

4.9.3 Disadvantages of Portable Geometry Systems

- No dynamic load is applied to the track.
- A conventional geometry system, operated by a trained crew and testing on a regular schedule, might give somewhat more consistent results than spot checks with a portable system.
- Operation of a conventional geometry system on a regular passenger route might be easier to manage than a portable system.

5 PERFORMANCE GUIDELINES TO EVALUATE AND VALIDATE SYSTEM PERFORMANCE

The following guidelines will be useful in evaluating and selecting a system.

5.1 Required Features

- The geometry system should sample data at least once every foot or four times per meter.
- The geometry system should be capable of displaying data in either imperial or metric units, with the ability to display historical data and locate track exceptions while data is being collected. Distance should be measured and displayed in units of miles/feet or kilometers/meters.

- The geometry system should be capable of measuring and displaying curvature in units of degrees per 100 ft of arc or as a radius (in feet or meters).
- The gage point should be easily changeable by the operator and displayed on the operator's workstation.
- The geometry system should be capable of measuring at least the following track parameter data channels:
  - Track Gage
  - Cross level
  - Superelevation
  - Curvature (degrees or radius)
  - Lateral Alignment, 62-ft MCO (or metric equivalent)
  - Lateral Alignment, 31-ft MCO (or metric equivalent)
  - Lateral Alignment Space Curves, of user-definable cutoff wavelength
  - Vertical Alignment (Surface), 62-ft MCO (or metric equivalent)
  - Vertical Alignment (Surface), 31-ft MCO (or metric equivalent)
  - Vertical Alignment Space Curves, of user-definable cutoff wavelength
  - Variation in Cross level over 62 and 31 ft
  - Lateral and Vertical
  - Gradient
- The system should measure all channels at least to the accuracies, as Table 5 shows.
- These are intended to serve as guidelines and represent minimum accuracies; many systems are an order of magnitude or greater than these.
- The chord lengths used in computing the lateral and vertical alignment data should be adjustable. MCO data channels should be available in both biased and de-biased form.
- The characteristics of lateral and vertical space curve data should be adjustable by the user. These settings should be recorded in geometry data file.
- For transit agencies that intend to use geometry data for dynamic modeling, the following should be required:
  - Space curve channels (lateral and vertical) should be available and filter cutoffs should be adjustable by the user
  - Lateral alignment track center space curve
  - Vertical alignment track center space curve
  - These channels should be either available directly or easily calculated if system is to be used for dynamic modeling
- GPS, supplemented by odometer/tachometer input, should be an integral part of the geometry system. GPS location should be recorded with each data record.
- The ability to display and record custom channels is important to some transit operations and might be made available as options, as they usually require additional hardware and software. Examples of custom channels include:
  - User-defined chordal offsets
  - Catenary and/or third-rail geometry
  - Flangeway width
- The geometry system should include a flexible display program that allows operators to change data channel scaling, position, and trace color with standard settings for various transit lines on which the system will be used.
- Options should be available for entering landmarks manually or with a route database indexed to GPS data to manually enter landmarks. This should include automatic entry and reporting of track class and locations where

Table 5 Recommended minimum accuracies for geometry data channels

Channel	Accuracy
Gage	+/– 0.5 mm
Cross level	+/– 2 mm
Superelevation	+/– 2 mm
Curvature	+/– 0.1 deg
Lateral Alignment Space Curve (each rail)	+/– 5 mm
Lateral Alignment Space Curve (track center)	+/– 5 mm
Lateral Alignment Midchord Offset (each rail)	+/– 3 mm
Surface Space Curve (each rail)	+/– 5 mm
Surface Space Curve (track center)	+/– 5 mm
Surface Midchord Offset (each rail)	+/– 3 mm
Variation in Cross level in 62 ft	+/– 3 mm
Variation in Cross level in 31 ft	+/– 5 mm
Variation in Cross level in other length	+/– 5 mm
Twist	+/– 3 mm
Warp	+/– 3 mm
Speed	+/– 0.1 KPH

track class changes, if possible. Synchronization to automatic location detector (ALD) or transponder inputs is not generally used by transit agencies but could be made available as options.

- Track class should be easily changeable during the test, preferably indexed to a route database and manually by operator. The operator's software should indicate all exception threshold limits for all track parameter channels displayed.
- The geometry system should have the ability to simultaneously test track to FRA, APTA, and internal track safety standards. At a minimum, the system should be able to switch between these standards for reporting purposes. All classes should be available, possibly with restricted speed restrictions.
- The geometry system software should allow the operator to edit all track geometry exceptions before final reporting. The editor should save a copy of the original, unedited exceptions, have rich text-editing features, and allow the operator to enter annotations for each exception.
- The geometry system software should produce clear and concise exception reports. Track class and the track standards should be indicated on the report. All exceptions (FRA, APTA, or internal) should be tagged by GPS location.
- The exception report should include at least the following:
  - A unique daily exception sequence number
  - Length of the exception
  - Threshold crossing locations
  - Maximum value
  - Location of maximum value (track location)
  - GPS location of maximum value
  - Location of nearest landmark
- The ability to archive geometry data, track exceptions, and make geometry data available for long-term maintenance planning. Software to read geometry data should be available to personnel in the engineering/maintenance-of-way department for these purposes.
- The manufacturer should specify the sign convention used in computing each channel. Surprisingly few manufacturers do this. For example, on some systems a feature with positive polarity in the surface channels indicates a depression or dip in the track, while in others it indicates a rise or bump in the track. The sign conventions used in surface, lateral alignment, curvature, cross level, and superelevation should be specified.
- For pushcart systems used in surveying, total station should be considered for transit agencies that wish to combine geometry with survey mapping.

5.2 Reliability, Service, Calibration, and Training

- The geometry system should function reliably under conditions ranging from almost continuous use to occasional use.
- Calibration procedures and frequency should be provided by the manufacturer. Clear distinctions should be made between the levels and types of calibration; for example, annual, monthly, and weekly maintenance calibration procedures should be distinguished from daily spot-checks of track geometry values, if such checks are required.
- Field service should be quick and simple, typically involving rapid changeout of functional modules. The geometry system should require a minimum of field service.
- The manufacturer should provide standard operating procedures for geometry system operators. The procedures should include some basic information on distinguishing valid exceptions from glitches caused by track conditions (while operators will naturally acquire considerable expertise in this area, engineering supervision and local track personnel will have much less experience in making these distinctions. It would be helpful for all to have information from the manufacturer to use as guidelines when issues arise in interpretation of geometry data).

5.3 Performance in Special Conditions

A geometry system should give reasonable performance in special situations and track conditions. Some of these conditions are listed below. It is unreasonable to expect a geometry system to perform perfectly under all of these conditions; however, if a particular condition causes corruption in one or more geometry data channels, the manufacturer should note this. An experienced user should be able to spot and mark the corrupted data and edit out or annotate exceptions caused by the corrupted data.

The following should not significantly affect system performance:

- At-grade road crossings
- Lightly ballasted-in or paved-in track
- Long at-grade road crossings
- Switch points
- Girder rail
- Guard rail (restraining rail)
- Steep grades
- Lubricated rail
- Tight curves

The following may affect system performance:

- Frequent stops and low-speed testing
- Switch frogs
- Crossing diamonds
- Ballasted-in or paved-in track, where the flangeway is not visible

Geometry systems that have optical non-contact rail position/rail profile measurement systems have special requirements. Non-contact optical systems should not be significantly affected by:

- Light rain
- Light snow
- Sun glare

Optical measurement systems, however, cannot reasonably be expected to perform in the following conditions:

- Heavy rain
- Heavy, blowing snow
- Heavy snow accumulation in the track gage (causes glare)
- Snow built up on the gage face of one or both rails
- Heavy, blowing autumn leaves
- Debris or trash accumulation in the track gage
- Unusually bright sun glare

Contact gage systems should perform equally in any of these conditions.

5.4 Safety Issues

- For geometry systems equipped with Class III or higher lasers, special training should be provided for operators and maintainers. Safety interlocks should be an integral part of such systems.
- Procedures for quickly and safely removing a pushcart system from the track should be provided by the manufacturer.

6 TEST PROCEDURES AND REQUIREMENTS TO EVALUATE AND VALIDATE SYSTEM PERFORMANCE

The test procedures outlined here can be useful in evaluating geometry system performance. Practical tests for repeatability and accuracy are presented.

6.1 Repeatability, Accuracy, and Linearity

6.1.1 Repeatability

Repeatability is the ability of a geometry system to substantially reproduce the same geometry measurement of a given length of track over repeated runs. Repeatability is, perhaps, the most important characteristic of a portable track geometry system; for most transit agencies, a geometry system with acceptable repeatability will meet all of their geometry testing needs. Repeatability is relatively simple to measure.

6.1.2 Accuracy

Accuracy differs from repeatability and should not be confused with it. Accuracy is the difference between what the system measures and a fixed, known standard measurement. System manufacturers should and often do provide absolute accuracy specifications. Sometimes manufacturer-supplied accuracy specifications are the result of meticulous measurement; sometimes they are estimated, based on how errors propagate through their system; other times they are estimated based on educated guesses.

6.1.3 Linearity

Linearity is the ability of a geometry system to reproduce identical changes in an input channel over the entire range of measurement of that channel. A system's linearity depends on the type of sensors used and the system's internal processing. Calibration procedures are designed to scale sensor data in such as way as to produce an unbiased, linear output. Carefully following the manufacturer's calibration procedures is the best way to maintain system linearity.

6.2 The Importance of Calibration

It is essential that operators and maintainers of track geometry systems be given very thorough training in system calibration. A system that is calibrated incorrectly will likely be inaccurate, will possibly be nonlinear, and may not produce repeatable data.

Contractors or transit agencies occasionally develop in-house calibration procedures that differ substantially from those provided by the manufacturer. If these are found to be more effective than those provided by the manufacturer, it might indicate that a transit agency has discovered a potential problem with the geometry system or has found a time-saving short-cut. The manufacturer should be informed of the new procedure and an analysis carried out to ensure it does not distort system accuracy or linearity.

It is important to distinguish between a manufacturer's calibration procedures and routine measurement verifications. A calibration procedure typically involves making zero and span adjustments (on contact systems) or reading optical targets to linearize a camera's field of view (on optical systems) and should be carried out at the manufacturer's specified intervals. Some transit agencies and freight railroads take *measurement verifications* during routine testing. Measurement verifications involve comparing the superelevation and gage readings to manual readings taken with a track level gage. They are usually done periodically during testing to check agreement of the geometry superelevation and gage channels with readings taken from a track level and to debias these channels when necessary. Measurement verifications affect only the bias in these channels; they do not affect gain, nor do they affect linearity. Measurement verifications are not a substitute for a full system calibration.

Occasionally, small biases will suddenly appear in the gage channel of an optical measurement system. These are usually caused by a change in the rail type, a change in rail reflectivity due to the presence of rust or scale, or the appearance of a rail lip that interferes with the rail image. These conditions can be found and compensated for with measurement verifications.

Measurement verifications, when properly used, may also compensate for thermal drift in a geometry system's superelevation and gage channels. They may also help convince skeptical track maintainers and personnel new to automated geometry measurement that the geometry system is producing valid data.

An inherent problem with frequent measurement verifications is that the track level gage used to make the measurements (usually an aluminum tube with a mechanical gage scale and spirit level indicator for superelevation) typically has much less accuracy than the geometry system itself. Conducting measurement verifications with an off-the-shelf track level will tell you a good deal about the accuracy and repeatability of the level itself, but will tell you very little about the geometry system whose measurement is to be verified.

When measurement verifications are practiced as part of a regular geometry inspection procedure, it is essential that the instrument used to read gage and superelevation have accuracy and repeatability at least as great as the geometry system being verified. This might be as simple as adding a high-quality temperature-compensated machinist's digital readout unit (DRO) to a track level; alternatively, a custom track level may be fabricated and equipped with a long DRO unit to measure the full track gage at the 5/8 in. gage point and an inclinometer to measure superelevation. The system should be run in simulate mode to clear all buffers before taking gage and superelevation readings for verification purposes.

6.3 Biases in Gage and Superelevation

Most portable geometry systems make provision for user entry of gage and superelevation readings. In several systems, these channels are, in fact, the only track parameters that the user may directly enter. All other channels are derived from them and from inertial sensors.

Gage and superelevation (as well as cross level) often suffer from bias. Small changes in measured value due to drift, typically of the order of 1.0 mm or less may result from thermal drift in the electronic systems used in the geometry measurement system. Manufacturers should specify the amount of drift that can be expected in the gage and superelevation channels. Drift may also be caused by the mechanical properties of the system, or, in the case of systems that use video cameras to measure gage and rail position, by changes in ambient lighting conditions or reflectivity of the rail surface, iris settings, and similar artifacts and limitations of the system design. In systems such as these, improper lighting conditions may introduce systematic error. An important duty of the system operator is to adjust the irises of cameras used on these systems. If the light level is not adjusted correctly, bias will be introduced. This is a skill that must be learned by the operator.

Alignment space curve and MCO data are most likely to show problems, as they require the most processing, being computed from practically every sensor in the system. These channels should be checked for repeatability first.

6.4 Tests for Repeatability

Before conducting any of the tests provided here, it is essential that the geometry measurement system under consideration be properly calibrated. The manufacturer's calibration procedures and schedules must be closely followed and strictly adhered to. It is assumed that the geometry system to be evaluated has been fully calibrated using the manufacturer's recommended calibration procedure.

Often, repeatability is the only practical test of track geometry system performance available to a transit agency. A high degree of repeatability usually indicates that a system does not suffer significantly from thermal drift. Repeatability does not imply accuracy, but lack of repeatability does imply lack of accuracy.

Factors which influence repeatability include speed, travel direction, system settings, and system calibration. A minute amount of random noise is introduced in the process of sampling analog signals; it is possible that this noise could influence repeatability as it propagates through the system. One of the most important factors influencing repeatability is phase differences in distance measurement. Distance is typically measured with a tachometer affixed to an axle; tachometer pulses are then counted to determine distance. It is difficult to synchronize sampling so that this process occurs exactly the same way every time a track is tested. Fortunately, most geometry software allows users to manually shift geometry data so that it lines up with previously recorded data.

6.4.1 Static Repeatability

Static repeatability can be tested using simulated vehicle motion. Gage and superelevation should be tested in this manner; other channels, such as alignment, cannot be tested this way because the simulated speed input does not allow proper compensation of gyrometers.

1. Select a good piece of tangent track with little or no rail head wear, good tie condition. Place the system on the track, and take geometry readings while simulating test vehicle motion. All geometry channels should be constant.
2. Calculate the mean and variance of the gage and superelevation data. This can be done by exporting the geometry data to a spreadsheet or text file or by using the software supplied by the manufacturer.
3. Any variation greater than bit flutter in the least significant bit of the gage channel indicates a potential lack of repeatability. The variance should be recorded for reference; small values of variation are acceptable.
4. Small variations in the superelevation channel data may be caused by operator-induced vehicle motion or vibration from the engine, depending on how the system is configured. These sources of noise should be systematically eliminated. A somewhat larger variance than bit flutter is acceptable in the superelevation. Record the variance for reference.
5. If the system has an optical, non-contact gage system, the variance in gage should be measured with the irises in various positions and the range of gage output noted.
6. The test should be repeated for different simulated speeds, if this is possible.

6.4.2 Dynamic Repeatability

Dynamic repeatability is the most common and most practical test of any track geometry system. This test applies to all of the geometry channels and gives a good indication of how speed-independent the measuring system is.

1. Select a section of good-quality track, approximately 2 miles long. The track should contain moderate to severe (3 degrees or more) reverse curves (an S-curve), preferably with compound curvature, and be banked (i.e., have superelevation). The test tack should have no grade crossings or special track work. No track maintenance should have been performed within the previous 3 months. Mark the start and end points.

2. At least two runs (one forward and one in reverse) should be made through the curves to exercise the track before the test begins.
3. Run through the curves (first forward, then in reverse) at 10 mph or the lowest speed that the gyro package can handle.
4. Overlay data collected from the forward and reverse runs. This collection can usually be done with software supplied by the vendor. It may be necessary to shift the data slightly to obtain optimal synchronization.
5. The traces from each test run should overlay almost exactly. Pay particular attention to superelevation, curvature, and gage; almost no variation should be noticeable in these channels between runs. Slight variations may be noticeable in the alignment channels, as these undergo significantly more processing.
6. Repeat the test runs at higher speeds, incrementing the speeds by 10 mph each run, until the maximum test speed or track speed is reached.
7. Tests made at various speeds should overlay almost exactly. Lack of agreement between runs often indicates trouble with the inertial sensors, lack of calibration in the inertial sensors, incorrect parameter settings in the system, or failing components in the inertial sensors.

6.5 Test for Accuracy

It must be emphasized once more that repeatability does not indicate or imply accuracy, but lack of repeatability may indicate lack of accuracy.

The overall measurement accuracy of a geometry system depends in a complex way on the individual accuracies of the sensors and subsystems that comprise the geometry system. Different channels will have different accuracies. Because of the way that errors propagate through the system, channels that receive relatively little processing, such as gage, can, in general, be expected to have greater accuracy than channels that are derived from many processes, such as alignment.

While quoted accuracies provided by manufacturers give a reasonable indication of accuracy, it must be remembered that these accuracies have likely been obtained in different ways and may not be directly comparable; some are quoted to two decimal places; others to only one. Some manufacturers provide far more extensive information than others; for example, one manufacturer conducted a very thorough analysis of not only repeatability and accuracy, but linearity, and reversibility. All manufacturers would do well to follow this example.

6.5.1 Static Test Track

A geometry system can be tested for accuracy on a quality piece of track of known characteristics and possibly with known dynamic response, although dynamic response is generally not a significant concern for operation of portable systems. As an added benefit, this track can be used to set the gage and superelevation values before a test; this is a far more accurate method than using a track level.

1. Select a piece of concreted-in slab track to be used as a test track. Ideally, the test track should be in a sheltered area, indoors, such as an unused side track in an underground station or paved-in track in a shop floor. Temperature and humidity should be relatively constant and the track should not be used for any other purpose. The rail should be of reasonable profile and have a uniform color and surface texture (typically fine rust or scale is acceptable and even desirable for many non-contact systems).
2. Track gage and superelevation (cross level) should be measured with surveying instruments to a precision of at least one significant figure more than is used by the geometry system (typically 0.10 mm or better, if possible). The gage should be measured at the gage point.
3. The geometry system is parked and stored on the test track. The test track's known gage and superelevation are entered before each test and verified after each test.
4. Static repeatability tests performed on the test track are used to determine system accuracy. With the portable system parked on the test track and with the known gage and superelevation values entered, run the system in simulate and note the variance of these measurements. Two standard deviations (twice the square root of the variance) is a good estimate of the variance.
5. For further analysis, several minutes of data can be collected with the system running in simulate mode at a slow speed. A histogram

can be used to estimate the probability distribution of the gage and superelevation data. This can be done in a spreadsheet or by statistical analysis software.

6. For non-contact systems, this procedure should be carried out for several different settings of the camera irises (if applicable), varied both individually and together. This process should give the user a very good idea of the system's accuracy.
7. The long-term characteristics of the test track can be monitored with LVDTs and data loggers or similar instrumentation.
8. If the system is a hi-rail system, this procedure should be repeated with the hi-rail engine running and with the engine off. There should be very little observable difference, if any.

6.5.2 Gage Fixture

A simple constant-gage fixture can be built for measurement and verification of gage for most non-contact optically measured gage systems. In many situations, a gage fixture provides better results than can be obtained with a track level.

The fixture is constructed so that its ends rest on the rail heads, joined by an aluminum bar in the track gage. Distance between inside surfaces is either 56.0 or 56.25 in., depending on system gage and should be measured to two decimal places. Gage face surfaces should be painted with primer to simulate rust on the rail. The fixture can be carried on the geometry vehicle for measurement verification.

6.6 Statistical Tests

It is usually not necessary to apply statistical tests to geometry data to make comparisons or determine equivalency of measurement unless different types of geometry systems are being compared (i.e., an older design to a new design or a contact system to a non-contact system). In this case, a Student's *t*-test can be used to verify that the measurements are identical to a specified confidence level.

6.7 Data Analysis Tests

Some simple tests can be done to verify that data collected from a track geometry system are self-consistent.

After collecting some geometry data, export the data to a text file and read it into a spreadsheet program. Subtract the lateral alignment space curve channels and compare the result to the gage channel data (if the signs do not agree, subtract the space curve channels the other way: either left minus right or right minus left will work, depending on the sign convention used by the system). These data may not agree because of (1) high-frequency content in the gage channel or (2) bias seen in the gage or alignment difference. The bias can be more accurately determined by averaging both the gage and the alignment difference and comparing. Sources of bias include operator verification error, light level (in optical systems), and drift. The differences in frequency content are caused by internal processing characteristics of the system, although sometimes these are adjustable.

In a similar manner, the surface space curves can be subtracted and compared to the cross level and superelevation data. Any observed biases in the superelevation are likely caused by operator error in entering spot-check superelevation values.

These tests will not work with midchord offset data, as the additional filtering applied to MCO data will exaggerate certain frequencies and attenuate others.

6.8 Perturbed Test Tracks

The most definitive way to measure system reproducibility and accuracy under controlled dynamic conditions is by using a calibrated test track.

A transit system can construct perturbed track zones for the purpose of geometry system verification. Test zones can be constructed on seldom-used track, and should include at least one surface perturbation and one lateral perturbation, of approximately 0.75 to 1.0 in. amplitude and wavelength of approximately one passenger car length. Plywood (vertical) or steel plate wedge shims and oversized tie plates (lateral) can be used for this purpose. Once installed, the perturbation section should have traffic run over it to settle the track. It should be surveyed several times each year to get a precision measurement of the perturbation and seasonal variation. A portable geometry system is run over the perturbed track at several different speeds and results compared to the survey results. Runs should be consistent (repeatability) and agree with the survey (accurate).

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