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TRACK GEOMETRY MEASUREMENT SYSTEM

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16. Abstract

This report describes the Track Geometry Measurement System (TGMS) developed for the Department of Transportation under contract no. DOT-TSC-1367. This report also contains a summary of the results of the test program that was conducted to validate the TGMS under various static and dynamic conditions.

The TGMS has the capability to measure or derive gage, crosslevel (superrelevation), warp (twist), curvature, maximum operating speeds for curves, vehicle speed and elapsed distance at speeds from near 0 to 30 mph. The TGMS is equipped with an automatic location detection system to accurately reference detected track geometry exceptions to permanent fixtures of the track roadbed. The track geometry measurements are compared to the Federal Railroad Administration Track Safety Standards and all detected exceptions are reported in real time by the onboard digital computer.

17. Key Words
Track Geometry Measurement System, Gage, Crosslevel, Superelevation, Warp, Twist, Curvature, Limiting Speed, Track Safety Standards

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PREFACE

The following members of the project staff at ENSCO, Inc. are to be commended for their significant contributions to the development of the track geometry measurement system: Mr. Patrick L. Boyd for the design of the mechanical aspects of the sensor assemblies and hydraulic control subsystem, Mr. Jon S. Rucker for the design of the analog processing subsystem, Ms. Laura J. Simkins, for the design of the computer algorithm, and Mr. Joseph P. Zaiko for the design of the digital control subsystem.

I would also like to acknowledge the contributions made by the following two members of the support staff at ENSCO, Inc.: Mr. Raymond J. Bazan for his assistance in ensuring that the technical documentation satisfied contractual specifications and Ms. Ann C. Champlain for her secretarial support throughout the duration of the project.

Finally, the cooperation and assistance provided by Mr. Paul J. Poirier, technical monitor, and Mr. Thomas F. Hayes, vehicle operator both of the Transportation Systems Center - during the testing and evaluation of the track geometry measurement system are gratefully acknowledged.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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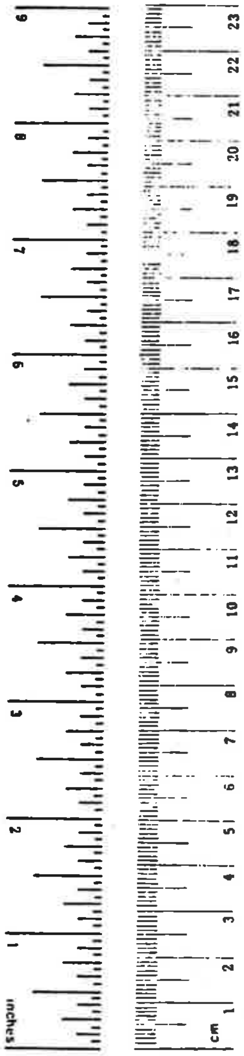
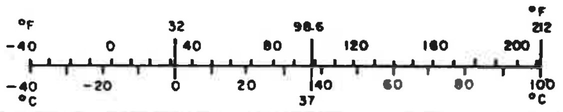
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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LIST OF ACRONYMS

ADB	Analog Data Bus
ALD	Automatic Location Detector
A/D	Analog to Digital
CAS	Compensated Accelerometer Sensor
DCU	Digital Control Unit
DDB	Digital Data Bus
DOT	Department of Transportation
D/A	Digital to Analog
EPROM	Erasable Programmable Read Only Memory
FRA	Federal Railroad Administration
TGCC	Track Geometry Control Console
TGMS	Track Geometry Measurement System
TGU	Track Geometry Unit
TSC	Transportation Systems Center
TSS	Track Safety Standards

1. INTRODUCTION

Track defects are one of the major factors contributing to train accidents.[1] A recent congressional evaluation of railroad safety has revealed that track defects represent approximately 40 percent of the four major classifications of train accidents.[2] With the ultimate objective of ensuring safe operating conditions on the nation's railroad system, the United States Department of Transportation (DOT) has established a set of Track Safety Standards (TSS) which provide "...minimum safety requirements for railroad track that is part of the general railroad system of transportation."[3]

To insure carrier compliance with the TSS in the most efficient manner, the Federal Railroad Administration (FRA) has sponsored the development of rail-bound and hy-rail type vehicles equipped with instrumentation to detect both external track geometry and internal rail flaw type defects. The latest rail-bound track inspection vehicle, T-6, containing both track geometry and rail flaw inspection instrumentation was developed by ENSCO, Inc. under contract to the FRA.[4] The primary goal with the high speed rail-bound vehicles is to inspect mainline track geometry and rail flaw instrumentation systems. These vehicles provide a more cost-effective way to inspect secondary or branch-line track.

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[1] Shulman, A.E. and Taylor, C.E., "Analysis of Nine Years of Railroad Accident Data: 1966-1974," Association of American Railroads Report No. R-233, April 1976.

[2] "An Evaluation of Railroad Safety," Congress of the United States, Office of Technology Assessment, OTA-T-61, LC 78-600051, May 1978.

[3] United States Code of Federal Regulations, Title 49, Transportation, Part 213, Track Safety Standards.

[4] Yang, Ta-Lun, "Significant Developments in FRA Test Cars, As Exemplified by T-6," ENSCO, Inc., October 1977.

The objective of the project to be discussed in this report was to design, develop, test and document the hardware and software for a Track Geometry Measurement System (TGMS) which would satisfy the specifications set forth in contract number DOT-TSC-1367. The TGMS was to be configured for installation on the latest FRA/TSC hy-rail track inspection vehicle. The TGMS has the capability to measure or derive gage, crosslevel (superelevation), warp (twist), curvature, maximum operating speeds for curves, speed and distance at speeds from near 0 to 30 mph. The TGMS is equipped with an automatic location detection system to accurately reference detailed track geometry exceptions to permanent fixtures of the track roadbed.

Provisions are incorporated into the design of the TGMS to permit the system operator to enter the following supplemental information manually: milepost number, track class, track type, track number, location number and message number. The TGMS is also equipped with self-test features to permit the system operator to verify that the digital computer and a majority of the peripheral devices are functioning correctly.

Special provisions have been incorporated into the design of the TGMS for future installation of profile and alignment instrumentation. The track geometry measurements are compared to the FRA TSS thresholds and all exceptions are listed in real time by the onboard digital computer. Measured and derived track geometry parameters are also available for display on a stripchart or other similar recording devices. A photograph of the FRA/TSC hy-rail vehicle on which the TGMS was installed is shown in Figure 1.

FIGURE 1. FRA/TSC HY-RAIL TRACK INSPECTION VEHICLE

2. DEFINITION OF SYSTEM MEASUREMENTS

The portions of the FRA TSS that are applicable to TGMS are reprinted in Figure 2. These standards appear in the United States Code of Federal Regulations, Title 49, TRANSPORTATION, Part 213, revised as of 1 October 1975. The TGMS as configured does not provide measurements of alignment and profile; therefore, the deviations listed in paragraphs 213.55 and 213.63, A and B, are not applicable to this configuration of the TGMS. All other track geometry measurements in the FRA TSS are provided as listed below:

1. Gage, ¶ 215.53 a., b.
2. Crosslevel (Superelevation), ¶ 213.57 a.
3. Maximum Operating Speed for Curves, V_{MAX}, ¶ 213.9 a., 213.57 b., and 213.59 a.
4. Track Surface, ¶ 213.63
   - C. Deviation from designated elevation on spirals where designated elevation is defined in the TGMS as the average value of elevation 50 feet on either side of the measurement point.
   - D. Deviation in crosslevel on spirals is defined in the TGMS as the difference in crosslevel between two points 31 feet apart.
   - E. Deviation from zero crosslevel at any point on tangent or from designated elevation on curves between spirals.
   - F. Variation in crosslevel between any two points less than 62 feet apart on tangents and curves between spirals.

The following supplemental information is provided to properly evaluate and locate track geometry anomalies. Provisions are

§ 213.9 Classes of track: operating speed limits.

(a) Except as provided in paragraphs (b) and (c) of this section and §§ 213.57(b), 213.59(a), 213.105, 213.113(a) and (b), and 213.137(b) and (c), the following maximum allowable operating speeds apply:

Over track that meets all of the requirements prescribed in this part for-	The maximum allowable operating speed for freight trains is-	The maximum allowable operating speed for passenger trains is-
Class 1 track...	10 m.p.h.	15 m.p.h.
Class 2 track...	25 m.p.h.	30 m.p.h.
Class 3 track...	40 m.p.h.	60 m.p.h.
Class 4 track...	60 m.p.h.	80 m.p.h.
Class 5 track...	80 m.p.h.	90 m.p.h.
Class 6 track...	110 m.p.h.	110 m.p.h.

§ 213.53 Gage.

(a) Gage is measured between the heads of the rails at right angles to the rails in a plane five-eights of an inch below the top of the rail head.

(b) Gage must be within the limits prescribed in the following table:

Class of track	The gage of tangent track must be-		The gage of curved track must be-	
	At least-	But not more than-	At least-	But not more than-
1......	4'8"	4'9 3/4"	4'8"	4'9 3/4"
2 and 3	4'8"	4'9 1/2"	4'8"	4'9 3/4"
4......	4'8"	4'9 1/4"	4'8"	4'9 1/2"
5......	4'8"	4'9"	4'8"	4'9 1/2"
6......	4'8"	4'8 3/4"	4'8"	4'9"

§ 213.55 Alinement.

Alinement may not deviate from uniformity more than the amount prescribed in the following table:

Class of track	Tangent track The deviation of the mid-offset from 62-foot line[1] may not be more than-	Curved track The deviation of the mid-ordinate from 62-foot chord[2] may not be more than-
1.......	5"	5"
2.......	3"	3"
3.......	1 3/4"	1 3/4"
4.......	1 1/2"	1 1/2"
5.......	3/4"	5/8"
6.......	1/2"	3/8"

[1] The ends of the line must be at points on the gage side of the line rail, five-eights of an inch below the top of the railhead. Either rail may be used as the line rail, however, the same rail must be used for the full length of that tangential segment of track.

[2] The ends of the chord must be at points on the gage side of the outer rail, five-eights of an inch below the top of the railhead.

§ 213.57 Curves; elevation and speed limitations.

(a) Except as provided in § 213.63, the outside rail of a curve may not be lower than the inside rail or have more than 6 inches of elevation.

(b) The maximum allowable operating speed for each curve is determined by the following formula:

$$V\ max = \sqrt{\frac{Ea + 3}{0.0007D}}$$

where

V max = Maximum allowable operating speed (miles per hour).

E a = Actual elevation of the outside rail (inches).

D = Degree of curvature (degrees).

FIGURE 2. FEDERAL RAILROAD ADMINISTRATION TRACK SAFETY STANDARDS

§ 213.59 Elevation of curved track; runoff.

(a) If a curve is elevated, the full elevation must be provided throughout the curve, unless physical conditions do not permit. If elevation runoff occurs in a curve, the actual minimum elevation must be used in computing the maximum allowable operating speed for that curve under § 213.57(b).

(b) Elevation runoff must be at a uniform rate, within the limits of track surface deviation prescribed in § 213.63, and it must extend at least the full length of the spirals. If physical conditions do not permit a spiral long enough to accommodate the minimum length of runoff, part of the runoff may be on tangent track.

§ 213.63 Track surface.

Each owner of track to which this part applies shall maintain the surface of its track within the limits prescribed in the following table:

Track surface	Class of track					
	1	2	3	4	5	6
A. 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"	1/2"
B. The deviation from uniform profile on either rail at the midordinate of a 62-foot chord may not be more than...........	3"	2 3/4"	2 1/4"	2"	1 1/4"	1/2"
C. Deviation from designated elevation on spirals may not be more than...	1 3/4"	1 1/2"	1 1/4"	1"	3/4"	1/2"
D. Variation in cross level on spirals in any 31 feet may not be more than...........	2"	1 3/4"	1 1/4"	1"	3/4"	1/2"
E. Deviation from zero cross level at any point on tangent or from designated elevation on curves between spirals may not be more than...	3"	2"	1 3/4"	1 1/4"	1"	1/2"
F. The difference in cross level between any two points less than 62 feet apart on tangents and curves between spirals may not be more than...	3"	2"	1 3/4"	1 1/4"	1"	5/8"

FIGURE 2. FEDERAL RAILROAD ADMINISTRATION TRACK SAFETY STANDARDS (CONT.)

incorporated into the system to permit the system operator to manually enter:

1. Milepost Number

   A three-digit designation corresponding to the milepost marker identification numbers.

2. Track Class

   A one-digit designation indicating the posted FRA TSS track class,i.e., 1 through 6.

3. Track Type

   A one-digit designation indicating whether the maximum operating speeds for freight or passenger trains is to be applied to the track.

4. Track Number

   A two-digit designation referring to a single track when multiple tracks are present.

5. Track Location Number

   A three-digit designation corresponding to a section of track located between selected natural or man-made targets.

6. Message Number

   A three-digit designation which relates an operator log entry to a specific track location by printing the message number on the data printout.

In addition, the following information is automatically provided by the TGMS:

1. Automatic Location Detection

   The Automatic Location Detector (ALD) is a metal detector that is activated by metallic objects along the track center line. These objects include rail impedance bonds, the closure rail at turnouts or special aluminum targets. Selected targets can be used by the operators as absolute distance reference locations.

2. Location Distance Count

   The elapsed distance in miles and feet since the last ALD location target detection.

3. Milepost Distance Count

   The elapsed distance in feet since the last milepost entry by the system operator.

4. Track Curvature

   Curvature is defined as the central angle (in degrees) contained by a 100-foot chord of the track center line. Utilizing curvature and vehicle speed data, a computation of the centrifugal acceleration is provided. The curvature data is also used to determine the track configuration- that is, tangent (straight), spiral (the transition between tangent and curved track) and curved (constant radius of curvature) track. This information is used to determine the proper thresholds for the FRA TSS exceptions which are a a function of the track configuration.

3. GENERAL DESCRIPTION

This section contains a brief description of the TGMS hardware and software. Further details can be found in the technical documentation supplied with the TGMS under contract no. DOT-TSC-1367.[5,6,7]

3.1 SYSTEM HARDWARE

A block diagram describing the TGMS from the basic inputs to the system outputs is shown in Figure 3. The basic inputs to the TGMS are the signals from an array of transducers which measure relative displacement, acceleration, angular rates, etc., from the system operator via a track geometry control console and from status transducers placed throughout the system which monitor the current operating status of the system. The necessary processing and control electronics are provided to condition the transducer signals and interact with the onboard digital computer, which analyzes the track data and produces an online report of exceptions to the FRA TSS.

The TGMS is equipped with a compact Track Geometry Control Console (TGCC). Total control of the TGMS and manual entry of data to the digital computer can be accomplished via the TGCC. The TGCC is installed in an adjustable mounting mechanism located near the front passenger seat as shown in Figure 4. Digital displays are provided on the TGCC to identify

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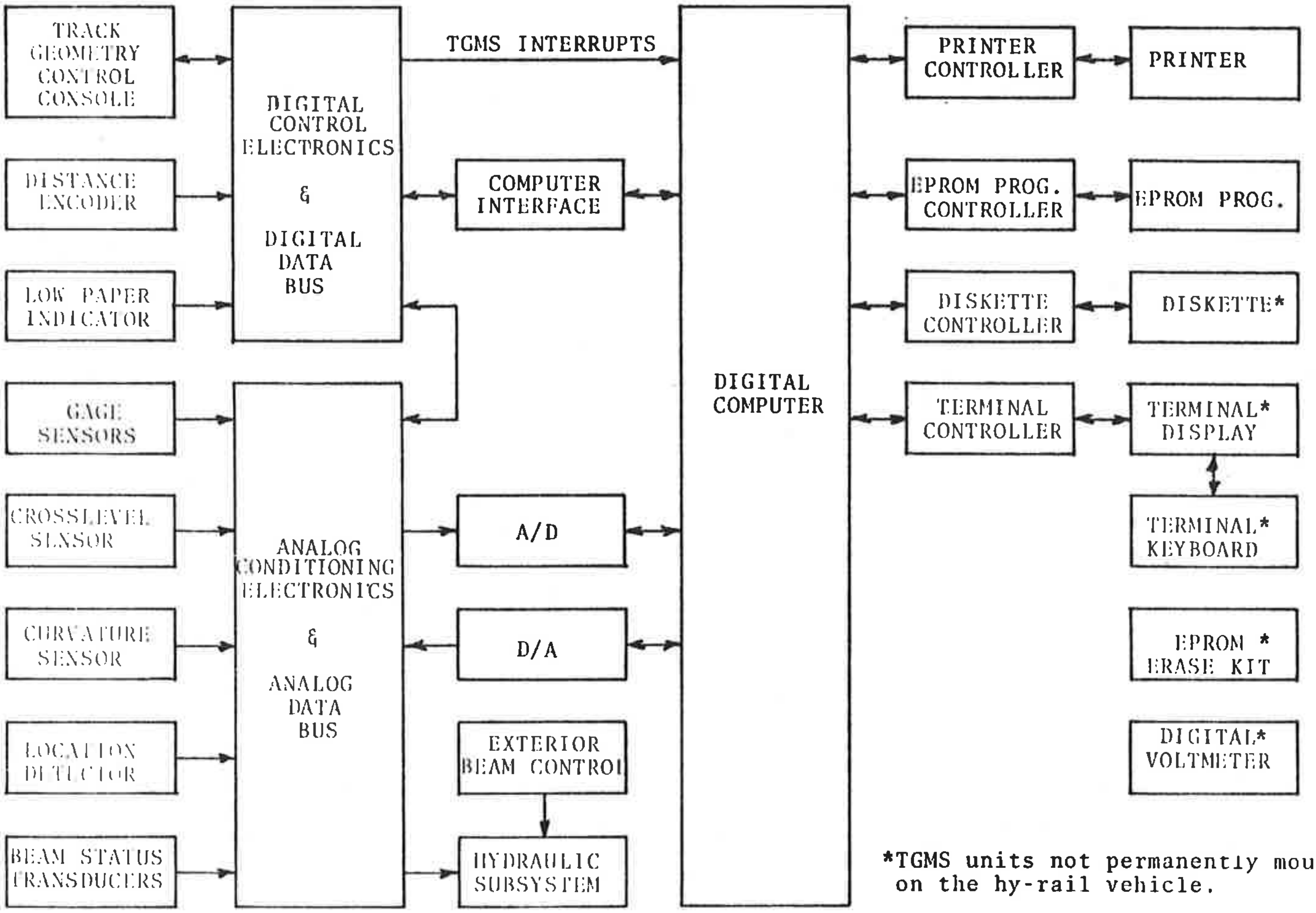
[5] "Track Geometry Measurement System: Operations Manual," ENSCO, Inc., Contract No. DOT-TSC-1367, September 1978.

[6] "Track Geometry Measurement System: Instruction Manual," Volume I - Instrumentation Manual, Volume II - Parts Lists, Volume III - Wire Lists, ENSCO, Inc., Contract No. DOT-TSC-1367, September 1978.

[7] "Track Geometry Measurement System: Computer Program Specifications and Maintenance Manual," Volume I - Technical Approach, Volume II - Appendices, ENSCO, Inc., Contract No. DOT-TSC-1367, December 1978.



*TGMS units not permanently mounted on the hy-rail vehicle.

FIGURE 3. BLOCK DIAGRAM OF TRACK GEOMETRY MEASUREMENT SYSTEM

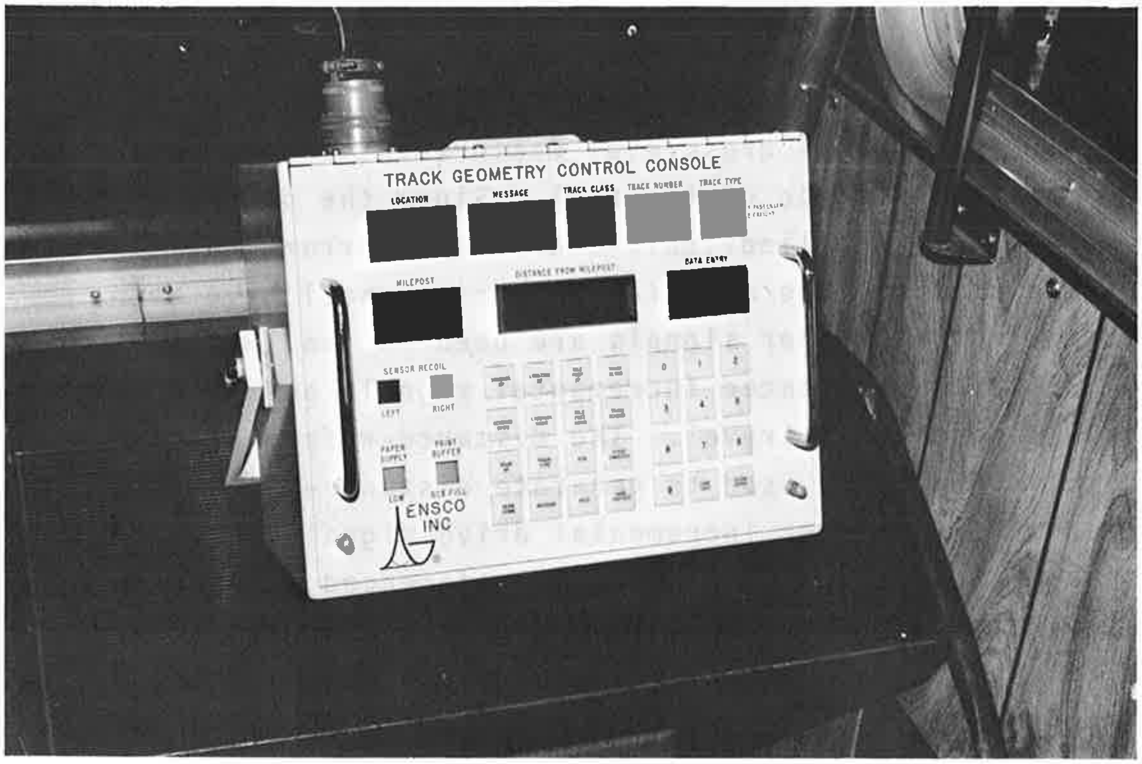


FIGURE 4. OPERATIONAL MOUNTING POSITION
OF THE TRACK GEOMETRY CONTROL CONSOLE

the current location, message, track class, track number, track type, milepost and elapsed distance from milepost numbers. The TGCC also has a display to permit the system operator to examine manual data entries prior to transferring them to the digital computer. Operational indicators are provided on the TGCC which contain the current status of the TGMS. The layout of the front panel of the TGCC is given in Figure 5. Further details concerning the operational controls and indicators on the TGCC are given in Appendix A.

The TGMS is equipped with an incremental encoder coupled to one of the cylindrical crosslevel measurement wheels which roll on the top surface of the rail. Since the drive wheel for the encoder is cylindrical, measurement errors normally associated with the use of a tapered drive wheel have been eliminated. The encoder signals are used in the TGMS to derive distance-referenced incremental signals and to determine the direction of travel. The distance-referenced incremental signals are used to generate distance-based interrupts to the digital computer incremental drive signal for an optional stripchart recorder. These distance-referenced incremental signals are also used to calculate vehicle speed and to derive the elapsed time between data sampling interrupts to the digital computer for use in the curvature computations. The direction of travel, forward or reverse, is used to automatically increment or decrement all distance measurement counters, respectively.

The digital control electronics serves as the communication link between the system operator and the digital computer. The digital control electronics analyzes the encoder signals to derive the distance-based incremental and associated signals discussed in the previous paragraph. The digital control electronics also receives information regarding the status of the TGMS from two additional sources: an indicator to inform the operator that the paper supply for the printer

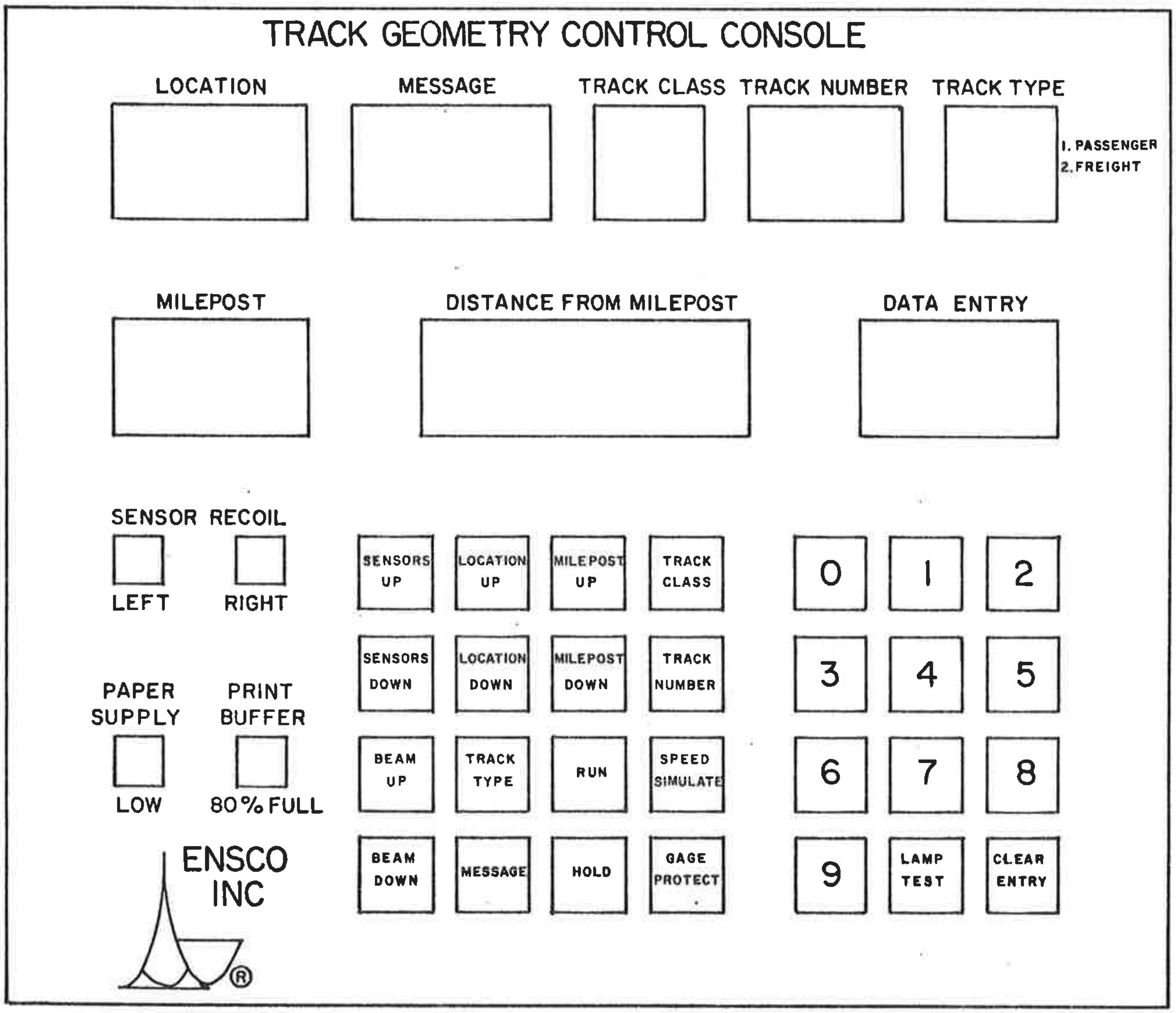


FIGURE 5. FRONT PANEL LAYOUT OF THE TRACK GEOMETRY CONTROL CONSOLE

is nearly depleted, and the status transducers to indicate the current operating configuration of the beam assembly. The digital control electronics generates the following three independent interrupts to the digital computer and formats three 16-bit words which are transferred via the computer interface electronics to the digital computer:

- A TGCC interrupt is generated whenever the operator pushes one of the applicable control buttons on the TGCC. Along with the TGCC interrupt, one 16-bit word is transferred to the digital computer containing a four-bit code designating which control function is selected and a 12-bit code containing a manual data entry of up to three decimal digits. After accepting the data entered by the operator, it is returned to the TGCC for display and the manual data entry display is cleared.
- A data sampling or block distance interrupt is generated for every foot of vehicle travel under standard operating conditions or at a constant rate equivalent to a vehicle speed of 33.3 mph under the speed simulate option. Along with the block distance interrupt, two 16-bit words are transferred to the digital computer. One contains the status of the TGMS at the time the block distance interrupt is processed, and the other contains the elapsed time between consecutive block distance interrupts for use in the TGMS.
- A termination of exception interrupt may be generated whenever the system operator elects to terminate any group exceptions in progress at the end of a track geometry inspection survey.

The track geometry measurement sensors consist of two displacement transducers for gage, two displacement transducers, an inclinometer, a roll rate gyro and a yaw rate gyro for crosslevel and curvature, and an eddy current sensor for location target detection. The displacement transducers for gage are mounted on a track geometry measurement beam assembly which is attached to the front hy-rail strut assembly as shown in Figure 6. The two displacement transducers for crosslevel are mounted on the upper rigid portion of the front hy-rail strut assembly and are connected to the beam assembly through steel cables as shown in Figure 6. The eddy current sensor is mounted in the center of the front hy-rail cross strut, which is also shown in Figure 6. The remaining track geometry measurement sensors are mounted in the Compensated Accelerometer Sensor (CAS), which is attached to the vehicle body as shown in Figure 7.

The measurement of track gage is derived from the two independent linear displacement transducers, each of which measures the distance between a fixed reference point on the track geometry measurement beam and a sensor carriage containing the follower wheel which maintains contact with the gage side of the rail head at a point 5/8 inch below the top of the rail. The voltages supplied by the left and right gage displacement transducers are summed in the gage electronics with a third voltage which is proportional to the distance between the fixed reference points on the beam assembly to yield the final measurement of track gage. The final three scaled voltages, representing gage sensor displacement measurements and track gage, are available both to the digital computer through Analog-to-Digital (A/D) converters and on the Analog Data Bus (ADB). The individual gage sensor displacement signals were provided for the efficient future implementation of a subsystem to measure rail alignment.

The measurement of track crosslevel is derived in the crosslevel electronics from five signals generated by the track geometry sensors. Car body roll relative to the gravitational direction is calculated from the inclinometer and the roll rate gyro signals with a correction for centrifugal acceleration calculated from the yaw rate gyro signal and speed information. The car

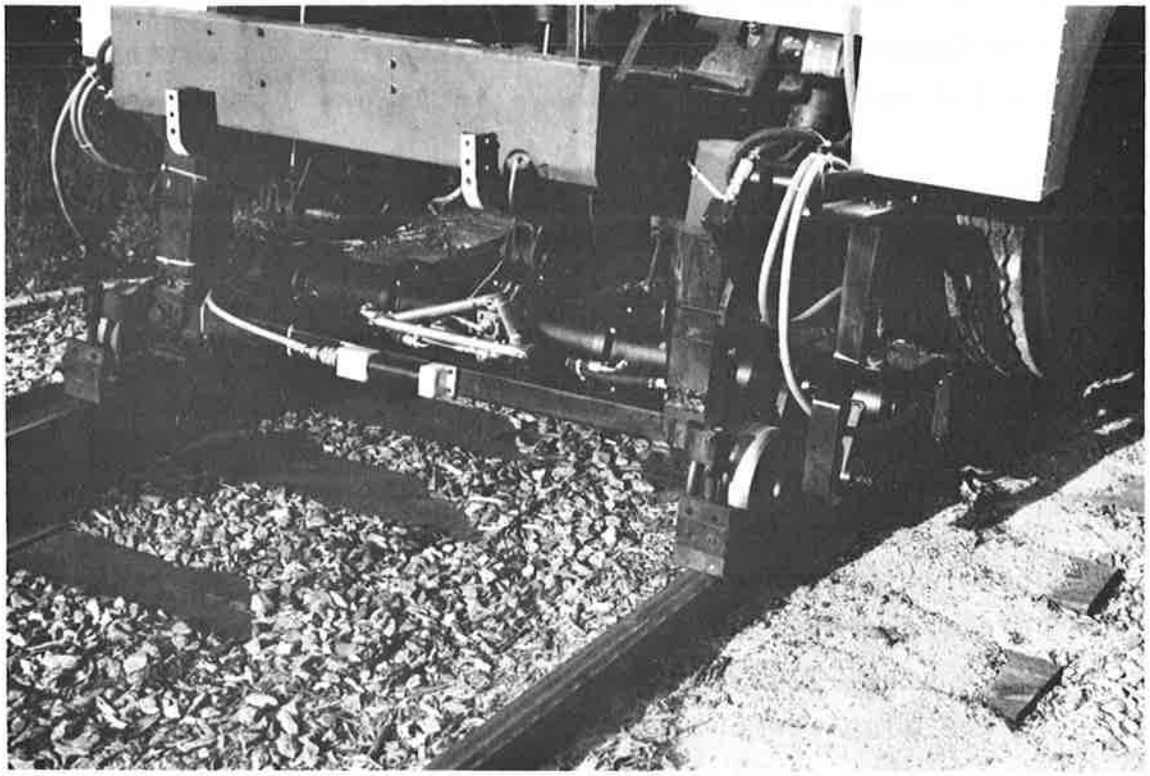


FIGURE 6. TRACK GEOMETRY MEASUREMENT BEAM

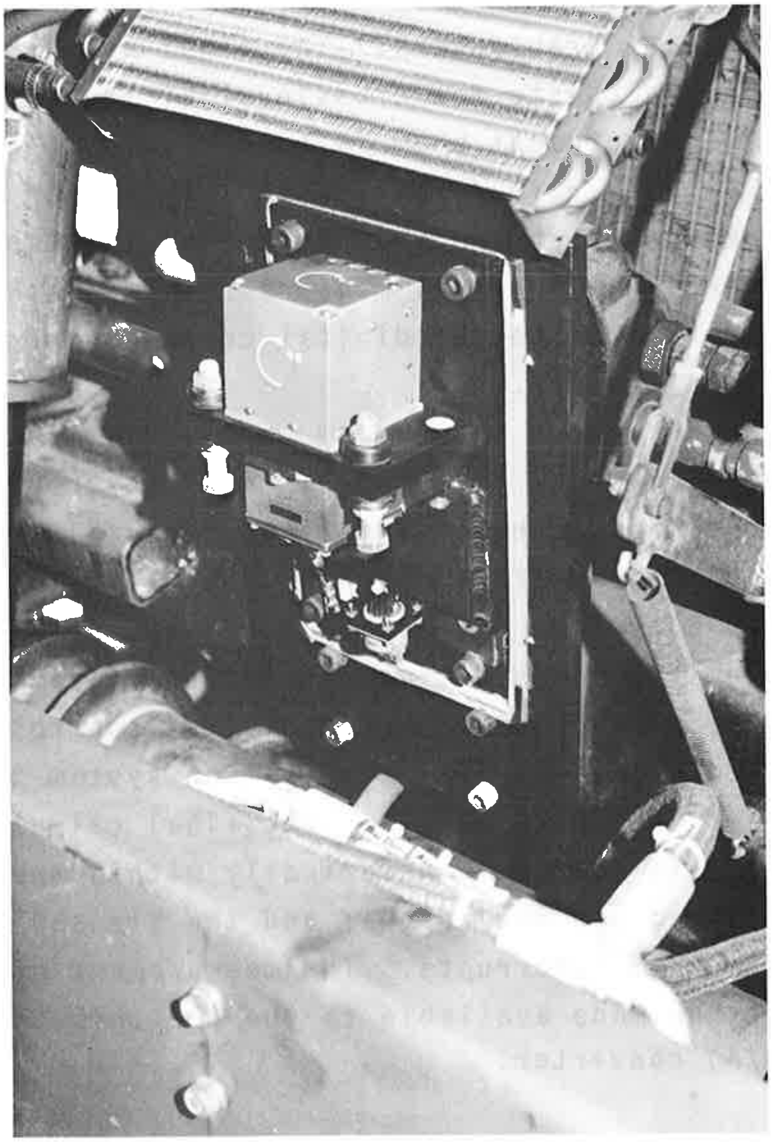


FIGURE 7. COMPENSATED ACCELEROMETER SENSOR, PROTECTIVE COVER REMOVED

body roll angle is combined with the relative car body to track roll angle measurement obtained from the two crosslevel linear displacement transducers. The final angular measurement is used to calculate the crosslevel of the track. The track geometry measurement beam is supported by a cylindrical wheel riding on each rail. This design yields car body to track measurements which are independent of the tapering of the hy-rail wheels. The final measurement of track crosslevel is made available both to the digital computer through an A/D converter and on the ADB.

The measurement of track curvature is derived from the yaw rate gyro signal and speed information. The filtered yaw rate signal is made available both to the digital computer through an A/D converter and on the ADB. Speed information is derived from the elapsed time between block distance interrupts which is calculated by the digital control electronics and transferred to the digital acquisition system through a 16-bit computer interface module. The final calculation of track curvature is performed numerically within the computer using the filtered yaw rate signal and the elapsed time between block distance interrupts. The measurement of track curvature is then made available to the ADB through a Digital-to-Analog (D/A) converter.

The TGMS is equipped with a digital computer to perform the necessary parameter evaluation and exception threshold checking of the track-geometry-related information. The digital computer also produces an exception report detailing the exceptions located by the TGMS and produces a complete log of the measurement operations. The printer on which the exception report is produced is a positive tractor-feed machine capable of simultaneously producing an original and up to five copies of the exception report at a rate of 300 lines per minute. The exception report is printed line by line to maximize the information available to the track inspector during measurement operations.

With the exception of the TGCC and CAS, the remaining instrumentation in the TGMS is installed in a single rack as shown in Figure 8. The instrumentation in the rack includes the Texas Instruments 990/10 digital computer, the Digital Control Unit (DCU), the Track Geometry Unit (TGU), the Teletype Model 40 printer, the printer shelf, paper drawer and the Marine Electronic Model ST 1000 M7390-60 frequency converter for power conditioning. A Digital Data Bus (DDB) is located behind the hinged front panel of the DCU and the ADB is located behind the hinged front panel of the TGU. The vertical panel adjacent to the Texas Instruments 990/10, DCU and TGU can be easily removed for access to regulated power and the connector for the TGCC when it is mounted on the rack. The printer assembly including the printer, printer shelf and paper drawer can be operated in the extended position.

3.2 SYSTEM SOFTWARE

The TGMS computer program, HYRAIL, serves as the interface between the instrumentation and the track inspectors. The program processes the data from the track geometry measurement sensors and from data entered manually by the operator to generate a report containing both detected exceptions and an operational log. Integrating the detected exceptions and the operational log into one report minimizes the possibility of any ambiguity when the report is used by the track inspector. In addition to creating the track geometry exception report, computed and basic track geometry parameters are made available on the analog and digital data buses for optional display.

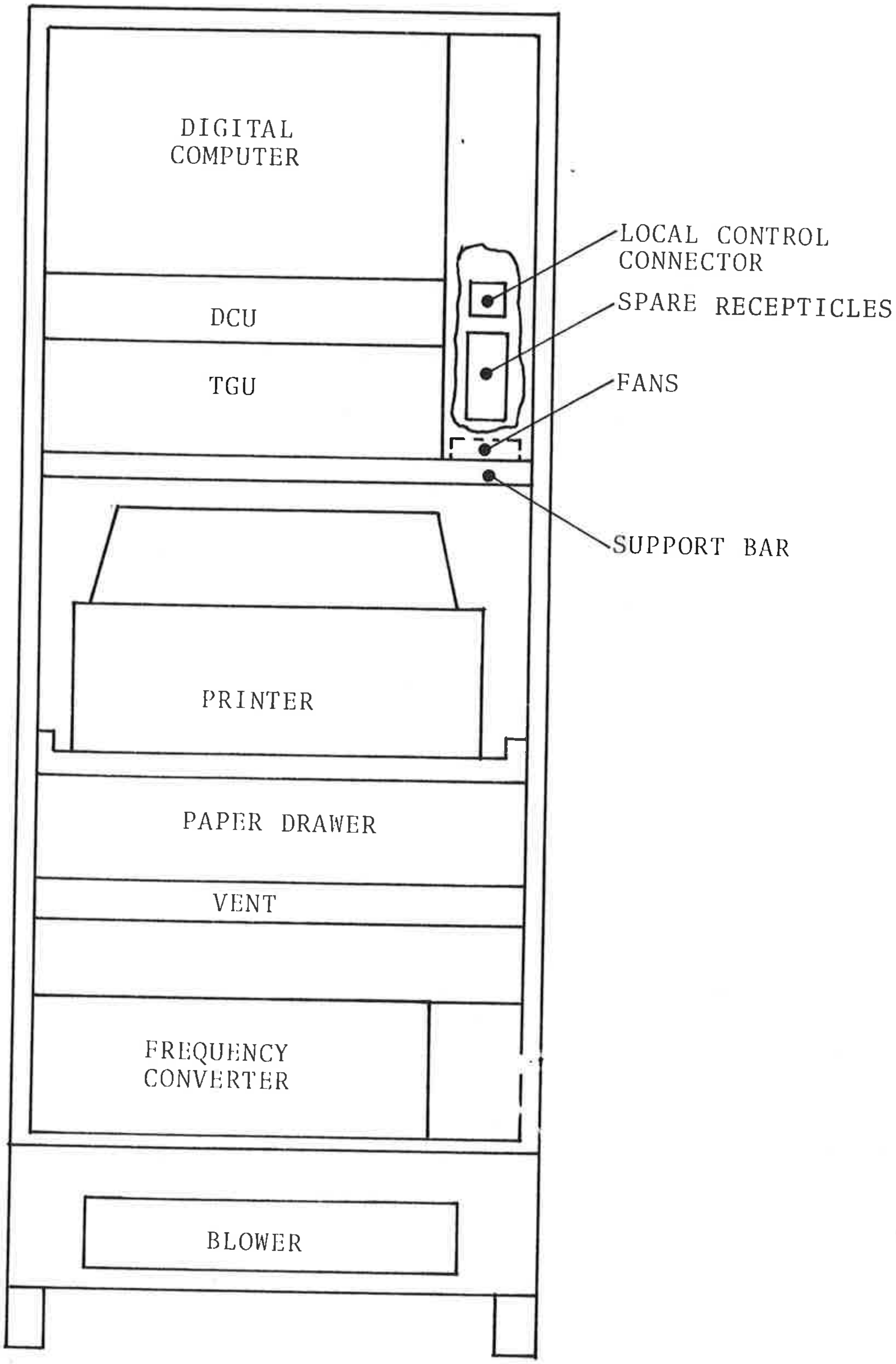


FIGURE 8. TRACK GEOMETRY MEASUREMENT SYSTEM INSTRUMENTATION RACK

A flow chart describing the process required to determine railroad compliance with the track safety standards is shown in Figure 9. The first step is to determine the posted class of track being inspected. Next, the type of track (that is, tangent, spiral, or curve) must be determined. On a moving vehicle, this decision must be based on vehicle-borne instrumentation and real-time processing. This aspect of the processing of track geometry information is a key factor in the performance of the TGMS. Once the type of track is determined, each track geometry parameter must be calculated and compared to appropriate limiting values defined in the track safety standards. While operating in a curved track, the limiting speed for the curved track must also be calculated.

To accomplish the objectives of determining compliance of the track with the FRA TSS, the Hy-Rail Program has two basic phases as shown in Figure 10. During the initialization phase, all of the initial operating parameters for the program are defined. An option is included in the program which will permit the operator to modify certain constants under special test conditions. In the standard operating mode, all required data constants are predefined within the Hy-Rail Program to further simplify the operator's task and to eliminate the possibility of human error. After defining the program constants, the cover page of the report is printed and the TGCC is automatically reset in preparation for a track geometry inspection survey.

During the track geometry analysis phase, the Hy-Rail Program accepts data from the track geometry measurement sensors and data entered manually by the operator. The program then derives the specified track geometry parameters from the sensor inputs and checks for exceptions to the FRA TSS. Detected exceptions are printed in the on-line geometry exception report.

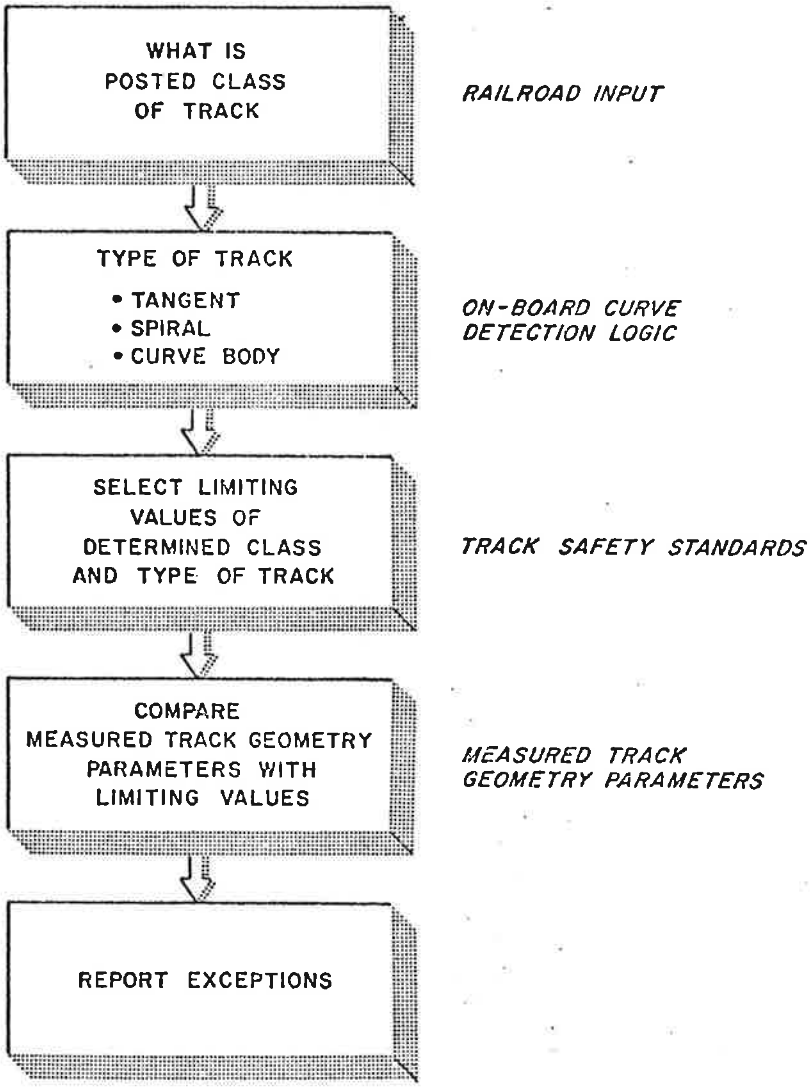


FIGURE 9. FLOW CHART FOR DETERMINING COMPLIANCE OF TRACK WITH THE TRACK SAFETY STANDARDS

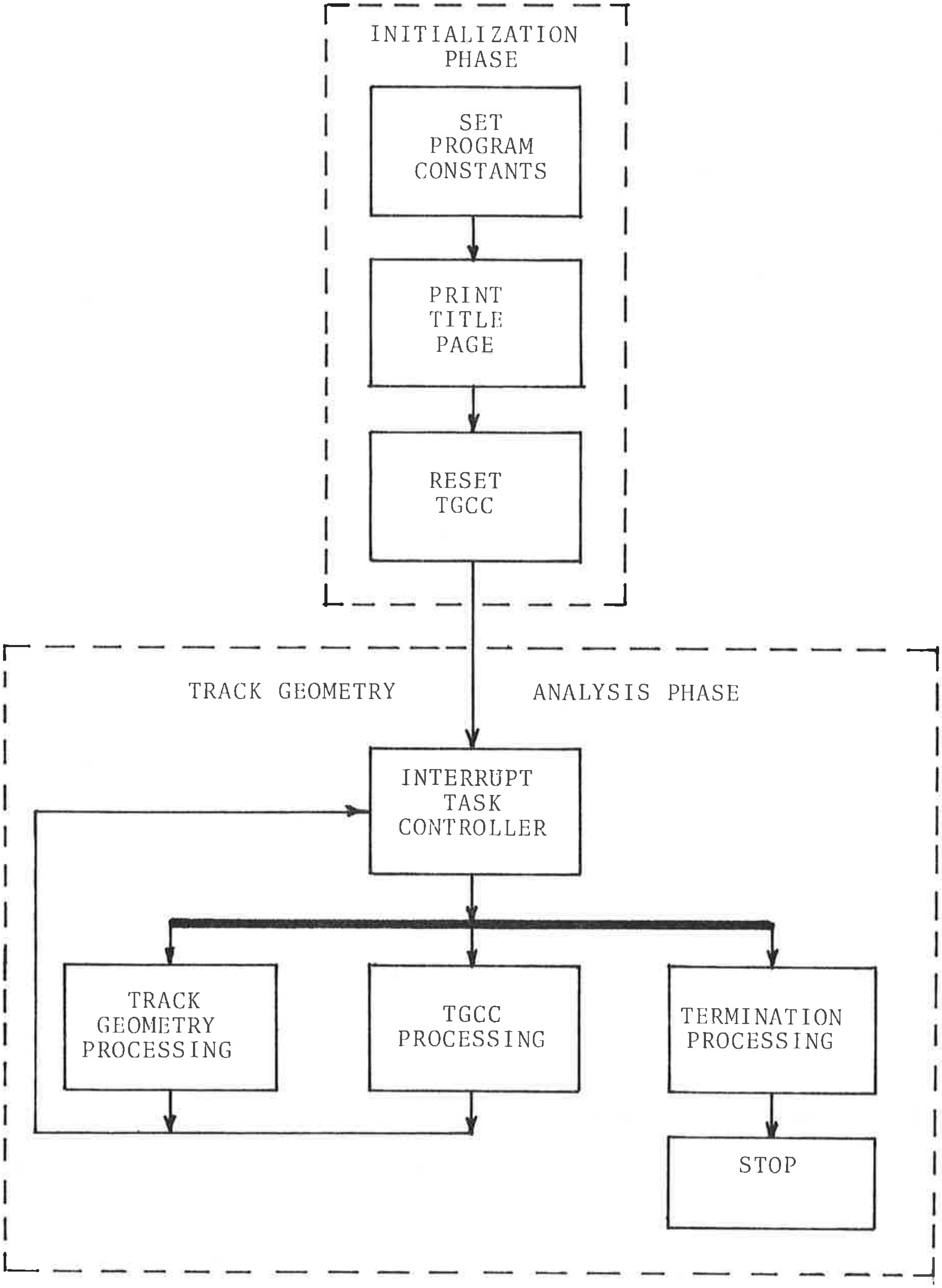


FIGURE 10. FLOW CHART OF THE TRACK GEOMETRY COMPUTER PROGRAM, HY-RAIL

A track geometry analysis phase is divided into four areas, as shown in Figure 10. Program processing is managed by a real-time operating system which responds to the TGMS interrupts discussed in the previous section. Whenever a block distance interrupt is received, the program performs a track geometry processing cycle which includes reading sensor and status data, computing track geometry parameters, checking for exceptions to the FRA TSS, and creating a line to be printed on the report if any exceptions are identified. Whenever a TGCC interrupt is received, the program reads the control console status word, determines the control functions or data entry the operator desired, processes the operator request, and creates a reference line to be printed on the report as part of the operations log. Whenever a manual termination interrupt is received, the program closes any exceptions in progress and creates a line to be printed on the report for each exception manually terminated. The interrupt task controller monitors the interrupts to assure that they are processed on a priority basis and that any critical processing steps are not interrupted. The lines to be printed are stored in a memory buffer capable of holding over 300 lines and are printed on a time-available basis. If the interrupt task controller receives a manual termination interrupt, any lines in the computer print buffer will be printed and no further interrupts will be accepted until the digital computer is reinitialized.

4. TRACK GEOMETRY MEASUREMENT SUBSYSTEMS

The theory of operation of the three track geometry measurement subsystems is described in this section. Further details concerning these measurement systems are given in the technical documentation supplied with the TGMS.

4.1 GAGE SYSTEM

The gage subsystem measures the distance between the heads of the rails at right angles to the rails in a plane 5/8 of an inch below the top of the rail head. The measurement of track gage is derived from two independent linear displacement transducers. Each of the transducers is mounted on the track geometry measurement beam with measurement cables attached to a carriage assembly containing a sensor wheel which maintains contact with the gage side of the rail head at a point 5/8 of an inch below the top of the rail. The voltages from these two displacement transducers are scaled and summed in an analog preprocessor with an offset voltage to yield a signal representing track gage over a range of 55.50 to 59.25 inches. The voltages from the individual displacement transducers are made available to the digital computer for future implementation of a rail alignment subsystem. The voltage representing track gage is made available to the digital computer for determining exceptions to the FRA TSS.

The track geometry measurement beam on which the gage linear displacement transducers are mounted is attached to the rear of the front hy-rail strut assembly as shown in Figure 6. The beam assembly consists principally of a centrally located rotary actuator, left and right gage sensor wheel carriage subassemblies, crosslevel reference wheels, sturdy tubes that house internal hydraulic components, guidance shafts for the sensor wheel carriage subassemblies, the sensor wheel carriage subassemblies, and the crosslevel reference wheels.

A gage wheel sensor carriage assembly is shown in Figure 11. Each carriage assembly contains two ball bearing bushings. These bushings slide on a splined shaft to allow smooth motion of the carriage assembly perpendicular to the rails for measuring track gage while maintaining the gage sensor wheel contact at a point 5/8 of an inch below the top of the rail head. One bushing contacts the inner race of the splined shaft, and the other contacts the outer race of the splined shaft to increase the rigidity of the fit of the carriage assembly to the splined shaft. The axle about which the sensor wheel rotates is pinned to the sensor wheel arm. An extension of the axle, equipped with a lockable adjusting screw, is held between a flat spring on the bottom of the sensor wheel arm and another adjusting screw on the arm above the axle. The pin, the spring, and the adjusting screw in the arm fix the position of the axle to the arm; and the adjusting screw in the axle sets the spring preload which holds the axle in position. The arm in turn is held in the carriage by a large pin and three spring-loaded plungers in the sides of the carriage. A hydraulic cylinder fastened to the splined shaft forces the carriage out and loads the sensor wheel against the side of the rail, as shown in Figure 12. An accumulator in the hydraulic circuit allows the sensor wheel to move in and out to follow changes in gage while maintaining a relatively constant contact force.

The design of the beam assembly provides for various motions of the beam body and of the components relative to the body to accomplish both operational and protective requirements. The

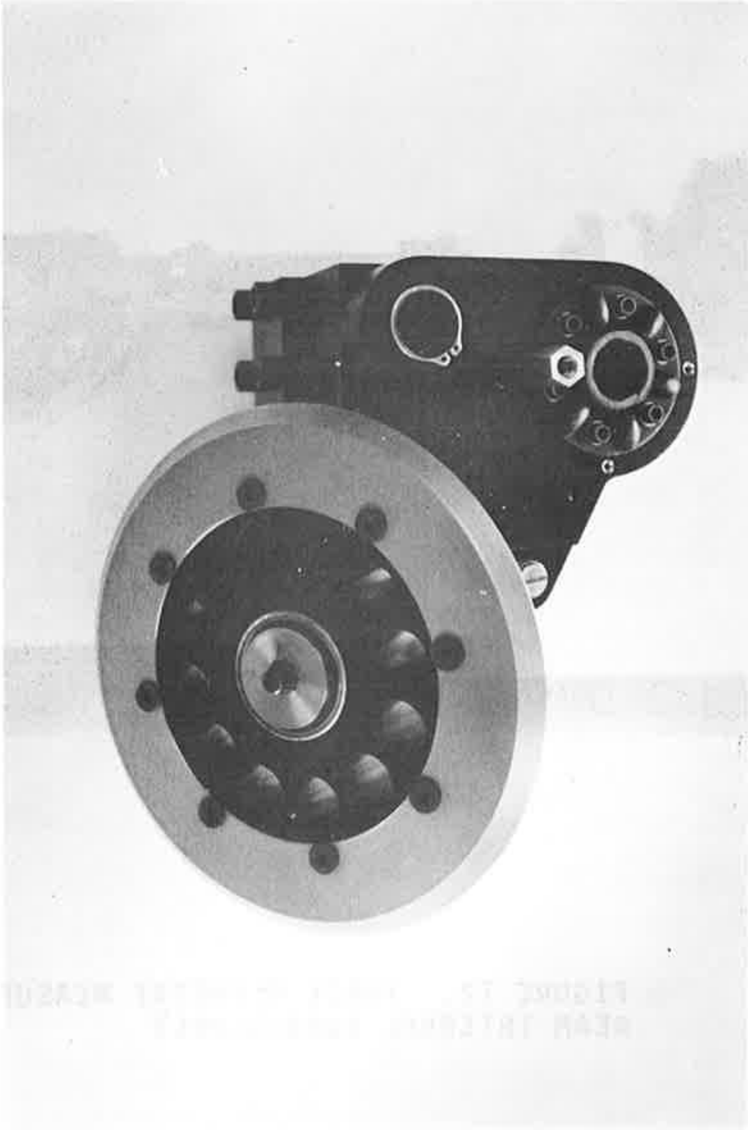


FIGURE 11. GAGE WHEEL SENSOR CARRIAGE ASSEMBLY

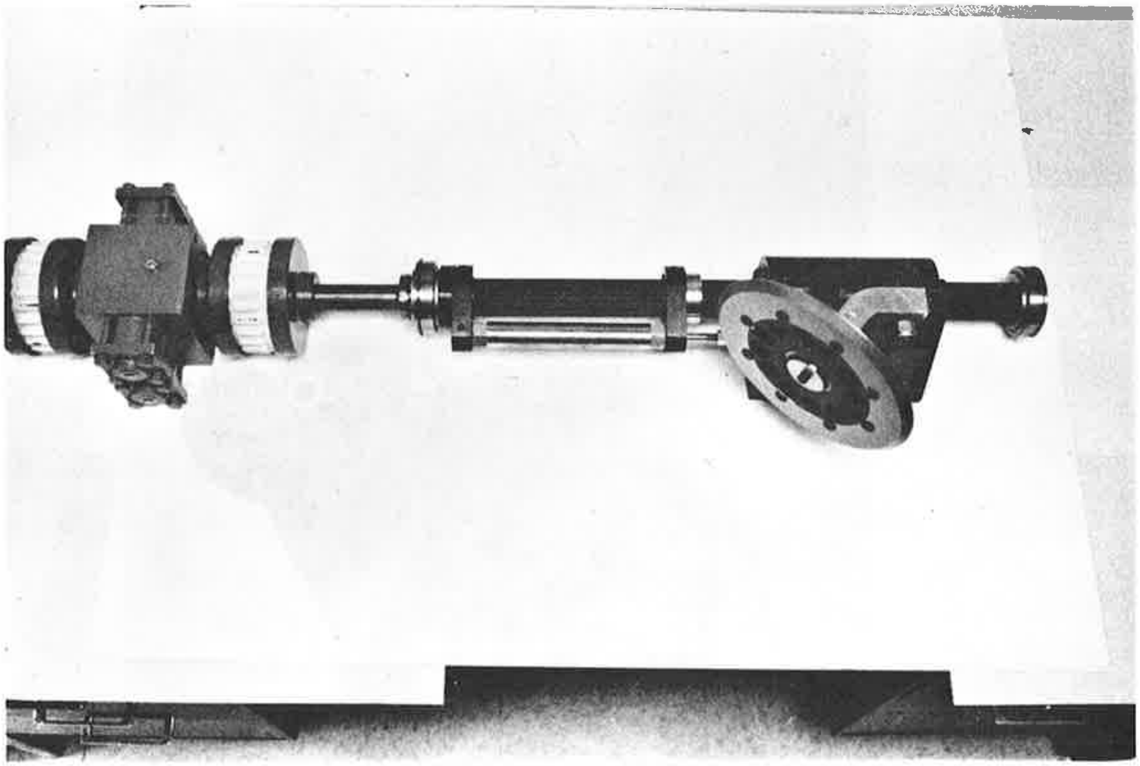


FIGURE 12. TRACK GEOMETRY MEASUREMENT BEAM INTERNAL SUBASSEMBLY

vertical hydraulic actuator and the three linkages to the hy-rail cross bar provide the motion necessary for crosslevel tracking and for the negotiating of warped rails. The triangular center arm fixes the center of the beam to the centerline of the vehicle, but the spherical bearing at the connection allows the beam several degrees of rotation about an axis parallel to the rails. The straight lower arms, also ending in spherical bearings, orient the beam such that the gage sensor wheels contact a point 5/8 of an inch below the rail head while the crosslevel reference wheels rest on the rail heads without obstructing the crosslevel tracking motion. Gage sensor wheel retraction motion is provided by the rotary hydraulic actuator, which is fastened to the rotating gage measurement assemblies by flexible couplings. The rotary actuator has two positions: one position holds the rotating assemblies in the proper orientation for gage measurement as shown in Figure 13; and the other position causes the splined shafts to rotate 45°, lifting the gage sensor wheels above the rails as shown in Figure 14. Also, the entire TGMS beam may be retracted through the upward movement of the vertical actuator shafts. This final operational motion is necessary for the TGMS beam to clear the verticle frame and bumper when the hy-rail struts are being retracted. This motion is accomplished by Teflon-faced ramps which guide the beam around the obstruction and by a relief valve in the vertical actuator retraction circuit which allows the ramps to displace the beam against the hydraulic pressure.

Several auxilary motions have been included in the TGMS beam design to prevent its destruction when objects in violation of the contractual clearance profile are encountered. The spring-loaded plungers which position the gage sensor arms in their carriages allow the arms to recoil upon impacting an obstruction and raise the sensor wheels above the rails. The flat spring

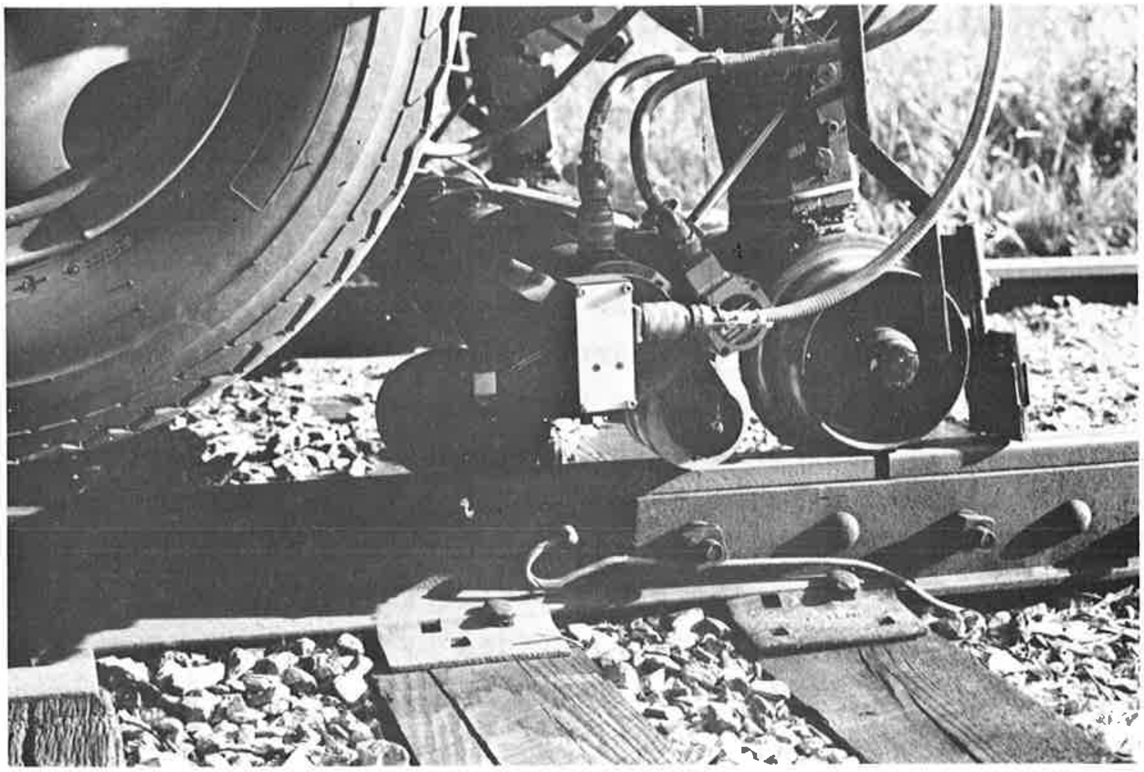


FIGURE 13. TRACK GEOMETRY MEASUREMENT BEAM WITH GAGE SENSORS DEPLOYED

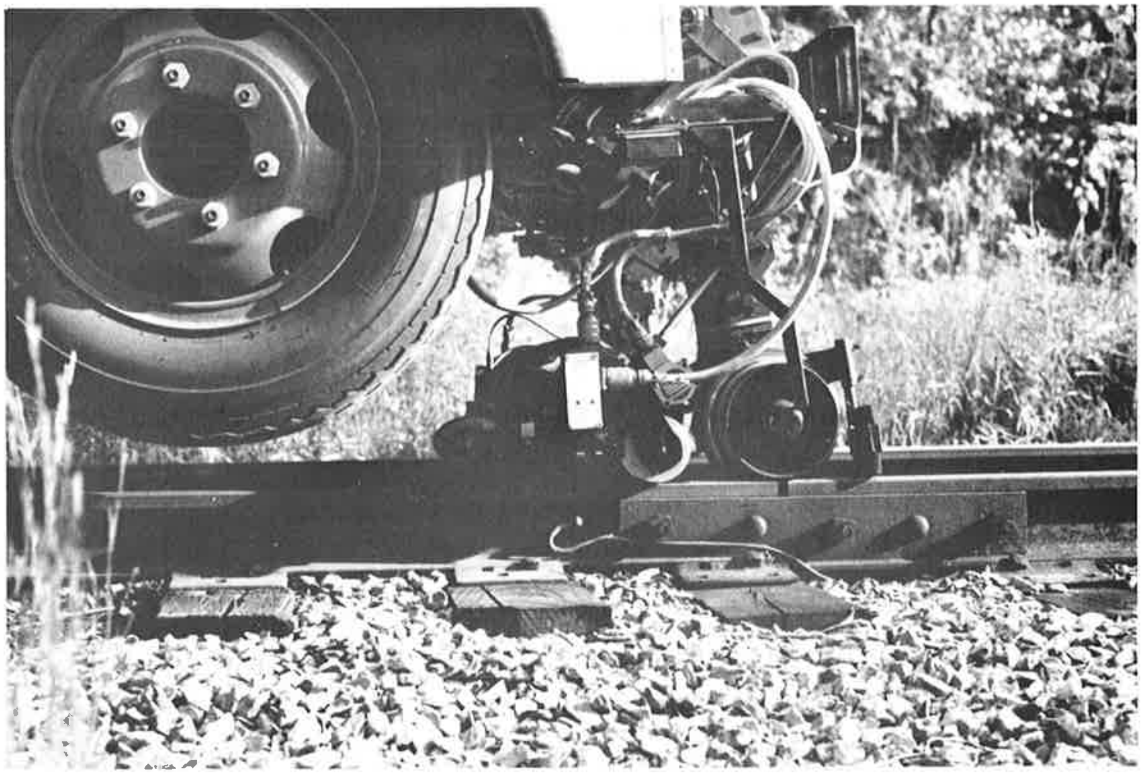


FIGURE 14. TRACK GEOMETRY MEASUREMENT BEAM WITH GAGE SENSORS RETRACTED

which holds the sensor wheel axle in place is designed to allow the sensor wheel to follow a lateral rail mismatch at high speed with less impact than would be required to accelerate the sturdy carriage to clear the mismatch. Furthermore, under an extreme mismatch the spring will fail before other more costly damage takes place. Some flexibility has also been designed into the beam attachment arms to protect the TGMS beam against vertical mismatch impact. The beam attachment arms are mounted with rubber bushings at the hy-rail strut end, and the cross-level reference wheels are cantilevered about an outboard disc to provide elastic deflection under impact. Another protective feature is the gage protect provision in the hydraulic circuit which allows inward motion of the gage sensor wheels and prevents further outward movement while passing through frogs and switches.

Several additional features are provided on the TGMS beam. Limit switches are fastened to the gage sensor carriage which contact the gage sensor arms. In the event of sensor recoil, the limit switch triggers a warning light on the TGCC. The operator may retract the sensors, causing the spring plungers to reset. The limit switch position also indicates to the digital computer whether the gage sensor arm is in the measurement position. Another limit switch, imbedded in the right end of the housing, contacts the gage displacement transducer mounting plate to monitor the position of the rotary actuator. A limit switch is also provided which contacts the vertical actuator to determine whether the beam is retracted or in the measurement position.

The finish of the various parts has been designed to be compatible with the railroad environment. The gage sensor wheel rims are fashioned from 440C stainless steel. This alloy, which is also used for premium bearing races, provides a very hard (Rc40) surface and high toughness while maintaining the corrossion resistance of ordinary soft stainless steel. The crosslevel reference wheels are made of 4130 chromium-molybednum alloy steed, heat-treated to a Rc30 hardness. The heat treatment provides a balance between hardness and ductility and is done to prevent failure due to brittleness or bending. The unit is then cadmium-plated to prevent corrosion. The aluminum parts have been anodized to achieve both a pleasing appearance and considerable surface hardening.

4.2 CROSSLEVEL SYSTEM

The crosslevel subsystem measures the difference in elevation between the left and right rails. The resulting crosslevel signal is scaled to 1 volt/inch - positive output voltage corresponds to a left rail high condition. Track crosslevel is derived from the vehicle body roll angle and the relative angle between the vehicle body and the track. The vehicle body roll angle is derived from the outputs of an inclinometer and a roll rate gyro. The inclinometer signal must be corrected for lateral acceleration caused by track curvature. The yaw rate and the vehicle speed must be properly combined with the inclinometer output to develop the dynamic car body roll angle. The relative angle between the vehicle body and the track is measured by two linear displacement transducers. The inclinometer, roll rate gyro, and yaw rate gyros are mounted in the Compensated Accelerometer Sensor (CAS). The linear displacement transducers are mounted underneath the vehicle body directly over the track geometry measurement beam. The crosslevel linear displacement transducer measurement cables are attached to the mounting brackets of the cylindrical reference wheels, which are in contact with the top surface of each of the rails. All transducer signals are input to the TGU for the final calculation of track crosslevel.

The calculation of vehicle body roll angle is derived by noting that the inclinometer is subjected to lateral acceleration, a_ℓ, from the following source when the vehicle is moving:

- Component of gravitational acceleration due to the roll angle of the vehicle, a_θ, given by

  $$a_\theta = g \sin \theta$$

  where g is the acceleration of gravity, and
  θ is the roll angle of the vehicle body.

- Lateral accelerations due to centrifugal acceleration in curves, a_ϕ, given by

  $$a_\phi = \dot{\phi} v \cos \theta$$

  where $\dot{\phi}$ is the vehicle yaw rate in radians/seconds and
  v is the vehicle forward velocity in feet/seconds

- Lateral accelerations due to the lateral translation motion of the vehicle, $a_{\ddot{r}}$, caused primarily by lateral motion of the hy-rail vehicle with respect to the rails and vehicle linkage/suspension characteristics.

- Lateral acceleration due to the translation motion of the CAS sensor assembly about the roll origin, $a_{\ddot{\theta}}$, given by

  $$a_{\ddot{\theta}} = \ddot{\theta} h$$

  where h is the height of the inclinometer from the roll origin expressed in feet, and
  $\ddot{\theta}$ is the roll acceleration of the car body in radians/seconds^2.

  (The value of h in the present system is approximately 3 feet.)

- Lateral accelerations due to the translational motion of the CAS sensor assembly about the yaw origin, $a_{\ddot{\theta}}$, given by

  $$a_{\ddot{\phi}} = \ddot{\phi} \ell \cos\theta$$

  where ℓ is the distance of the inclinometer from the yaw origin expressed in feet, and
  $\ddot{\phi}$ is the vehicle yaw acceleration in radians/seconds^2.

  (The value of the ℓ in the present system is approximately eight feet).

The two components of lateral acceleration sensed by the inclinometer of $a_{\ddot{r}}$ and $a_{\ddot{\phi}}$ are grouped and considered as a noise source, a_n. The final output of the inclinometer signal is, therefore, given by $a_\ell = a_\theta + a_{\ddot{\phi}} + a_{\ddot{\theta}} + a_n$.

To measure the vehicle body roll angle, the only signal of interest from the inclinometer is the portion corresponding to a_θ. To minimize the effects of the remaining lateral accelerations sensed by the inclinometer, the lateral acceleration due to $a_{\dot{\phi}}$ and $a_{\ddot{\theta}}$ are evaluated and subtracted from the output of the inclinometer. The remaining signal is then low-pass filtered to minimize the disruptive effects of a_n. The inclinometer output is therefore used to contribute only to low-frequency components of the vehicle body roll angle signal. The transfer equation for the low pass filter is of the form

$$T_{\text{LOW PASS}} = \frac{\omega_0^{\,4}}{s^4 + as^3 + bs^2 + cs + \omega_0^{\,4}}$$

The high frequency components of the vehicle roll angle signal are supplied by the roll gyro by performing a high-pass filtering operation. The transfer equation for the high-pass filter is of the form

$$T_{\text{HIGH PASS}} = \frac{s^3 + as^2 + bs + c}{s^4 + as^3 + bs^2 + cs + \omega_0^{\,4}}$$

The high-pass filter used on the roll rate gyro is the complementary part of the low-pass filter used on the inclinometer, thereby retaining all frequency components in the crosslevel signal- i.e., $T_{\text{LOW PASS}} + sT_{\text{HIGH PASS}} = 1$. The roll rate gyro is not sensitive to linear accelerations and therefore does not need to be low-pass filtered. The final roll angle of the vehicle body is given by the sum of low-frequency and high-frequency components of the vehicle body roll angle signals. The vehicle body roll angle is then converted to inches using a 59.0-inch measurement base. The scaled car body crosslevel signal is then combined with the relative vehicle-to-track angle derived from the two crosslevel displacement transducers, which is also scaled to inches using a 59.0-inch measurement base. The resulting signal is the crosslevel of the track scaled to 1 volt/inch.

4.3 CURVATURE SYSTEM

The curvature subsystem measures the change in the azimuthal heading of the hy-rail vehicle over a range of ±15°/100 feet at speeds between 3 and 30 mph. The basic measurement of track curvature (degrees/100 feet) is used to derive a measurement of rate of change of track curvature (degrees/100 feet/100 feet) and a measurement of centrifugal acceleration (ft/sec^2). The measurements of track curvature and rate of change of track curvature are then analyzed to determine the track configuration- i.e., tangent (straight), spiral (transition between tangent and curved track) and curved (constant radius of curvature). The track configuration is used to select the proper FRA TSS exception thresholds which are a function of the track configuration.

The basic datum in the determination of track curvature is the change of the azimuthal angle per sample interval, $w_z = \frac{d\phi}{dt}$. If the datum is sampled at time, t, with a sample interval, α, then the basic datum $\phi(t;\alpha)$ is given by

$$\phi(t;\alpha) = \int_{t-\alpha}^{t} w_z\ (\tau)d\tau.$$

To derive this output, it is necessary to find the kernel, $h(t;\alpha)$, which convolves with $w_z(t)$ in the time domain to produce $\phi(t;\alpha)$ - i.e.,

$$\phi(t;\alpha) = \int_{-\infty}^{\infty} h(t-\tau;\alpha)\ w_z(\tau)d\tau$$

$$= \int_{-\infty}^{\infty} h(\tau;\alpha)\ w_z(t-\tau)d\tau$$

The kernel which will accomplish this objective is the rectangular impulse response given by

$$h(t;\alpha) = \begin{cases} 0; -\infty < t < 0 \\ 1;\ 0 \leq t \leq \alpha \\ 0;\ \alpha < t < \infty. \end{cases}$$

Although a perfect realization of $h(t;\alpha)$ is not possible, an excellent approximation can be achieved by a hybrid processor that includes complementary analog and digital filters.

The analog filter selected for the curvature preprocessor has a frequency response of the form

$$X(s) = \frac{2a\rho}{s+2\rho}$$

where

$s = \sqrt{-1}$ x radian frequency,

$\rho = f_c/2^{15}$ where f_c is the frequency of the clock used to measure the elapsed time during the sampling interval, α, and

a is the gain of the filter adjusted to yield a steady state response of 1 volt/degree/second.

For the analog filter developed for the curvature system under the present contract, f_c = 12.5 KHz. Therefore, the single pole of the filter is located at $f_c = \rho/\pi = .1214$ Hz. The characteristics of the filter were selected to minimize the response of the filter to track alignment deviations which are treated as a noise source, and to the quasi-periodic form of the chordal response of the hy-rail vehicle to track alignment.

The complementary digital filter applied to the sampled analog signal must have a frequency response inversely proportional to $X(s)$ to yield an overall frequency response which approximates that of $h(t;\alpha)$. Applying a bilinear transformation to the inverse of $X(s)$ yields a digital filter which has a freuency response of the form

$$Y(z) = (1 + \tfrac{1}{2}\rho\alpha) - (1 - \tfrac{1}{2}\rho\alpha)\ z^{-1}$$

where z^{-1} is the z transform notation for one sample delay.[8] The resultant signal after this phase of the digital filtering has units of degrees/foot.

The final evaluation of track curvature in degrees/100 feet is calculated by applying a filter with a z transform of the form

$$B(z,N) = \frac{z^{-n}}{2N} \sum_{i=-N}^{N-1} z^{-i}$$

where

N is the half length of the smoothing window, i.e., 50 feet; and

n is the delay needed to line up the track curvature data with other geometry parameters, i.e. 8 feet.

The rate of change of track curvature in degrees/100 feet/100 feet is calculated by applying a filter with a z transform of the form

$$C(z,N,M) = \frac{M}{(2N)^2} z^{-n} \left(\sum_{i=-2N}^{-1} z^{-i} - \sum_{i=0}^{2N-1} z^{-i} \right)$$

where N and n are defined as above and M is the rate of change of curvature base length of 100 feet.

Actual implementation of the filter $B(z,n)$ is achieved by noting that

$$B(z;N) = \frac{z^{-n+N}}{2N} \left[\frac{1 - z^{-2N}}{1 - z^{-1}} \right].$$

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[8] Oppenheim, A.U. and Schafer, R.W., "Digital Signal Processing," New Jersey: Prentice-Hall, Inc., 1975, p. 45.

Therefore, if x_i is the sampled filtered yaw rate signal, then track curvature, b_i, in degrees/100 feet is given by

$$q_i = x_{i-n+N} - x_{i-n-N} + q_{i-1},$$

$$b_i = q_i/2N.$$

Similarly, actual implementation of the filter $C(z;N,M)$ is achieved by noting that

$$C(z;N,M) = \frac{M}{(2N)^2} z^{-n+2N} \left(\frac{1-2z^{-2N}+z^{-4N}}{1-z^{-1}}\right).$$

Therefore, rate of change of track curvature, c_i, in degrees/100 feet/100 feet is given by

$$r_i = x_{i-n+2N} - 2x_{i-n} + x_{i-n-2N} + r_{i-1},$$

$$c_i = r_i \frac{M}{(2N)^2}.$$

The track curvature data, b_i, and rate of change of track curvature data, c_i, are analyzed by the track geometry measurement algorithm to automatically determine the track configuration using analysis techniques developed at ENSCO.

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[9] "Special Algorithms in the T-6 Track Geometry Software," ENSCO, Inc., Contract No. DOT-FR-54190, December 1977.

5. TRACK GEOMETRY EXCEPTION REPORT

The track geometry exception report cover page is printed during system initialization and should be filled in by the operator at the beginning of a track inspection run. An example of the track geometry exception report is given in Figure 15. Three program constants are given on the cover page of the track geometry exception report- i.e., the window length for location detection and the *X* and *Y* hysteresis values used in exception checking.

Searching for automatic location targets will start at the point where the LOCATION UP or LOCATION DOWN buttons on the TGCC are depressed and will continue until the vehicle travels a distance corresponding to the ALD window length. This permits the system operator to select specific targets while excluding other targets from automatic detection. The *X* and *Y* hysteresis values are used to combine track geometry exceptions to simplify the interpretation of the track geometry exception report. During exception checking, a track geometry parameter must exceed the threshold for a given class of track for the length defined as the *X* hysteresis before it is considered an exception to the FRA TSS. The exception is not terminated until the track geometry parameter falls below the threshold for a given class of track for the length defined as the *Y* hysteresis before the exception is terminated.

An example data page of the track geometry exception report is given in Figure 16. The data page contains a page header, including a page number and 48 lines of detected exceptions and/or operation log information. Each item of information is printed on one line, and track geometry exceptions are easily recognizable since only track geometry exceptions have numerical

```
                    HY-RAIL VEHICLE TRACK GEOMETRY REPORT

PREPARED FOR:       FEDERAL RAILROAD ADMINISTRATION
                    WASHINGTON, DC

PREPARED BY:        ENSCO, INCORPORATED
                    SPRINGFIELD, VA

DATE:

STARTING TIME:

TEST DESCRIPTION:


PROGRAM CONSTANTS   ALD WINDOW   -    FT
                    X HYSTERESIS -    FT
                    Y HYSTERESIS -    FT

OPERATOR:

NOTES:




HY-RAIL PROGRAM REV.A
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FIGURE 15. EXAMPLE OF TRACK GEOMETRY EXCEPTION REPORT, TITLE PAGE

```
                   HY-RAIL VEHICLE TRACK GEOMETRY REPORT            PAGE   2

   LOCATION             :        TRACK         :             DATA
MILE         LOC        :                      :                LENGTH   MIN
POST: FEET:  NO: MI-FEET: NO: TYPE: CONF: CLASS: PARM: THRES +-: FEET : CLASS

 107   218   37  11 5271   1   P      T     2    GAGE  57.50 +    15      0
       248       12 0021              T          GAGE  57.50 +    19      1
       277          0047              T          GAGE  56.00 -    11      0
       768   38     0541              T          LOCU
       868          0641              T          ALD
      3044       00-2176              S          WARP   1.75 +     6      1
 108                2434              S          MPU
       103          2537              T          M102
       110          2544   2          T          TRKN
      4206       01-1360       F      T          TRKT
      4406          1560              C          VMAX     25 -    15      1
 109                2600              C          MPU
       100          2700              C          GSNR
       110          2710              S          GSND
       503          3203              T     3    TRKC
      1503   39     4203              T          LOCU
      1632          4332              T          AND
      1682          4382              S          M115
```

FIGURE 16. EXAMPLE OF TRACK GEOMETRY EXCEPTION REPORT, DATA PAGE

data under the data field of the header. The data page is divided into three sections as defined in the header information. The left portion of the page contains milepost and location distance reference information. The center portion of the page contains track identification information, such as the track number, track type, curve configuration, and track class. The right portion of the page contains the detected exceptions and the operation log information. The only item that does not have a column heading is the loss of data due to a print buffer full condition. This will be reflected by an asterisk on the left side of the page preceeding a line of track geometry exception report.

Following is a description of the abbreviations appearing in the header on a data page.

ABBREVIATIONS	DEFINITION
MILEPOST	Milepost Number
FEET	Elapsed distance in feet since the last milepost number entry made by the operator
LOC NO	Location Number
MI-FEET	Elapsed distance in miles and feet from the last automatic location target detection
NO	Track Number
TYPE	Track Type
CONF	Curve Configuration
CLASS	Track Class
PARM	Parameter
TRES	Exception Threshold
±	Exception Polarity

LENGTH FEET	Exception Length
MIN CLASS	Minimum Class

Following is a description of the abbreviations which can appear under the various headings on a data page:

TRACK TYPE

P	PASSENGER
F	FREIGHT

CURVATURE CONFIGURATION

T	TANGENT
S	SPIRAL
C	CURVE

PARAMETER	DETECTED TRACK GEOMETRY EXCEPTIONS
GAGE	Gage exception detected by the TGMS. The gage exception checking thresholds are different for tangent and nontangent track as prescribed in ¶215.53b of the FRA TSS.
XLVR	Reverse crosslevel exception detected by the TGMS.
XLV6	Crosslevel greater than six inches detected by the TGMS.
XLEV	Deviation from zero crosslevel exception detected by the TGMS. The deviation from zero crosslevel exception checking thresholds are defined only for tangent track as prescribed in ¶213.63E of the FRA TSS given in Figure 2.
XLVD	Deviation from designated elevation exception detected by the TGMS. The deviation from designated elevation exception checking thresholds are different for spirals and curves as prescribed in ¶213.63C and E of the FRA TSS given in Figure 2.
WARP	Warp exception detected by the TGMS. Warp on spiral track is defined as the difference in crosslevel at two measurment points 31 feet apart. The thresholds for warp or spiral track are given in ¶213.63D of the FRA TSS given in Figure 2. Warp on tangent or curved track is defined as the maximum difference in crosslevel between any two measurement points up to 62 feet apart, inclusively.

	The thresholds for warp on tangent or curved track are given in ¶213.63F of the FRA TSS given in Figure 2.
VMAX	V_{max} calculated in accordance with the equation given in ¶213.57B of the FRA TSS was less than the operating speed limit associated with the posted track class given in ¶213.9a of the FRA/TSS.

PARAMETER	OPERATOR OR SYSTEM STATUS
MPU	Milepost up entered by operator.
MPD	Milepost down entered by operator.
LOCU	Location up entered by operator.
LOCD	Location down entered by operator.
ALD	Target detected by automatic location detector within detection window.
AND	Target not detected by automatic location detector within detection window.
MXXX	Message number entered by operator where XXX is the three-digit message number.
TRKN	Track number entered by operator.
TRKT	Track type entered by operator.
TRKC	Track class entered by operator.
GSNR	Gage sensors retracted by operator.
GSND	Gage sensors placed in down position by operator.
GPTN	Gage sensors placed in protect mode by operator.
GPTF	Gage sensors placed in normal gage measurement mode by operator.
BMUP	Track geometry measurement beam placed in up position by operator.
BMDN	Track geometry measurement beam placed in down position by operator.

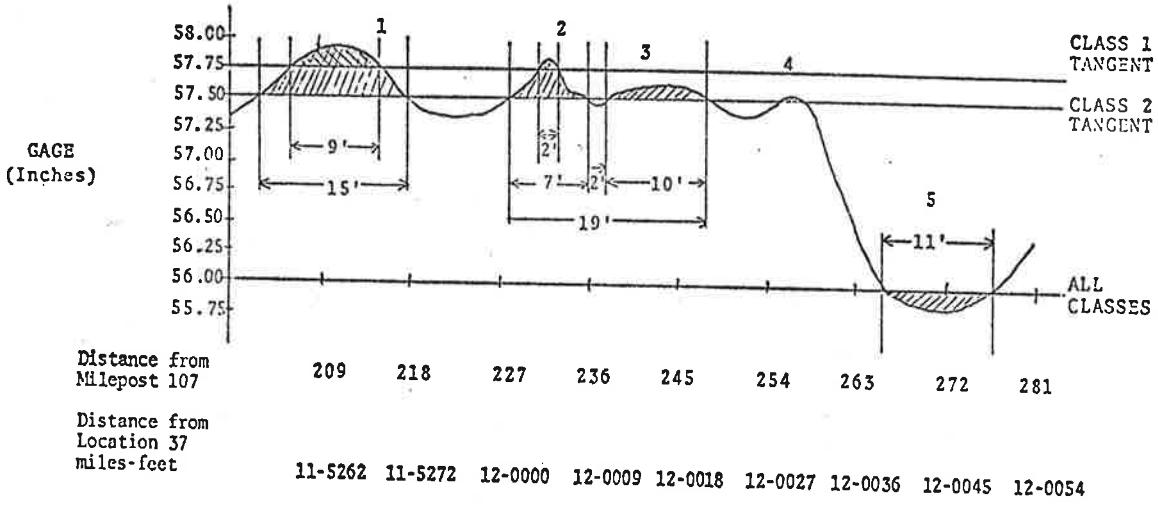
RUN	Track geometry exception reporting placed on-line by operator.
HOLD	Track geometry exception reporting placed off-line by operator.
DIRF	Forward direction detected from tachometer.
DIRR	Reverse direction detected from tachometer.
RECL	Gage sensor recoiled on left side of vehicle (driver side).
RECR	Gage sensor recoiled on right side of vehicle (passenger side).
CURA	Curve analysis algorithm active because vehicle speed has exceeded the minimum speed specified for the inertial curvature system. Vehicle speed must exceed 3.3 mph for curve analysis to be performed. Curve analysis will then be performed until the vehicle speed falls below 3 mph.
CURI	Curve analysis algorithm inactive because vehicle speed is below the minimum speed specified for the inertial curvature system. See the discussion associated with CURA for further details.
SPEED SIMULATE	System has been placed in a speed-simulate or time-based mode for system checkout.
TACHOMETER	System has been placed in tachometer or distance-based mode as required for a track geometry inspection survey.

The computed track geometry parameters are evaluated against FRA TSS thresholds or operator-entered thresholds. On-line exception detection is performed on the following computed parameters: GAGE, XLVR, XLV6, XLEV, XLVD, WARP and VMAX as defined earlier in this section. The exception-detecting software incorporates a hysteresis variable. Each suspected defect is tested to insure that the exception occurs for X number of feet before the exception is registered. When a particular parameter passes below the threshold,it is again tested for Y number of feet before the termination is registered and an output line is generated. The X and Y values have a range of 0 to 31 feet at 1-foot intervals. Values for a particular run can be modified during the computer initialization. If the X and Y distances are set to zero, instantaneous threshold crossings register as exceptions.

To illustrate the exception detection system, a sample graph for the gage parameter is shown in Figure 17. The abscissa is given in feet along the track; the ordinate, in inches of gage. Areas where gage exceeds FRA TSS track class 1 and 2 are shaded. The gage signal exceeds the threshold band at the five circled locations. For illustrating the exception detection logic assume X and Y are set to 3 feet.

Referring to Figure 17, exception 1 begins at 203 feet past milepost 107. The gage value remains above the threshold for 3 feet, which will cause the exception to be flagged internally to the system. The gage value goes below the threshold at 218 feet from milepost 107. Since the gage value remains below the threshold for three feet, the exception length is 15 feet. Beginning at 206 feet from milepost 107, the gage value also goes above the FRA TSS track class 1 threshold for a distance greater than 3 feet; hence, the minimum track class will be registered as 0. The exception polarity is positive as the gage exceeds the threshold. The characteristics of this exception are given in the first data line of the sample exception report given in Figure 17.

Exception 2 begins at 229 feet and passes the X hystersis distance test. At 236 feet, the gage value goes below the threshold, but does not remain below the threshold for 3 feet. At 238 feet, the value again exceeds the threshold but is not flagged because exception 2 has not been terminated. At 248 feet, the value goes below the threshold and remains below for more than 3 feet,



a) GRAPH OF TRACK GAGE EXCEPTION

```
                          HYRAIL VEHICLE TRACK GEOMETRY REPORT              PAGE     2

         LOCATION             :         TRACK          :             DATA
MILE           LOC            :                        :                     LENGTH  MIN
POST:  FEET:   NO:  MI  FEET: NO: TYPE: CONF: CLASS: PARM: THRES  +-:  FEET: CLASS

107    203     37   11  5256   1    P      T      2    GAGE  57.50   +     15     0
       229          12     2                T          GAGE  57.50   +     19     1
       266          12    39                T          GAGE  56.00   -     11     0
```

b) TRACK GEOMETRY EXCEPTION REPORT

FIGURE 17. TRACK GEOMETRY EXCEPTION REPORT EXAMPLE TO DEMONSTRATE HYSTERESIS EXCEPTION DETECTION LOGIC

causing the exception to be terminated and flagged for output. During the exception, the value also exceeded the track class 1 threshold, but not for a distance greater than 3 feet. Therefore, the minimum track class will be registered as 1. The characteristics of this exception are given in the second data line of the track geometry exception report given in Figure 17.

Exception 4 does not pass the X hysteresis distance test and is ignored. Exception 5 is a negative polarity exception that passes the X and Y distance tests. The minimum class is 0 since the exception value goes below the threshold for all classes. The characteristics of this exception are given in the third data line of the track geometry exception report given in Figure 17.

6. ACCEPTANCE TESTS

The acceptance testing of the Track Geometry Measurement System (TGMS) was conducted in accordance with the provisions set forth in contract no. DOT-TSC-1367. Further details concerning the acceptance tests and the supporting raw data can be found in the test plan and test results report, respectively.[10,11] Final testing of the TGMS was based on an operational demonstration, a performance evaluation, and an endurance run. ENSCO personnel were responsible for the maintenance, start-up, calibration and operation of the TGMS and for conducting the actual test program. Transportation Systems Center (TSC) personnel were responsible for the maintenance and operation of the hy-rail vehicle, data recording instrumentation, and processing of the data recorded during the test program. Transportation Systems Center personnel were also responsible for the selection of the test site and for coordinating all test activities with the Providence and Worcester Railroad.

6.1 OPERATIONAL DEMONSTRATION

When the installation and preliminary checkout of the TGMS were completed, the maintenance, start-up, calibration and general operation of the TGMS were demonstrated. The documentation supplied with the TGMS served as the basis of the demonstration. No discrepancies between the documentation and system operation were identified during the operational demonstration. Several recommendations/clarifications were incorporated into the draft versions of the documentation to increase their general utility to the system operator.

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[10] "Track Geometry Measurement System: Test Plan," ENSCO, Inc., Contract No. DOT-TSC-1367, April 1978.

[11] "Track Geometry Measurement System: Test Results Report," ENSCO, Inc., Contract No. DOT-TSC-1367, December 1978.

6.2 PERFORMANCE TESTS

The test section selected by the government for the test and evaluation of the performance characteristics of the TGMS was located between mileposts W18 and W19 on the Gardner Branch of the Providence and Worcester Railroad (P&W RR). The test section was 1500 feet in length and contained approximately 750 feet of tangent track and 750 feet of tangent/spiral/curve track. The track was designated as class 2 by the P&W RR and consisted of mixed and relayed 100-lb, 1920-vintage bolted rail. In accordance with the safety requirements of the contract, the maximum speed during the performance tests was limited to the maximum allowable speed for freight trains on class 2 track, i.e., 25 mph. (The maximum test speed for the performance test was further limited to 15 mph by the government in the interest of safe hy-rail vehicle operations.)

The east rail was selected as the reference rail for the performance test. Station locations were established at 12½-foot intervals on the tangent portion of the track and 6¼-foot intervals on the spiral and curved portions of the track. Automatic Location Detector (ALD) targets were installed in the test section on nominal 50-foot centers. The ALD targets were placed approximately in the centerline of the track. Special consideration was given to the placement of the ALD targets at station locations S-(-10) and S-30 to obtain a test subsection which had a length of 500 feet. Two additional ALD targets were installed at each end of the test section to serve as an absolute starting point and a speed control point for each test run. These two targets were placed 250 feet and 500 feet from each end of the test section. A diagrammatic layout of the test track is given in Figure 18.

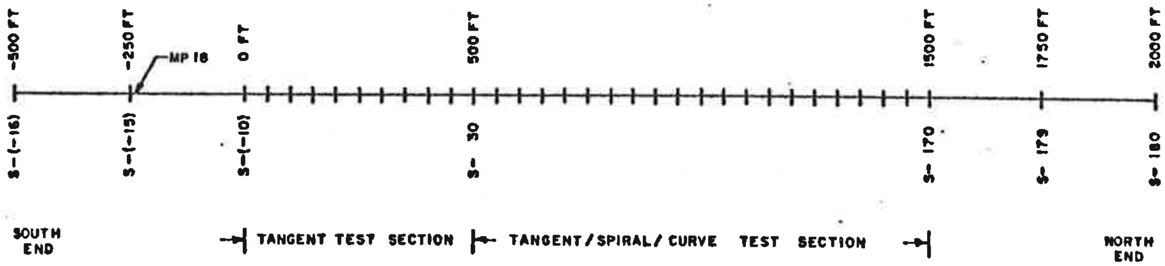

FIGURE 18. LAYOUT OF TRACK SELECTED FOR PERFORMANCE TEST

Unloaded static manual measurements of track gage, crosslevel and curvature were obtained at each station location within the test section. The unloaded track gage and crosslevel measurements were obtained through the use of a manually operated gage and crosslevel bar delivered with the TGMS. The track curvature measurements were obtained with a stringline midchord offset device. No vehicles were within the test section while these measurements were being collected. The unloaded track gage and crosslevel measurements were collected for the purpose of examining the differences between loaded and unloaded track conditions. The unloaded track curvature measurements were collected for the purpose of performing an absolute tolerance test on the curvature measurement system.

Loaded static manual measurements of track gage and crosslevel were obtained at the same station locations defined for the unloaded static manual measurements. The front hy-rail wheels were located as close as practical to the station locations while the loaded static manual track gage and crosslevel measurments were being collected. The physical size of the manually operated gage and crosslevel bar and the size of the hy-rail wheel dictated that the actual load point for the front hy-rail wheels be approximately eight inches away from the station locations when the manual measurements were performed. Since it would not have been meaningful to perform three-point chord measurements with loading of only one point, loading static manual curvature measurements were not collected in accordance with the test plan. The means and standard deviations of the differences between the unloaded and loaded static manual track gage and crosslevel measurements are given in Table 1.

TABLE 1. SUMMARY OF THE MEANS AND STANDARD DEVIATIONS OF THE DIFFERENCES BETWEEN THE UNLOADED AND LOADED STATIC MANUAL TRACK GAGE AND CROSSLEVEL MEASUREMENTS

LOADED-UNLOADED MEASUREMENTS	MEAN INCHES	STANDARD DEVIATIONS INCHES
GAGE	.036	.052
CROSSLEVEL	.012	.062

Loaded static electronic measurements of track gage and crosslevel were obtained at the same station locations defined for the unloaded and loaded static manual measurements. The loaded static electronic measurements of track gage and crosslevel were obtained from test points in the analog circuitry. The voltages on these test points represent the voltages presented to the analog-to-digital computer from the gage and crosslevel measurement subsystems. Due to the fact that the curvature subsystem is inertial, no loaded static electronic track curvature measurements were obtained in accordance with the test plan.

Comparisons of the loaded static manual and electronic track gage and crosslevel measurements were made to verify compliance with the tenth of an inch absolute tolerance acceptance criteria for these two parameters. In every one of the 181 comparisons the differences between the loaded static manual and electronic measurements for track gage and crosslevel were less than a tenth of an inch, thereby satisfying the absolute tolerance acceptance criteria. Although not part of any acceptance criteria,the mean and standard deviations of the differences between the loaded static manual track gage and crosslevel measurements are given in Table 2. Considering the fact that it was necessary to move the vehicle to align the various geometry measurements with the station locations and that the accuracy of the manually operated gage and crosslevel bar is rated at .03 inches,the standard deviations in Table 2 reflect an excellent comparability between the loaded static manual and electronic track gage and crosslevel measurements. The measured dispersion in the track crosslevel measurements is attributable to additional human judgement required to level the manually operated gage and crosslevel bar when manual track crosslevel measurements are being obtained.

TABLE 2. SUMMARY OF THE MEANS AND STANDARD DEVIATIONS OF THE DIFFERENCES BETWEEN THE LOADED STATIC MANUAL AND LOADED STATIC ELECTRONIC TRACK GAGE AND CROSSLEVEL MEASUREMENTS

MANUAL-ELECTRONIC MEASUREMENTS	MEAN INCHES	STANDARD DEVIATION INCHES
GAGE	.008	.026
CROSSLEVEL	.003	.047

Comparisons of the unloaded static manual and the loaded dynamic electronic track curvature measurements obtained during the low speed (5 mph) performance tests were made to verify compliance with the 1° absolute tolerance acceptance criteria for the curvature measurements. The low speed performance tests were selected as part of the acceptance criteria since they represent the most difficult test for the inertial curvature measurement system. In every one of the 181 comparisons, the differences between the two sets of track curvature measurements were less than 1°/100 ft, thereby satisfying the acceptance criteria.

Although not part of any acceptance criteria, comparisons of the unloaded static manual and the loaded dynamic electronic track curvature measurements obtained during the high speed (15 mph) performance tests were made, and the 1°/100 ft absolute tolerance criteria were also applied. In every one of the 181 comparisons, the differences between the two sets of track curvature measurements were also less than 1°/100 ft. In addition, the mean and standard deviations of the differences of unloaded static manual and the loaded dynamic electronic track curvature measurements obtained during both the low (5 mph) and high (15 mph) speed performance tests were calculated and are given in Table 3. The results reflect the excellent average performance characteristics of the curvature measurement system.

Twenty-two test runs were conducted on the test track at various speeds and in different directions on two consecutive days to determine the repeatability of the track gage, crosslevel and curvature measurements. A summary of the twenty-two runs

TABLE 3. SUMMARY OF THE MEANS AND STANDARD DEVIATIONS OF THE DIFFERENCES BETWEEN THE UNLOADED STATIC MANUAL AND THE LOADED DYNAMIC ELECTRONIC CURVATURE MEASUREMENTS

LOADED-UNLOADED CURVATURE MEASUREMENTS	MEAN °/100 FT	STANDARD DEVIATION °/100 FT
RUN 1 (5 MPH)	-.050	.295
RUN 2 (5 MPH)	-.037	.298
RUN 5 (15 MPH)	-.003	.310
RUN 6 (15 MPH)	-.001	.305

is given in Table 4. Exception reports and stripchart recordings for each of the twenty-two runs are given in the test results report. An example of a stripchart recording and exception report produced by the TGMS during run number 11 are given in Figures 19 and 20, respectively.

An extensive analysis of the analog recordings made during the acceptance tests was conducted by an independent contractor, Kentron International, Inc.,to determine if the measurement subsystems satisfied the applicable acceptance criteria. The raw repeatability results were combined using standard statistical techniques for obtaining the pooled means and variances of the difference between measurements obtained during any two given test runs. The test section was subdivided into two sections for the purpose of this repeatability analysis. Section one extended from station location S-(-10) through S-38 and consisted of 600 feet of tangent track. Section two extended from station location S-38 to S-170 and consisted of 900 feet of tangent/spiral/curve track. The results for the entire 1500 feet of the test track and the acceptance limits for the data were also determined. A summary of the results of the repeatability analysis is contained in Tables 5 through 12.

Examining the results of the repeatability analysis contained in Tables 5 through 12 reveals that the acceptance criteria were satisfied for all combinations of the various runs which were analyzed. A summary of the means and standard deviations for the track gage, crosslevel and curvature measurement subsystems, which includes all runs analyzed over the entire length of the test track, is given in Table 13.

TABLE 4. SUMMARY OF REPEATABILITY PERFORMANCE TESTS

RUN	DIRECTION	SPEED	NOTES
1	North	5 MPH	Constant Speed
2	North	5 MPH	Constant Speed
3	North	10 MPH	Constant Speed
4	North	10 MPH	Constant Speed
5	North	15 MPH	Constant Speed
6	North	15 MPH	Constant Speed
7	North	3-15 MPH	Variable Speed and Acceleration
8	North	3-15 MPH	Variable Speed and Acceleration
9	South	5 MPH	Constant Speed
10	South	5 MPH	Constant Speed
11	South	5 MPH	Constant Speed
12	South	5 MPH	Constant Speed
13	South	10 MPH	Constant Speed
14	South	10 MPH	Constant Speed
15	South	15 MPH	Constant Speed
16	South	15 MPH	Constant Speed
17	South	3-15 MPH	Variable Speed and Acceleration
18	South	3-15 MPH	Variable Speed and Acceleration
19	South	3-15 MPH	Variable Speed and Acceleration
20	South	3-15 MPH	Variable Speed and Acceleration
21	North	3-15 MPH	Variable Speed and Acceleration
22	North	3-15 MPH	Variable Speed and Acceleration

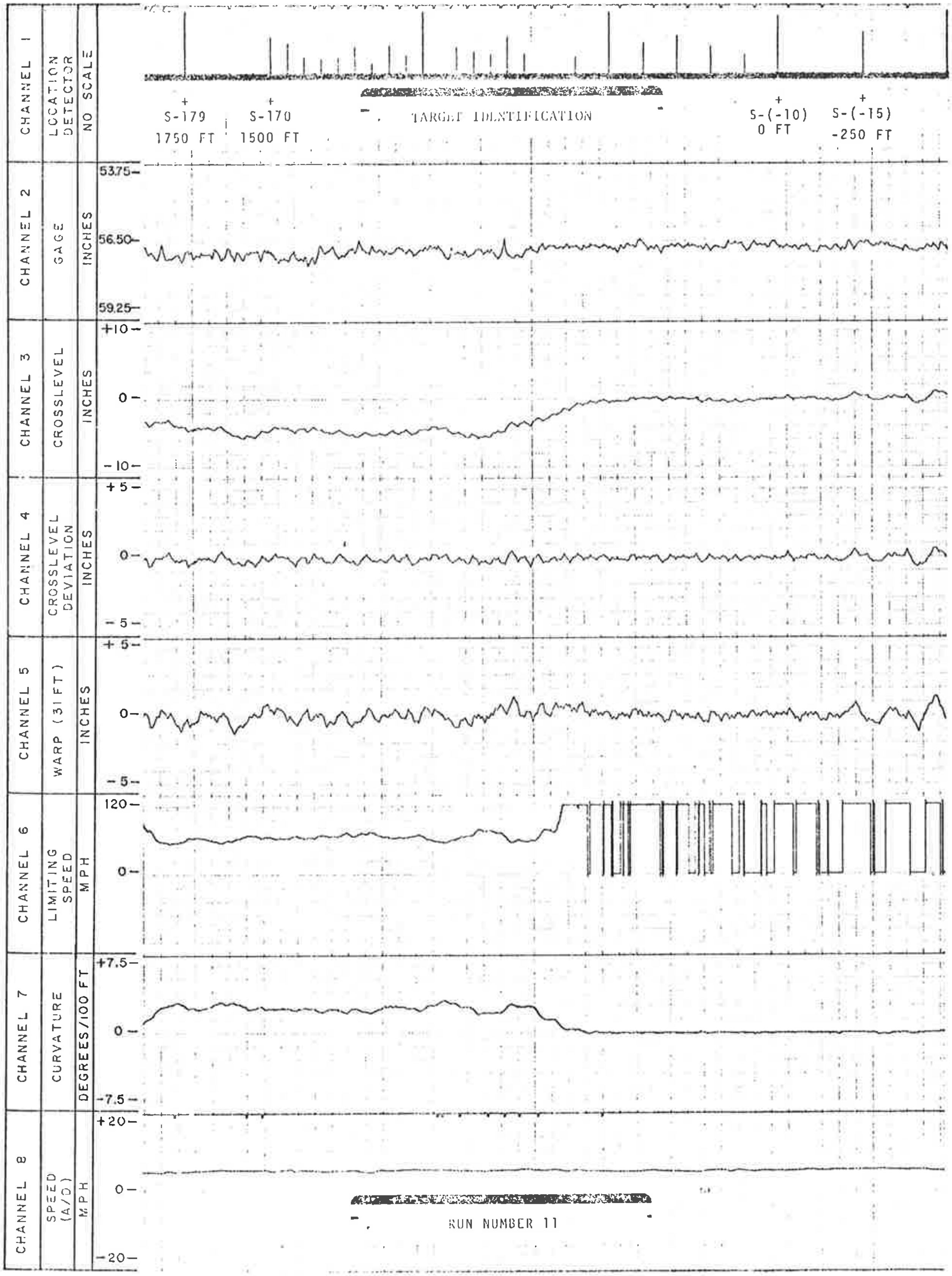

FIGURE 19. STRIPCHART RECORDING FROM PERFORMANCE TEST RUN NUMBER 11

```
      LOCATION            :          TRACK            :                DATA
MILE         LOC          :                           :                      LENGTH  MIN
POST: FEET:   NO: MI FEET: NO: TYPE: CONF: CLASS: PARM: THRES +-: FEET: CLASS


   0     0     0   0     0   1     F           6    TACHOMETER
         0               0                          GPTF
         0               0                          M010
         0               0                          RUN
         0     4         0                          LOCU
         9               9                          CURA
       151             151                          AND
       277             277               T          GAGE  56.750  +     6     5
       229             229               T          XLEV   0.500  +    54     1
       229             229               T          WARP   0.625  +    54     3
       285             285               S          XLVD   0.500  +     7     5
       284             284               S          WARP   0.500  +    18     4
       336             336               S          GAGE  57.000  +     4     5
       336             336               S          XLVD   0.500  +     4     5
       334             334               S          WARP   0.500  +    11     5
       346             346               S          GAGE  57.000  +    25     5
       366             366               S          WARP   0.500  +     5     5
       383             383               S          GAGE  57.000  +    33     5
       412             412               S          WARP   0.500  +     4     5
       295             295               S          VMAX     110  -   121     3
       417             417               C          GAGE  57.000  +    29     5
       466             466               C          GAGE  57.000  +    26     5
       417             417               C          WARP   0.625  +    82     3
       498             498               C          GAGE  57.000  +    33     5
       548             548               C          XLVD   0.500  +     4     5
       541             541               C          GAGE  57.000  +    26     5
       578             578               C          GAGE  57.000  +    21     5
       603             603               C          GAGE  57.000  +    14     5
       549             549               C          WARP   0.625  +    88     2
       417             417               C          VMAX     110  -   200     3
       618             618               S          GAGE  57.000  +    18     5
       643             643               S          GAGE  57.000  +    10     5
       662             662               S          GAGE  57.000  +    10     5
       665             665               S          WARP   0.500  +     7     4
       618             618               S          VMAX     110  -    54     4
       673             673               C          WARP   0.625  +    83     3
       701             701               C          GAGE  57.000  +    63     5
       781     3       781               C          LOCD
       827             827               C          ALD
       770             770               C          GAGE  57.000  +    57     5
       761             761               C          WARP   0.625  +    66     5
       673             673               C          VMAX     110  -   154     3
      2657             325               T          XLEV   0.500  +    45     5
      2701             369               T          GAGE  56.750  +    31     4
```

FIGURE 20. TRACK GEOMETRY EXCEPTION REPORT FROM PERFORMANCE TEST RUN NUMBER 11

```
         LOCATION            :           TRACK          :               DATA
MILE          LOC                                       :                      LENGTH  MIN
POST:  FEET:   NO: MI FEET:  NO:  TYPE:  CONF:  CLASS:  PARM:   THRES   +-:   FEET:  CLASS

 0       0      0    0    0    1    F                6   M011
         0                0                              RUN
         0                0                              TACHOMETER
         0                0                              GPTE
        10               10                              CURA
       258              258                   S          XLVD     0.500  +       5     5
       256              256                   S          WARP     0.500  +      12     5
       271              271                   S          GAGE    57.000  +      21     5
       280              280                   S          WARP     0.500  +       5     5
       315              315                   S          GAGE    57.000  +      25     5
       250              250                   S          VMAX       110  -     100     3
       351              351                   C          GAGE    57.000  +      36     5
       388              388                   C          GAGE    57.000  +      25     5
       419              419                   C          GAGE    57.000  +      16     5
       331              331                   C          WARP     0.625  +     107     3
       443              443                   C          GAGE    57.000  +       8     5
       469              469                   C          XLVD     0.500  +       5     5
       466              466                   C          GAGE    57.000  +      21     5
       503              503                   C          GAGE    57.000  +      15     5
       526              526                   C          GAGE    57.000  +      14     5
       483              483                   C          WARP     0.625  +      57     2
       331              331                   C          VMAX       110  -     209     3
       541              541                   S          GAGE    57.000  +       5     5
       541              541                   S          VMAX       110  -      45     4
       587              587                   C          GAGE    57.000  +       9     5
       587              587                   C          WARP     0.625  +      91     3
       623              623                   C          GAGE    57.000  +      56     5
       706     3        706                   C          LOCD
       749              749                   C          ALD
       692              692                   C          GAGE    57.000  +      57     5
       682              682                   C          WARP     0.625  +      67     5
       587              587                   C          VMAX       110  -     162     4
      1041              292                   C          GAGE    57.000  +      12     5
       976              227                   C          WARP     0.625  +     131     4
       970              221                   C          VMAX       110  -     137     3
      1108              359                   C          VMAX       110  -      13     3
      1133              384                   S          GAGE    57.000  +      20     5
      1145              396                   C          WARP     0.625  +      26     4
      1122              373                   C          VMAX       110  -      51     3
      1186              437                   C          GAGE    57.000  +       6     5
      1196              447                   S          WARP     0.500  +      13     5
      1199              450                   S          GAGE    57.000  +      21     5
      1174              425                   S          VMAX       110  -      83     4
      1283              534                   S          GAGE    57.000  +      21     5
      1258              509                   C          WARP     0.625  +      49     4
      1258              509                   C          VMAX       110  -      49     4
      1334              581                   S          XLVD     0.500  +       5     5
```

FIGURE 20. TRACK GEOMETRY EXCEPTION REPORT FROM PERFORMANCE TEST RUN NUMBER 11 (CONT.)

TABLE 5. MEANS AND STANDARD DEVIATIONS OF GAGE MEASUREMENTS FOR IDENTICAL CONSTANT SPEED RUNS IN THE SAME DIRECTION

COMPARISON OF RUN NUMBERS	SECTION 1		SECTION 2		SECTION 3	
	$\mu_{.06}$* INCHES	$\sigma_{.12}$ INCHES	$\mu_{.06}$ INCHES	$\sigma_{.12}$ INCHES	$\mu_{.06}$ INCHES	$\sigma_{.12}$ INCHES
1-2	-.004	.008	.000	.010	-.002	.009
3-4	.002	.012	.000	.012	.001	.012
5-6	.001	.009	.001	.008	.001	.008

*The subscript indicates the acceptance limit for the numbers given in the column.

TABLE 6. MEANS AND STANDARD DEVIATIONS OF GAGE MEASUREMENTS FOR ANY TWO RUNS

COMPARISON OF RUN NUMBERS	SECTION 1		SECTION 2		SECTION 3	
	μ .08 INCHES	σ .15 INCHES	μ .08 INCHES	σ .15 INCHES	μ .08 INCHES	σ .15 INCHES
1-2	-.004	.008	.000	.010	-.002	.009
3-4	.002	.012	.000	.012	.001	.012
5-6	.001	.009	.001	.008	.001	.008
1-4	-.013	.008	-.007	.013	-.009	.012
4-5	.001	.010	.003	.012	.002	.012
1-5	-.011	.012	-.003	.019	-.006	.017
1-11	-.028	.026	-.009	.030	-.017	.030
3-13	-.016	.027	-.003	.033	-.008	.032
5-15	-.019	.028	-.010	.036	-.013	.033
3-20	-.014	.030	-.007	.034	-.010	.032
22-13	NOTE 1	NOTE 1	.016	.034	.016	.034
22-20	NOTE 1	NOTE 1	.012	.032	.012	.032

Note 1: Run number 22 was a special test run to examine the tracking characteristics of the hy-rail vehicle and was conducted only in Section 2.

TABLE 7. MEANS AND STANDARD DEVIATIONS OF CROSSLEVEL MEASUREMENTS FOR IDENTICAL CONSTANT SPEED RUNS IN THE SAME DIRECTION

COMPARISON OF RUN NUMBERS	SECTION 1		SECTION 2		SECTION 3	
	μ .10 INCHES	σ .20 INCHES	μ .10 INCHES	σ .20 INCHES	μ .10 INCHES	σ .20 INCHES
1-2	-.003	.024	-.011	.031	-.008	.029
3-4	-.002	.024	.000	.031	.001	.029
5-6	.004	.020	-.004	.037	.000	.032

TABLE 8. MEANS AND STANDARD DEVIATIONS OF CROSSLEVEL MEASUREMENTS FOR ANY TWO RUNS

COMPARISON OF RUN NUMBERS	SECTION 1		SECTION 2		SECTION 3	
	μ .15 INCHES	σ .30 INCHES	μ .15 INCHES	σ .30 INCHES	μ .15 INCHES	σ .30 INCHES
1-2	-.003	.024	-.011	.031	-.008	.029
3-4	.002	.024	.000	.031	.001	.029
5-6	.004	.020	-.004	.037	.000	.032
1-4	-.043	.025	-.033	.048	-.037	.041
4-5	-.044	.026	-.003	.085	-.020	.070
1-5	-.087	.033	-.054	.109	-.067	.089
1-11	-.018	.040	-.056	.088	-.041	.075
3-13	.016	.042	-.014	.117	-.008	.096
5-15	.016	.045	-.023	.154	-.007	.124
3-20	.030	.044	-.034	.108	-.008	.094
22-13	NOTE 1	NOTE 1	-.137	.108	-.137	.108
20-22	NOTE 1	NOTE 1	.118	.077	.118	.077

Note 1: Run number 22 was a special test run to examine the tracking characteristics of the hy-rail vehicle and was conducted only in Section 2.

TABLE 9. MEANS AND STANDARD DEVIATIONS OF CURVATURE MEASUREMENTS FOR IDENTICAL CONSTANT SPEED RUNS IN THE SAME DIRECTION

COMPARISON OF RUN NUMBERS	SECTION 1		SECTION 2		SECTION 3	
	μ .3 °/100 FT	σ .6 °/100 FT	μ .3 °/100 FT	σ .6 °/100 FT	μ .3 °/100 FT	σ .6 °/100 FT
1-2	-.004	.040	-.009	.107	-.007	.087
3-4	.029	.047	.025	.050	.027	.049
5-6	-.002	.035	.004	.084	.001	.069

TABLE 10. MEANS AND STANDARD DEVIATIONS OF CURVATURE MEASUREMENTS FOR IDENTICAL CONSTANT SPEED RUNS IN OPPOSITE DIRECTIONS

COMPARISON OF RUN NUMBERS	SECTION 1		SECTION 2		SECTION 3	
	μ .4 °/100 FT	σ .7 °/100 FT	μ .4 °/100 FT	σ .7 °/100 FT	μ .4 °/100 FT	σ .7 °/100 FT
1-11	-.088	.086	-.078	.470	-.087	.367
3-13	-.032	.071	-.027	.447	-.029	.349
5-15	+.001	.076	.069	.490	.042	.384

TABLE 11. MEANS AND STANDARD DEVIATIONS OF CURVATURE MEASUREMENTS FOR ANY TWO VARIABLE SPEED RUNS IN OPPOSITE DIRECTIONS

COMPARISON OF RUN NUMBERS	SECTION 1		SECTION 2		SECTION 3	
	μ .6 °/100 FT	σ 1.2 °/100 FT	μ .6 °/100 FT	σ 1.2 °/100 FT	μ .6 °/100 FT	σ 1.2 °/100 FT
20-22	NOTE 1	NOTE 1	.210	.462	.210	.462

NOTE 1: Run number 22 was a special run to examine the tracking characteristics of the hy-rail vehicle and was conducted only in Section 2.

TABLE 12. MEANS AND STANDARD DEVIATIONS OF CURVATURE MEASUREMENTS FOR ANY TWO RUNS

COMPARISON OF RUN NUMBERS	SECTION 1		SECTION 2		SECTION 3	
	$\mu_{.6}$ °/100 FT	$\sigma_{1.2}$ °/100 FT	$\mu_{.6}$ °/100 FT	$\sigma_{1.2}$ °/100 FT	$\mu_{.6}$ °/100 FT	$\sigma_{1.2}$ °/100 FT
1-2	-.004	.040	-.009	.107	-.007	.087
3-4	.029	.047	.025	.050	.027	.049
5-6	-.002	.035	.004	.084	.001	.069
1-4	-.003	.044	.011	.065	.005	.058
4-5	-.045	.040	-.030	.086	-.036	.072
1-5	-.049	.046	-.049	.087	-.049	.074
1-11	-.088	.086	-.078	.470	-.087	.367
3-13	-.032	.071	-.027	.447	-.029	.349
5-15	.001	.076	.069	.490	.042	.384
3-20	.011	.069	.223	.425	.138	.348
22-12	NOTE 1	NOTE 1	-.036	.508	-.036	.508
22-20	NOTE 1	NOTE 1	.210	.462	.210	.462

NOTE 1: Run number 22 was a special test run to examine the tracking characteristics of the hy-rail vehicle and was conducted only in Section 2.

TABLE 13. SUMMARY OF THE MEANS AND STANDARD DEVIATIONS FOR GAGE, CROSSLEVEL AND CURVATURE MEASUREMENTS

MEASUREMENT SUBSYSTEM	ACCEPTANCE LIMITS		MEASURED LIMITS	
	μ	σ	μ	σ
GAGE	.08 in	.15 in	.003 in	.025 in
CROSSLEVEL	.15 in	.30 in	.018 in	.082 in
CURVATURE	.60 degs	1.20 degs	.015 degs	.305 degs

During each of the twenty-two test runs all ALD targets within the test zone were detected with no false alarms, which satisfied the automatic location detection system acceptance criteria. Also, for each of the twenty-two test runs the number of feet counted between station locations S-(-10) and S-30 was 500 ± 1 feet, which satisfied the distance measurement system acceptance criterion.

Special test data were collected by the government during the performance test to verify the accuracy of the speed measurement system. The acceptance criterion for the speed measurement system was that the average speed over a fixed distance between ALD targets be within ±.5 mph of the actual average speed of the hy-rail vehicle. The calibration and linearity of the speed measurements was checked by comparing the average speed measurement over a 100-foot section of track with the actual average speed of the hy-rail vehicle derived from the average count of positive zero crossings per block distance interrupt of a 1 KHz signal which was recorded on the analog tapes during the acceptance test. The results of the analysis of the speed measurement system is given in Table 14. The maximum difference detected between the two sets of speed measurement was .03 ft/sec (.02 mph), which clearly satisfies the ±.5 mph acceptance criterion.

The daily calibration of the TGMS was performed only once at the beginning of each test day during any of the acceptance tests. Since each of the acceptance criteria was satisfied, no parameter exhibited a change in calibration that would cause degradation of system performance in excess of the acceptance tolerances, thereby satisfying the acceptance criteria for calibration stability.

TABLE 14. ANALYSIS OF SPEED MEASUREMENTS

RUN	SYSTEM SPEED FT/SEC	DERIVED SPEED FT/SEC	DIFFERENCE FT/SEC
1	9.65	9.65	0.00
2	7.72	7.69	0.03
3	13.54	13.57	-0.03
4	20.65	20.68	+0.03

The tangent/spiral/curve transition analysis logic performed in the TGMS is dependent on the quality of the track alignment. The primary tangent/spiral transition was consistently located within approximately 4 feet while heading in the northerly direction and within approximately 10 feet while heading in the southerly direction. However, the two transition points were approximately 100 feet apart due to the discrete thresholding logic and variation of the response of the curvature system within acceptance limits. All transition points, however, were within 150 feet of their actual locations on the track in accordance with original specifications of the system.

Comparison of the various exception reports with the stripcharts collected during the test program demonstrated that the TGMS has accurately reported existing exceptions to the FRA TSS and that the location and length of the exceptions are within the tolerance specifications for the TGMS. Two minor problems were identified during the test and evaluation of the TGMS which were rectified after the completion of the acceptance test. Six bits of one data mask within the ALD detection algorithm were entered incorrectly into the computer during the software development phase, which caused a non-print condition for exceptions located up to 221 feet past the first ALD target detected within the ALD search window initiated by the system operator. However, since the tests were conducted in both directions on the test track, all exceptions were identified and reported on the track geometry exceptions reports. The polarity of the centrifugal acceleration compensation signal in the crosslevel system was reversed. This error was corrected mathematically using the track curvature and vehicle speed measurements collected for each of the repeatability tests.

Finally, vehicle road/guide wheel misalignment caused a spurious track curvature measurement whenever the operator accelerated or decelerated at the limit of the vehicle capacity. This phenomenon could be corrected through the use of an additional gage-type displacement transducer but was deemed unnecessary since this is not normal testing procedure.

6.3 ENDURANCE TEST

After the operational demonstration and performance tests were completed, an endurance run was performed on the Gardner Branch of the Providence and Worcester Railroad extending between mileposts W10 and W25. Most of the track was designated as class 1 by the P&W RR and consisted of mixed and relayed, 100 lb., 1920 vintage bolted rail. Due to the low-speed requirement imposed by the track and hy-rail vehicle, the endurance test was limited to 12 hours in accordance with the contractual specifications. The distance traveled during the endurance test was approximately 65 miles. No failures of any TGMS components occurred during the endurance test, which satisfied the acceptance test criterion.

Two incidents did occur during the endurance test which are noteworthy. The first incident occurred when the right cross-level displacement transducer snagged a branch protruding over the rail head. The breakaway mechanism designed into the cross-level displacement transducer cable released, preventing any damage to the instrumentation. The breakaway mechanism was reengaged, Transportation System Center personnel checked the daily cross-level calibration as a training exercise, and the test was continued without further incident. The second incident occurred when the hy-rail vehicle hit a lateral mismatch while traveling in reverse at a speed of approximately four mph. The hy-rail vehicle rear hy-rail wheels rode up the mismatch and derailed.

Results of the test activities indicate that the relative alignment between the highway wheels and the hy-rail guide wheels should be reexamined for potential safety hazards.

7. CONCLUSIONS

The TGMS has the capability to measure or derive gage, cross-level (superelevation), warp (twist), curvature, maximum operating speeds for curves, vehicle speed and elapsed distance at speeds from near 0 to 30 mph. The TGMS is equipped with an automatic location detection system to accurately reference detected track geometry exceptions to permanent fixtures of the track roadbed. The track geometry measurements are compared to the FRA TSS in real time and all detected exceptions are reported by the onboard digital computer in a concise report.

Analysis of the data collected during the acceptance test has demonstrated that the track geometry measurement system performance satisfies the acceptance criteria. The average performance of the track geometry measurement system, taking into consideration runs in opposite directions at various speeds on different days, yielded the results shown in Table 15.

The automatic location detection system detected 100% of the targets within the test section and had 0 false alarms for all 22 runs. The distance measurement system accuracy was better than .2%, and the elapsed distance of the 500 foot test section was measured to within 1 foot as demonstrated on each of the track geometry exception reports. The speed measurement system average accuracy was better than .07%, which corresponds to an error of .02 mph. The calibration of the track geometry measurement system was stable. The daily calibration check is simple and can be performed rapidly by one individual with minimum training. The track geometry exception report repeatability was excellent, and track geometry exception detections were located in accordance with contractual obligations.

TABLE 15. AVERAGE PERFORMANCE OF THE TRACK GEOMETRY MEASUREMENT SYSTEM

MEASUREMENT SUBSYSTEM	ACCEPTANCE LIMITS		MEASURED LIMITS	
	μ	σ	μ	σ
GAGE	.08 in	.15 in	.003 in	.025 in
CROSSLEVEL	.15 in	.30 in	.018 in	.082 in
CURVATURE	.60 degs	1.20 degs	.015 degs	.305 degs

8. RECOMMENDATIONS

The TGMS currently has the capability to provide the track inspector with accurate measurements of track gage, crosslevel (superelevation), warp (twist), curvature, the maximum operating speeds for curves, vehicle speed and elapsed distance at speeds from near 0 to 30 mph. The addition of instrumentation to measure track profile and/or alignment would further improve the utility of the track inspection vehicle to the track inspector. The mechanical, electrical, electronic and software features of the TGMS have been designed to facilitate the addition of these two measurement capabilities.

The track geometry exception report,which is produced by the digital computer onboard the vehicle,was designed to report detected exceptions, their location relative to milepost markers and location targets, their length and the minimum FRA TSS track class. In addition, in accordance with contractual requirements for each detected exception, the track geometry exception report printed the threshold associated with the posted track class for that particular category of exception. Prior to completion of the present contract and subsequent to the test activities, several software modifications were incorporated into the track geometry measurement software to improve the utility of the track geometry exception report. The most significant modification included the changes required to print the maximum value of the detected exception instead of the threshold. An example of the revised track geometry exception report is shown in Figure 21.

Packaging of the track geometry measurement system within the hy-rail vehicle was constructed in accordance with contractual specifications in an attempt to minimize lateral space requirements. If, at a future date, the space is available, it would be

```
        LOCATION            :           TRACK           :              DATA
 MILE          LOC          :                           : ENTRY    MAX      LENGTH  MIN
 POST: FEET:  TO: MI FEET: NO: TYPE: FACT: CLASS: TYPE:  EXCEPT : FEET: CLASS

   0       0    0   0     0    1     F           6    SPEED SIMULATE
           0              0                           GPTF
           1              1                           RUN
           1              1                           CURA

         221              221          C          GAGE   55.137 -   3855     0
         221              221          C          XLVR    1.640 +   3855     0
         221              221          C          VMAX        0 -   3855     0
        4077             4077          S          GAGE   55.160 -     35     0
        4090             4090          S          XLVD    2.730 +     33     0
        4127             4127          T          XLEV    4.405 +     48     0
        4130             4130          T          XLEV    2.135 +     19     1
        4133             4133          T          WARP    6.540 +    138     2
        4899             4899          S          XLVD    0.785 +      6     5
        4899             4899          S          XLVR    2.112 +      6     0
        4899             4899          S          VMAX        0 -      6     0
        4906             4906          C          XLVD    3.175 +     49     2
        4906             4906          C          WARP    4.465 +     49     2
        4912             4912          C          XLVR    2.335 +     43     2
        4912             4912          C          VMAX        0 -     43     2
        4956             4956          S          XLVD    1.105 +     40     3
        4971             4971          S          WARP    2.235 +     32     4
        5006             5006          T          WARP    2.235 +     27     1
        6176         1    896          T          WARP    2.740 +     62     1
        6176              896          T          XLEV    2.135 +    108     1
        6285             1005          S          XLVD    1.920 +     23     0
        6315             1035          C          XLVR    2.335 +     43     0
        6315             1035          C          VMAX        0 -     43     0
        6309             1029          C          XLVD    2.320 +     75     1
        6315             1035          C          WARP    4.465 +     69     0
        6385             1105          S          WARP    2.230 +      5     0
        6404             1124          S          XLVR    0.110 +      4     2
        6404             1124          S          VMAX        0 -      4     2
        6409             1129          T          WARP    2.230 +     12     1
        6459             1179          T          WARP    4.470 +     94     0
        6461             1181          T          XLEV    2.340 +    173     1
        6635             1355          S          XLVD    1.950 +     24     0
        6654             1374          S          VMAX      105 -      5     5
        6660             1380          C          XLVD    2.210 +     44     1
        6665             1385          C          WARP    4.470 +     63     0
        6665             1385          C          XLVR    2.340 +    119     0
        6660             1380          C          VMAX        0 -    124     0
        6841             1561          S          WARP    4.470 +     32     0
        6802             1522          S          XLVD    2.225 +     78     0
        6841             1561          S          XLVR    2.130 +    118     0
        6841             1561          S          VMAX        0 -    118     2
        7016             1736          S          WARP    4.465 +     31     0
        6976             1696          S          XLVD    2.225 +     79     0
```

FIGURE 21. TRACK GEOMETRY EXCEPTION REPORT, REV. E

advantageous to separate the instrumentation contained in the rack into two separate groups. The first group would consist of the digital computer, the track geometry unit, the digital control unit, power conditioning equipment, and the blower in a standard-width (19 inch) instrumentation rack. The printer and paper feed mechanism could then be placed side by side on a work bench for the convenience of the system operator and track inspector.

To maintain maximum operational efficiency, it would be desirable to maintain a stock of electronic spares at the board level for the digital computer and the track geometry signal conditioning equipment. Also, certain items were selected for inclusion in the TGMS because of their superior performance characteristics. These items have relatively long lead time deliveries and should also be stocked.

9. REFERENCES

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*Material on file at DOT/TSC.

APPENDIX A

TRACK GEOMETRY MEASUREMENT SYSTEM OPERATIONAL CONTROLS AND INDICATORS

Total control of the Track Geometry Measurement System (TGMS) can be accomplished via the Track Geometry Control Console (TGCC) during a track inspection survey. The following descriptions of the control and display functions provided by the TGCC are given to demonstrate the automatic features which simplify the operation of the TGMS. The operational mounting position of the TGCC is shown in Figure 4. A detailed layout of the front panel of the TGCC is shown in Figure 5.

A.1 OPERATIONAL CONTROLS

The following paragraphs contain a description of each control button available on the TGCC and the action taken by the TGMS after the button is depressed.

A.1.1 Sensors Up

This button is used to place the gage sensor measurement wheels in the up or retracted position. When this button is depressed the gage sensors will rotate 45° upward and then traverse in toward the center of the beam. When the gage sensors rotate upward, a microswitch on the beam assembly is activated and the light in the SENSORS UP button will turn ON. A reference line will be printed on the exception report with GSNR in the parameter column to record the operator command. Checking for gage exceptions will not be performed while the gage sensors are in the retracted position. Analysis of any gage exception in progress will be terminated and printed on the track geometry exception report.

A.1.2 Sensors Down

This button is used to place the gage sensor measurement wheels in the down or measurement position. When this button is depressed, the gage sensors will rotate 45° downward and extend out until the gage sensors contact the rails. When the gage sensors rotate 45° downward, a microswitch on the beam assembly is activated and the light in the SENSORS DOWN button will turn ON. A reference line will be printed on the exception report with GSND in the parameter column to record the operator command. Checking for gage exceptions will not begin unless the beam is down, the down microswitch is activated, and a 44 foot delay has been performed to give the sensors time to achieve full contact pressure against the rail.

A.1.3 Beam Up

This button is used to place the track geometry measurement beam in the up or retracted position. When this button is depressed, the track geometry measurement beam assembly will rotate upward until it contacts the hy-rail struts. Just prior to reaching the full retraction position, a microswitch on a beam control hydraulic cylinder will be activated and the light on the BEAM UP button will turn ON. A reference line will be printed on the exception report with BMUP in the parameter column to record the operator command. Checking for track geometry exceptions will not be conducted while the beam is in the retracted position.

A.1.4 Beam Down

This button is used to place the track geometry measurement beam in the down or measurement position. When this button is depressed, the track geometry measurement beam assembly will rotate downward until the cylindrical reference wheels contact the top of the rails. Just after leaving the full retracted position, a microswitch on a beam control hydraulic cylinder will be activated and the light in the BEAM DOWN button will turn ON. A reference line will be printed on the exception report with BMDN in the parameter column to record the operator command. Checking for track geometry exceptions will not begin until the beam down microswitch is activated and a 44 foot delay has been effected to give the beam time to achieve full contact pressure against the rail.

A.1.5 Location Up

This button is used to enter a location number and to initiate system detection of an ALD target. If the LOCATION UP button is depressed without having entered data, the current location number will be incremented by 1. The new location number will be displayed in the LOCATION window on the TGCC. A reference line will be printed on the exception report with LOCU in the parameter column to record the operator command. If an ALD target is detected within the predefined search length, an additional reference line will be printed with ALD in the parameter column, and the counters monitoring the elapsed distance since the last ALD target detect will be reset to 0. If an ALD target is not detected within the predefined search length, the additional reference line will be printed with AND in the parameter column and the counters associated with elapsed distance since the last ALD target detect will not be reset.

A.1.6 Location Down

This button is used to enter a location number and to initiate system detection of an ALD target. If the LOCATION DOWN button is depressed without having entered data, the current location number will be decremented by 1. The new location number will be printed on the exception report with LOCD in the parameter column to record the operator command. If an ALD target is detected within the predefined search length, an additional reference line will be printed with ALD in the parameter column and the counters monitoring the elapsed distance since the last ALD target detect will be reset to zero. If an ALD target is not detected within the predefined search length, the additional reference line will be printed with AND in the parameter column and the counters associated with elapsed distance since the last ALD target detect will not be reset.

A.1.7 Track Type

This button is used to enter the type of track, passenger or freight being inspected. An operator entry of 1 signifies a track type of passenger,and an operator entry of 2 signifies a track type of freight. If the TRACK TYPE button is depressed without having entered data, the new track type number will be changed from a 1 to a 2 or from a 2 to a 1, depending on the current track type number. If the TRACK TYPE button is depressed and the data entered is not a 1 or a 2, the new track type number will default to a 2 which contains the most restrictive threshold categories. The new track type number will be displayed in the TRACK TYPE window on the TGCC. A reference line will be printed on the exception report with TRKN in the parameter column to record the operator command. Analysis of any limiting speed exceptions in progress will be terminated and printed on the track geometry exception report.

A.1.8 Message

This button is used to enter the number of a message which represents an event for which there is no corresponding TGCC button. If the MESSAGE button is depressed without data having been entered, the existing message number will be incremented by 1. The new message number will be displayed in the MESSAGE window on the TGCC. A reference line will be printed on the exception report with MXXX, where XXX is the new message number, in the parameter column to record the operator command.

A.1.9 Milepost Up

This button is used to enter the number of a new milepost and indicates that the milepost numbers are increasing in the direction of travel. If the MILEPOST UP button is depressed without data having been entered, the existing milepost number will be incremented by 1. The new milepost number will be displayed in the MILEPOST window on the TGCC. A reference line will be printed on the exception report with MPU in the parameter column and the elapsed distance from milepost counters on the exception report and on the TGCC will be reset to 0.

A.1.10 Milepost Down

This button is used to enter the number of a new milepost and indicates that the milepost numbers are decreasing in the direction of travel. If the MILEPOST DOWN button is depressed without data having been entered, the existing milepost number will be decremented by 1. The new milepost number will be displayed in the MILEPOST window on the TGCC. A reference line will be printed on the exception report with MPD in the parameter column and the elapsed distance from milepost counters on the exception report and on the TGCC will be reset to 0.

A.1.11 Run

This button is used to begin track geometry exception checking. A reference line will be printed on the exception report with RUN in the parameter column.

A.1.12 Hold

This button is used to stop track geometry exception checking. A reference line will be printed on the exception report with HOLD in the parameter column. All operator commands via the TGCC may still be performed even though track geometry exception checking has stopped.

A.1.13 Track Class

This button is used to record the posted class of the track being inspected. The track class defines the maximum operating class thresholds to be used for exception checking. If the TRACK CLASS button is depressed without data having been entered or if the data entered is not in the range from 1 to 6, the new track class number will default to 6, which is the most restrictive threshold category. The new track class number will be displayed in the TRACK CLASS window on the TGCC. A reference line will be printed on the exception report with TRKC in the parameter column to record the operator command. Analysis of all track geometry exceptions in progress will be terminated using the old track class number and printed on the track geometry exception report. Analysis of track geometry data using the new posted track class number is initiated.

A.1.14 Track Number

This button is used to record the number of the track being inspected in an area where multiple track occur in the same route. If the TRACK NUMBER button is depressed without data having been entered, the existing track number will be incremented by 1. The new track number will be displayed in the TRACK NUMBER window on the TGCC. A reference line will be printed on the exception report with TRKN in the parameter column to record the operator command.

A.1.15 Speed Simulate

This button is used to switch between a time-driven data sampling interrupt mode (SPEED SIMULATE) and a distance-driven data sampling interrupt mode (TACHOMETER). The TGMS is in the SPEED SIMULATE mode whenever the light under the speed simulate button is ON. This mode is for calibration or special test conditions and should not be depressed when track inspection operations are in progress. When the system status word indicates that the system is in a speed simulate mode, a reference line will be printed with SPEED SIMULATE in the parameter column to record the change in system status. When the system status indicates that the system is in a tachometer mode, a reference line will be printed with TACHOMETER in the parameter column to record the change in system status.

A.1.16 Gage Protect

This button is used to switch the gage sensors between protect and normal gage measurement modes. Placing the gage sensors in a protect mode means the sensors may move toward the center of the beam but may not move out toward the rail. The gage protect mode should be employed while traversing areas of track where there is a gap in the rail head, i.e., switches, frogs, etc. Exception checking for gage will cease while in the gage protect mode and analysis of any gage exceptions in progress will be terminated and printed on the exception report. When the system status indicates that the gate sensors are placed in the gage protect mode, a reference line will be printed with GPTN in the parameter column to record the change in system status. When the system status indicates that the gage sensors are placed in the normal measurement mode or gage protect off, a reference line will be printed with GPTF in the parameter column to record the status of the system. When the gage sensors are placed in the normal measurement mode, checking for gage exceptions will not begin until a 44-foot delay has been performed to give the sensors time to achieve full contact pressure against the rail.

A.1.17 Data Entry 0-9

These buttons are used to enter digital data associated with the functional parameters - i.e., milepost, message, etc. The data entries will be displayed in the data entry window on the TGCC and should be entered starting with the most significant digit.

A.1.18 Clear Entry

This button is used to clear the DATA ENTRY display to correct an erroneous data entry prior to performing a functional command. The DATA ENTRY display is cleared automatically after the functional command has been processed.

A.1.19 Lamp Test

This button is used to check that all data display segments are functional. The lamp test does not interfere with normal operations of the TGMS.

A.2 OPERATIONAL INDICATORS

The TGCC has four special-purpose operational indicators which it is important to monitor during a track inspection survey. The meaning of each operational indicator and the action to be taken when the light is automatically activated is described in the following paragraphs.

A.2.1 Sensor Recoil (Left or Right)

The gage sensors are protected by a mechanical release mechanism in the event of a severe impact. In the event the release mechanism is activated, the corresponding sensor recoil light will activate (left or right). The operator should stop the vehicle to inspect the gage sensors. To reset the mechanical protection mechanism, the operator should depress the SENSORS UP button on the TGCC. To reinitiate gage measurement, the operator should depress the SENSORS DOWN button on the TGCC.

A.2.2 Paper Supply Low

When the PAPER SUPPLY LOW light comes on, it indicates that the paper in the paper drawer is nearly empty. It is recommended that the operator plan to stop the vehicle at a convenient location and refill the paper supply. After the paper supply is refilled, the PAPER SUPPLY LOW light will go off.

A.2.3 Print Buffer 80% Full

When the PRINT BUFFER 80% FULL light comes on, it indicates that there are over 240 lines waiting to be printed within the computer. The operator should slow the vehicle down in order to give the line printer time to catch up. If the operator does not slow the vehicle down, data may be lost. An asterisk printed on the left side of the exception report indicates that exception report lines were lost.

APPENDIX B

CHANNEL ASSIGNMENTS AND SIGN CONVENTIONS FOR DATA INPUT TO THE DIGITAL COMPUTER

Channel	Measurement	Measurement Range	Range in Volts	Scale Factor
0	ALD	Detection +2 Volts	+10	N/A
1	Gage, Left[1]	2.75 in	10	.275 in/volt
2	Gage, Right[1]	2.75 in	10	.275 in/volt
3	Gage, Track[2]	56.50 +2.75 in -1.00 in	-10.00 + 3.64	.275 in/volt
4	Crosslevel[3]	±10 in	±10	1 in/volt
5	Yaw Rate[4]	±10°/sec	±10	1°/sec/volt
6	Speed Analog	±40 mph	±10	4 mph/volt
7-15	Not Used	N/A	N/A	N/A

Notes:

1) The signals from the left and right gage transducers have a total mechanical range of 2.75 inches with a nominal voltage output of ± 5 volts.

2) Nominal gage of 56.50 inches is calibrated to be 0 volts at the A/D. Wide track gage is indicated by a negative polarity gage signal in accordance with contractual requirements.

3) Left rail high (driver side) is considered as positive crosslevel in accordance with contract requirements.

4) The yaw rate signal will be negative while traversing a curve to the right with the vehicle heading in a forward direction.

APPENDIX C

CHANNEL ASSIGNMENTS AND SIGN CONVENTIONS FOR DATA INPUT FROM THE DIGITAL COMPUTER

Channel	Measurement	Measurement Range	Range in Volts	Scale Factor
0	Gage, Track	56.50 +2.75 in -1.00 in	0 -10.00 + 3.64	.275 in/volt
1	Crosslevel[1]	±10 in	±10	1 in/volt
2	Crosslevel, Average	±10 in	±10	1 in/volt
3	Crosslevel, Deviation	±10 in	±10	1 in/volt
4	Warp, 31 ft	±10 in	±10	1 in/volt
5	Curvature[2]	±15°/100 ft	±10	1.5°/100 ft/volt
6	Centrifugal Acceleration[3]	$\pm .15$ ft/sec^2	±10	.015 ft/sec^2/volt
7	Limiting Speed, V_{max}	0 to 120 mph	0 to +10	12 mph/volt

Notes:

1) Left rail high (driver side) is considered as positive crosslevel in accordance with contract requirements.

2) Curvature will be negative while traversing a curve to the right with the vehicle heading in a forward direction.

3) Centrifugal acceleration will be positive while traversing a curve to the right with the vehicle heading in a forward direction.

APPENDIX D

REPORT OF NEW TECHNOLOGY

ENSCO, Inc. has not claimed any inventions for work performed during the development of the track geometry measurement system under contract no. DOT-TSC-1367. However, several unique features were incorporated into the design of the track geometry measurement which are noteworthy.

Special design considerations were given to reducing and simplifying the daily startup and calibration requirements of the track geometry measurement system to the extent that they can be performed rapidly by one individual with minimum training.[1]

The digital computer was configured as a stored program processor thereby virtually eliminating the need for the system operator to understand or interface directly with the onboard computer.[2]

Also, the digital signal processing techniques used for real time calculation of the track curvature[3] and the variable base length track warp[4] (1 to 62 feet) resulted in a significant improvement in the performance characteristics of the track geometry measurement system.

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[1] See pages 2, 70, 72

[2] See page 9, Appendix A

[3] See pages 37-39

[4] See page 44

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