Field Demonstration of the Use of Track Strength Data to Optimize Tie Replacement Requirements for High Speed Operations

Final Report

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Railway Tie Association
115 Commerce Drive; Suite C
Fayetteville, GA 30214
770-460-5553
FAX 770 460 5573
www.rta.org

ZETA-TECH

ZETA-TECH Associates, Inc.
900 Kings Highway North
Cherry Hill, NJ 08034
(856) 779-7795
FAX: (856) 779-7436
e-mail: info@zetatech.com
www.zetatech.com

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Executive Summary

This study represented a collaborative effort between the Federal Railroad Administration, Railway Tie Association, CSX Transportation, and ZETA-TECH Associates, Inc. to optimize crosstie upgrade and maintenance practices. Specifically the focus of this study was to compare tie replacement strategies based on conventional, visual inspection, and to compare these strategies to one based on track strength measurements taken from Gage Restraint Measurement System (GRMS) inspection data. As a secondary objective, a third set of replacement strategies, based on the TieInspect data collection and analysis system was also examined. This report presents the results of a füll-scale field demonstration allowing for a side-by-side comparison of alternate **upgrade** approaches (GRMS, CSX Conventional and *TieInspect™*) and **maintenance** approaches (GRMS, CSX Conventional and *TieInspect™*). The study consisted of four test miles, each with a unique upgrade and maintenance combination as shown in Table A.

TABLE A: Test Miles and Corresponding Upgrade/Maintenance Approaches

MP	UPGRADE	UPGRADE TIES INSTALLED	MAINTENANCE	MAINTENANCE TIES INSTALLED
10	*TieInspect*	*888*	*TieInspect*	184
21	GRMS	878	GRMS	162
22	Conventional	838	Conventional	352
23	GRMS	356	Conventional	551

Analysis of the strength of the track, as measured by CSX's GRMS inspection car and defined by the measured Gage Widening Ratio (GWR), showed that the average or mean GWR is representative of the track strength across the each test zone (of one mile each) and forms the basis for evaluation of tie replacement performance. This study showed a GWR degradation range of 0.066 to 0.094 *in/100 MGT*[1] for the replacement methodologies investigated, noting that the test bed was Class 4 (79 mph passenger speed) predominantly tangent track. (with some limited curvature).

Table B below summarizes the behavior of the two GRMS track upgrade sections as compared to the conventional upgrade section, looking at mean GWR after upgrade.

TABLE B: Post Upgrade Comparison of GRMS vs. Conventional Tie Installation

	Mean GWR (in.)		Degradation Rate	
MP (Upgrade)	May-04	Jun-05	in/yr	Upgrade Ties
21 (GRMS)	0.216	0.275	0.054	878
22 (Conv)	0.195	0.260	0.060	838
23 (GRMS)	0.184	0.237	0.049	356

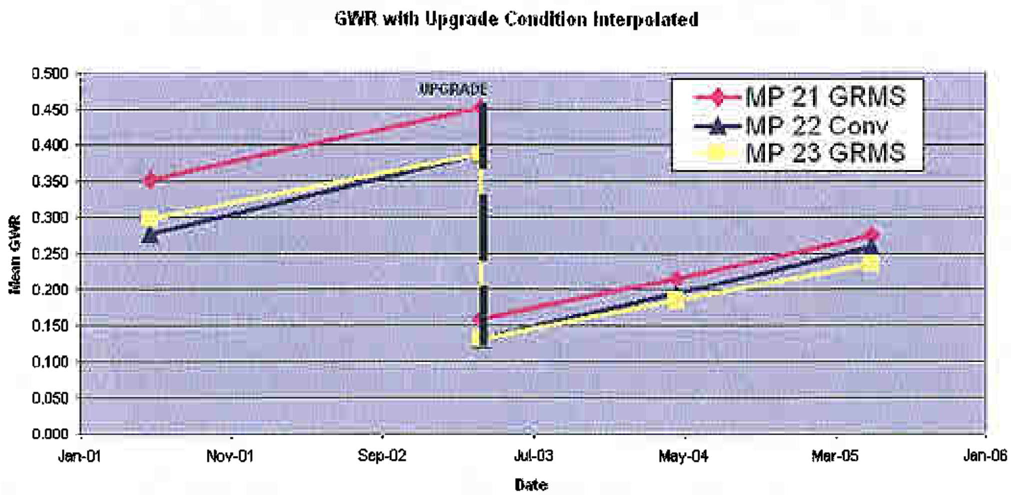
As shown in Table B, the GRMS miles outperformed the conventional mile in the effectiveness of the tie replacement/upgrade as defined by the corresponding mean GWR

[1] This corresponds to a *delta gage* degradation range of 0.037 to 0.053 *in/100 MGT.*

degradation rate. As can be seen, the lowest degradation rate corresponds to the GRMS upgrade mile (Mile 23) with the lowest number of ties installed; 356 vs. 838 for the conventional mile. In addition, examination of the GWR standard deviation show that the GRMS miles had higher pre-upgrade standard deviations, which indicates a wider scatter of tie condition, but ended up with lower standard deviations (less scatter) after the upgrade. This highlights the ability of the GRMS upgrade approach to provide a more uniform, stronger condition, based on the gage strength of the track.

The following Figure A presents the relative behavior of the three test miles graphically. As can be seen in this Figure, the conventionally upgraded mile (Mile 22) started off (pre-upgrade) with the best gage strength, as defined by mean, but was outperformed by the GWR miles, particularly MP 23. This is in spite of the fact that MP 23 had 58% fewer crossties installed. The other GRMS mile, MP 21 (GRMS), registered the largest improvement in mean GWR again due to successful targeting of weak spots.

FIGURE A: Mean GWR as a Function of Traffic and Upgrade

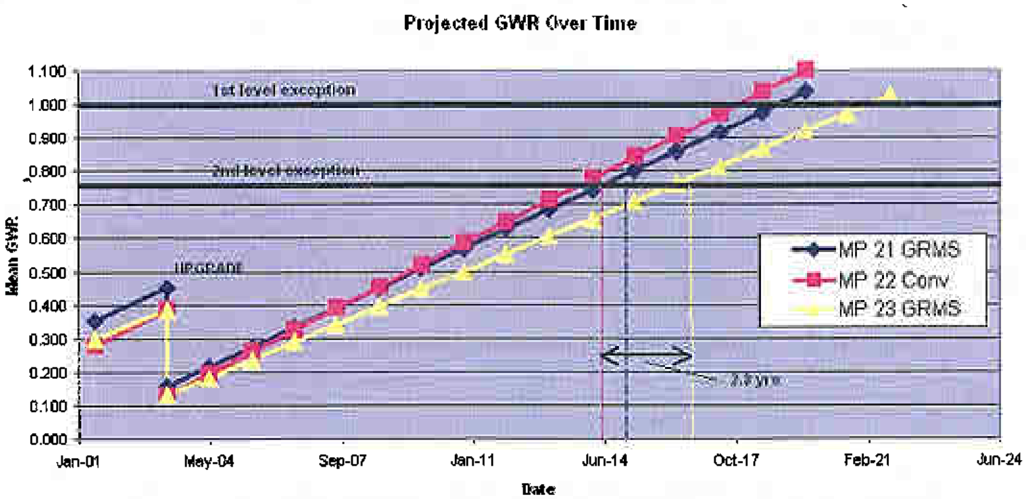


The effects of these relative degradation rates on the time it takes for the track to reach the GWR threshold levels[2] was calculated and presented in the Figure B below. Note, the 2nd or maintenance level used is 0.75 inches. A GWR value between 0.75 and 1 inch represents a second level exception and track speed must be set at the maximum for class 3 track (*FRA Track Safety Standards Part 213 pg 38*). A GWR reading of 1 inch or more represents a first level exception and track speed is to be reduced to 10 mph (*FRA Track Safety Standards Part 213 pg 37*). Noting the above, the conventional mile on average reaches a second level exception 2.8 years earlier than the best performing GRMS mile. This is a direct function of the higher degradation rate shown above. By averaging the two GRMS mile degradation rates and using the second level exception threshold, it can be shown that the GRMS upgrade approach provides an additional 2.1

[2] Time to reach GRMS 1st and 2nd level exceptions is less than average tie life due to the expected nonlinear tie life behavior.

years to reach the threshold. Extending this improvement to overall tie life, and noting average tie life for this location is 23 years[3], this would represent a 9.1% extension in tie life.

FIGURE B: Projected GWR Over Time



In addition to the GRMS vs. conventional tie installation comparison, MP 10 employed the *TieInspect* system and replacement logic for both the upgrade and maintenance cycle. Inspectors looked for all tie failure mechanisms including the ties ability to hold line and surface, splitting, breaks, plate cutting, plate movement, wheel cuts, decay or hollowness, and the ability to hold cut spikes. The inspections provided a full condition map and allowed for strategic tie replacement. Comparing this approach, using the *TieInspect* tie replacement logic and data, to the conventional CSX approach, tie requirements were reduced by 9.8% using the TieInspect system and replacement logic.

Results for the upgrade portion of this study showed that GRMS based tie replacement generated a stronger track structure, with a lower rate of track strength degradation than conventional techniques, while using fewer ties. That is because targeted tie replacement resulted in superior lateral track strength, and decreased lateral degradation rates with an overall extension in the time to GRMS thresholds.

Maintenance ties were installed in October 2005 with a post-maintenance GRMS run conducted in April 2006. Similar to the upgrade findings, the GRMS maintenance mile outperformed the conventional maintenance miles in average GWR improvement, with much fewer ties installed. Table C shows the direct comparison of average GWR improvement (From June 2005 to April 2006) and the number of ties installed for the maintenance cycle. The GRMS replacement methodology was once again successful in targeting and reducing GWR peaks.

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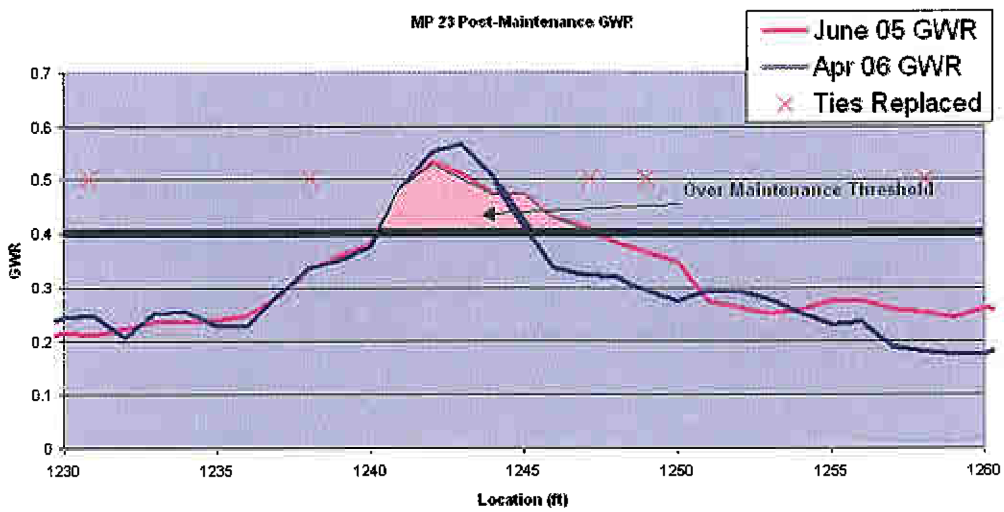
[3] Average tie life was calculated using the RTA SelecTie Model II, for the track and operating conditions of the Metropolitan Sub.

TABLE C: GWR Maintenance Results

MP	Maint	Avg. GWR Improvement	Ties
21	GRMS	0.046	162
22	Conv	0.030	352
23	Conv	0.019	551

As shown above, the conventional mile with the most ties installed saw the smallest GWR improvement from the maintenance cycle. This is largely because of instances were GWR peaks were missed, as shown in Figure C.

FIGURE C: Post Maintenance GWR for MP 23



Another issue investigated with the GRMS maintenance miles was the track profile effect, as tie replacement was based on lateral (not vertical) track performance. Examining the 62 ft chord left profile[4] for MP 21 showed good improvement in profile deviations (post-upgrade and post-maintenance), despite tie replacement focusing on lateral performance. Note the upgrade for this mile installed many more ties than the other GRMS upgrade mile (MP 23)

In total, 4,209 crossties were installed in this study. MP 22, had 1,190 ties spotted and installed based on current CSX practices. Tie requirements for the other miles were compared to conventional practices in an effort to optimize replacement strategies. To investigate the relative savings associated with each replacement philosophy an economic analysis was conducted using the total tie requirements. **This analysis has shown that strategic tie replacement can reduce tie costs on the order of 25 to 44 million annually.**

[4] Investigation into left and right profile (62' chord) showed similar results.

The current study was conducted over a 5-year period with post-upgrade GRMS monitoring spanning 3 years. Noting tie life can range from 20 to 30 years in this area, it is recommended that further GRMS monitoring occur to obtain a more complete picture of track degradation.

Introduction

Background

This study represents a collaborative effort between the Federal Railroad Administration, Railway Tie Association, CSX Transportation, and ZETA-TECH Associates, Inc. to optimize crosstie upgrade and maintenance methodologies utilizing GRMS (Gage Restraint Measurement System) inspection data[5]. This is a full-scale field demonstration allowing for a side-by-side comparison of alternate **upgrade** approaches (GRMS, *TieInspect™*, and Conventional[6]) and alternate **maintenance** (GRMS, *TieInspect™*, and Conventional) approaches. The study consists of four test miles, each with a unique upgrade and maintenance combination. Track condition and rates of degradation were monitored using GRMS data and visual inspections. A life cycle cost analysis was performed examining the relative economics of the upgrade and maintenance techniques employed at the end of the study.

The following tasks were successfully completed and are documented in the current report:

-Task 1 The Test Design *(completed Nov. 2001)*,
-Task 2 Test Location Selection *(completed Jan. 2002)*
-Task 3 Selection of Test Miles and Detailed Tie Inspection
    (completed Mar. 2002))
-Task 4 The Upgrade of the Test Miles *(completed April 2003)*.
-Task 5 and 6 Monitoring and Analysis of Track Condition
    -Post-upgrade GRMS vehicle run (*5/12/2004*)
    -Evaluation of Tie Upgrade Success (*Completed September 2004*)
    -GRMS vehicle run (*February 2005*[7])
    -GRMS vehicle run (*June 2005*)
    -Calculation and Analysis of Degradation Rates
    -Tie Selection and Spotting for Maintenance Cycle
    -Installation of Maintenance Ties
    -GRMS vehicle run (*April 2006, post-maintenance*)
    -Evaluation of Maintenance Cycle (lateral and vertical performance)
-Task 7 Life Cycle Costing Analysis
    -Total tie requirements
    -Economic Analysis
-Task 8 Final Report
    -Current CSX practices using GRMS data
    -Other GRMS based track maintenance studies

[5] CSX's GRMS inspection vehicle measures full track geometry as well as the relevant track strength measurements (gage restraint, delta gage, etc.)
[6] Conventional as defined here refers to the current method used by CSX for tie replacement and maintenance.
[7] Problems were encountered with this data run, and the results have not been used in any of the analyses.

The test miles were located within CSX's Metropolitan Subdivision (Gaithersburg, MD), which provided the optimal test requirements including:

-Passenger Carrying
-High Speed (79 mph)
-Uniform Traffic and Maintenance History
-Consistent GRMS Vehicle Runs

Table 1 shows the upgrade and maintenance technique employed for each test mile. MP 22 represented the control mile, which employed current CSX tie replacement strategies. The definitions for the other methodologies are given in the following section.

Table 1. Test Mile Descriptions

MP	UPGRADE	MAINTENANCE
10	*TieInspect*	*TieInspect*
21	GRMS	GRMS
22	Conventional	Conventional
23	GRMS	Conventional

The key time elements for this activity were as follows:

June 2001	Initial pre-upgrade GRMS run
April 2003	Installation of Upgrade Ties
May 2004	Post Upgrade GRMS run
June 2005	Post Upgrade GRMS run
October 2005	Installation of Maintenance Ties
April 2006	Post Maintenance GRMS run

This report encompasses five years of research and compares the performance of the different test sections, and specifically the performance of the different upgrade approaches used.

Task 1 Test Design (2001)

This study was designed to address two crosstie replacement issues of current interest: (1) to provide a direct comparison of alternate maintenance approaches, and (2) to utilize GRMS data to locate and remove weak spots at the individual tie level. To effectively address these issues it was decided that four one-mile test sites were needed, each with separate upgrade and maintenance philosophies. All four test miles were in zones where passenger trains reach 79 mph, as this study pertains to high speed operations. Comparisons were made based on relative degradation and cost (number of ties required).

Upgrade Definitions

The following definitions describe each tie upgrade replacement philosophy used in this study:

> **Conventional** upgrades were performed based on conventional CSX tie replacement strategy.
>
> The **GRMS** (Gage Restraint Measurement System) upgrade was based solely on lateral track strength data from CSX's GRMS vehicle (Figure 1A). Locations exceeding a defined Gage Widening Ratio (GWR) had ties "spotted" in. GWR is used because it is sensitive primarily to track strength. By design, it is not sensitive to wide gage as can be seen by the following equation typical of track strength inspection vehicles:

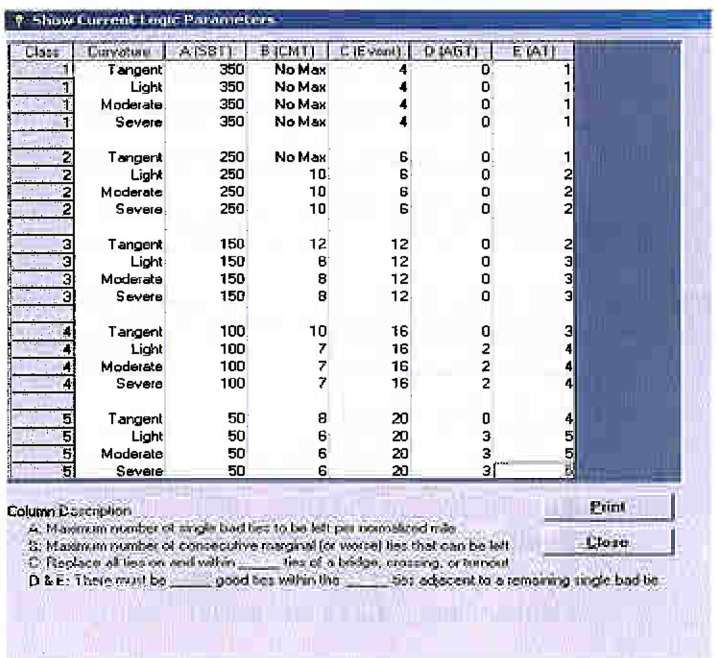
$$GWR = \frac{(LTG - UTG)}{L} * 16000$$

> where LTG is the loaded track gage, UTG is the unloaded track gage, and L is the laterally applied GRMS load. Projected Loaded Gage (PLG24) is not used for tie replacement, as it is sensitive to rail gage face wear, wide gage, and weakened track strength.

Figure 1A: CSX's GRMS Track Inspection Vehicle.

The ***TieInspect™*** upgrade is based on ZETA-TECH's *TieInspect™* replacement logic, which is dependent upon track class and curvature. Each test mile will have a tie-by-tie condition report, which is collected using ZETA-TECH's *TieInspect™* unit shown in Figure 1B. This logic utilizes the collected data and strategically breaks up bad clusters while assuring adequate replacement in the vicinity of bridges, crossings, and turnouts (See Figure 2). Thus, not all bad ties are replaced, but only those ties required to maintain track integrity.

Figure 1B. **ZETA-TECH's *TieInspect™* unit.**



Show Current Logic Parameters

Class	Curvature	A (SBT)	B (CMT)	C (Event)	D (AGT)	E (AT)
1	Tangent	350	No Max	4	0	1
1	Light	350	No Max	4	0	1
1	Moderate	350	No Max	4	0	1
1	Severe	350	No Max	4	0	1
2	Tangent	250	No Max	6	0	1
2	Light	250	10	6	0	2
2	Moderate	250	10	6	0	2
2	Severe	250	10	6	0	2
3	Tangent	150	12	12	0	2
3	Light	150	8	12	0	3
3	Moderate	150	8	12	0	3
3	Severe	150	8	12	0	3
4	Tangent	100	10	16	0	3
4	Light	100	7	16	2	4
4	Moderate	100	7	16	2	4
4	Severe	100	7	16	2	4
5	Tangent	50	8	20	0	4
5	Light	50	6	20	3	5
5	Moderate	50	6	20	3	5
5	Severe	50	6	20	3	5

Column Description

A: Maximum number of single bad ties to be left per normalized mile

B: Maximum number of consecutive marginal (or worse) ties that can be left

C: Replace all ties on and within _____ ties of a bridge, crossing, or turnout

D & E: There must be _____ good ties within the _____ ties adjacent to a remaining single bad tie

Print

Close

Figure 2. *TieInspect™* Replacement Logic.

Maintenance Definitions

The following definitions describe each tie maintenance philosophy used in this study:

> **Conventional** maintenance consisted of tie spotting and replacement in accordance with current CSX standards and practices.
>
> On **GRMS** maintenance miles, locations that exceed a defined GWR threshold had ties "spotted" in to bring within the gauge strength (as defined by GWR) to a specified "strength" level.. The maintenance threshold and upgrade thresholds were different as the upgrade threshold brings the test mile to a tighter standard initially.
>
> The ***TieInspect™*** maintenance was based on a tie condition inspection, where the current tie condition data was evaluated and a tie-by-tie replacement plan was generated from the current ***TieInspect*** tie replacement logic.

Task 2. Pre-Test Analysis and Inspection (2002)

With the test design completed, candidate test locations were provided by CSX transportation. The test line needed the following characteristics:

-Passenger and Freight Carrying
-High Tonnage
-High Speed
-Uniform Traffic and Maintenance History
-Near Middle of the Tie Gang Cycle
-Tie Gang in Vicinity
-Consistent GRMS Vehicle Runs

Noting these attributes, the CSX Metropolitan Subdivision was selected as the test line for the study. The Metro Subdivision had all of the key characteristics for the study:

Metro Subdivision
-High Speed (79mph)
-Passenger Carrying (MARC)
-High tonnage (64 MGT)
-Last Production Tie Gang 1993
-Production Tie Gang 4/2003, Small Tie Gang 9/2002
-Kensington, MD (one test mile)
-Gaithersburg, MD (3 test miles)

In order to narrow the line down to four study miles, CSX provided track charts, curvature data, tonnage data, tie gang schedules, GRMS runs, and passenger train schedules for these lines for analysis, evaluation and final selection.

Task 3. Selection of Test Sites and Detailed Tie Inspection (2002)

Four test miles had to be selected with similar speed, tonnage, curvature, and tie gang cycle, while having consistent GRMS data from the last two runs. Figure 3 shows one of the track charts used to extract mile-by-mile track information.

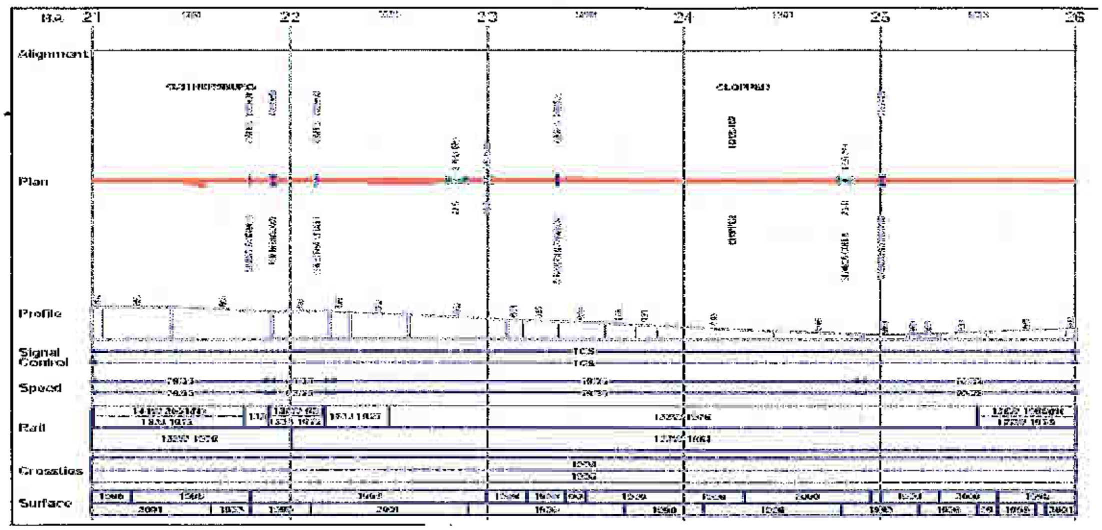


Figure 3. Metropolitan Subdivision Track Chart.

Several GRMS vehicle runs were also analyzed for GWR data consistency and relative rates of degradation as shown in Figures 4 and 5. Figure 4 shows a foot-by-foot record of two GWR runs over a potential test mile with excellent correlation.

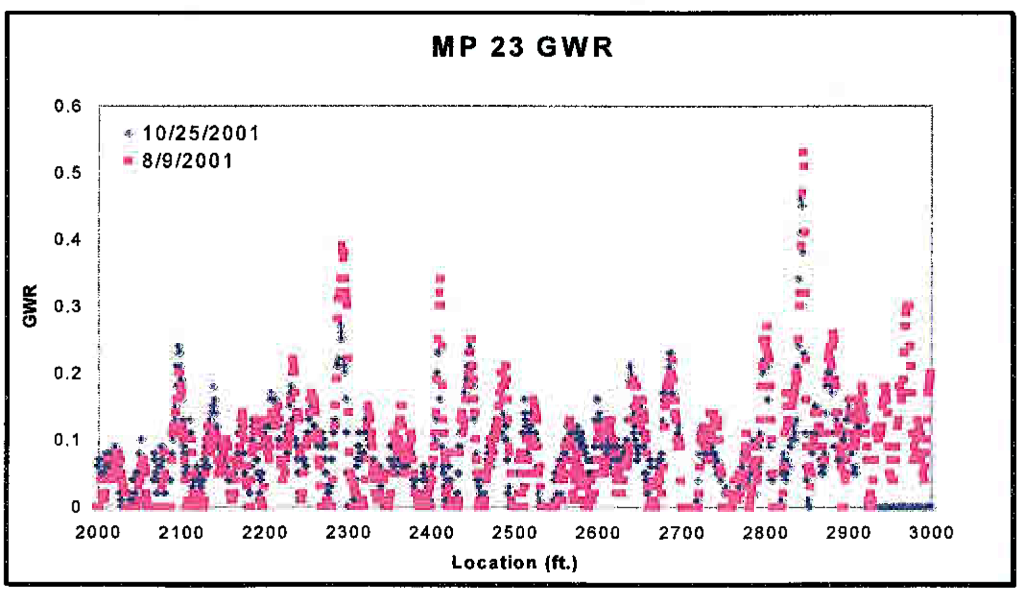


Figure 4. Two consistent GRMS runs.

Figure 5 plots mean GWR (for the mile) for two runs over all potential test miles. This was useful in determining both consistency and relative degradation between runs.

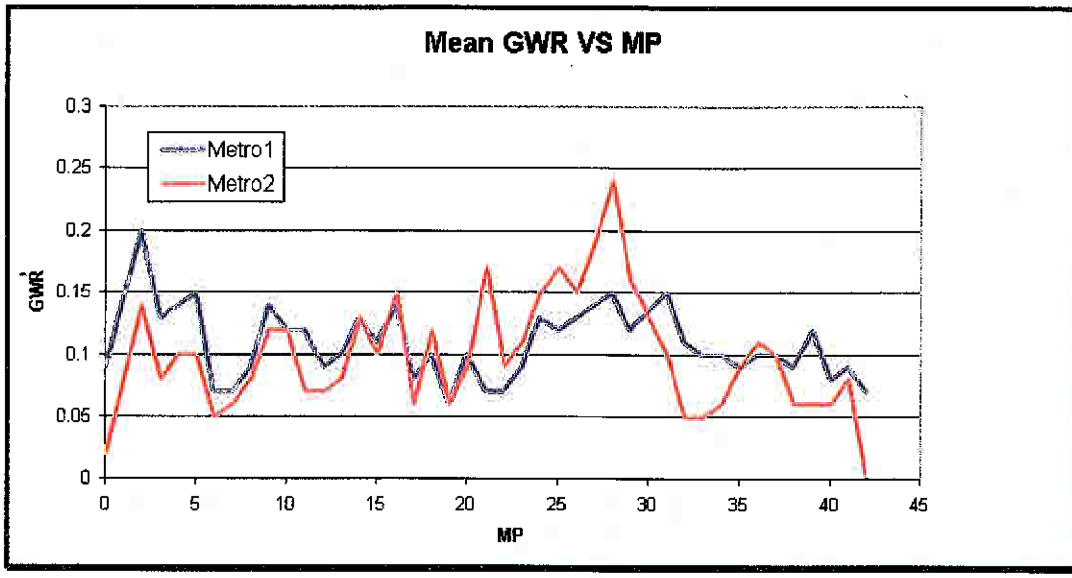


Figure 5. Mean GWR by mile.

To aid in test mile selection, a mile-by-mile database was compiled using the CSX track data and GRMS analyses as shown in Figure 6. For each candidate mile, speed, curvature, MGT, tie gang cycle, passenger train schedules, and two GRMS performances were analyzed.

MP	Track	Speed	Avg Curv	# of curves	max curvature	MGT	tie gang	2002 gang	GWR Max 1	GWR Max 2	GWR Mean 1	GWR Mean 2	E	W
20	2	79/55	0.65	2	1.333333	64	1993		0.54	0.43	0.1	0.09	9	11
21	2	79/55	0.844	2	2.2	64	1993		0.46	0.53	0.07	0.17	9	11
22	2	79/55	0.308	1	2	64	1993		0.45	0.4	0.07	0.09	9	11
23	2	79/55	0.17	2	0	64	1993		0.53	0.5	0.09	0.11	9	11
24	2	79/55	0.2101667	1	1.616667	64	1993		0.62	0.68	0.13	0.16	9	11
25	2	70/55	1.459167	4	1.2	64	1993		0.51	0.52	0.12	0.17	9	11
26	2	70/55	0.8736667	2	2.133333	64	1993		0.41	0.48	0.13	0.15	9	11
27	2	79/55	0.276	1	1.1	64	1993		0.48	0.56	0.14	0.19	9	11
28	2	79/55	0.883	3	1.133333	64	1993		0.45	0.62	0.15	0.24	9	11
70	2	40/40	3.106667	6	6.333333	95	1993		0.8	0.61	0.22	0.14	6	8
71	2	60/40	1.616667	5	2.25	95	1993		0.53	0.48	0.23	0.12	6	8
72	2	60/40	1.0125	4	2.916667	95	1993		0.36	0.15	0.07	0.01	6	8
73	2	60/40	0.445	3	1	95	1993		0.14	0.43	0.01	0.09	2	3
74	2	60/40	0.345	1	1	95	1993		0.31	0.44	0.06	0.1	2	3
75	2	60/40	0.7366667	2	2.166667	95	1993		0.48	0.54	0.06	0.16	2	3
76	2	60/40	0.225	2	1	95	1993		0.46	0.36	0.17	0.05	2	3
77	2	60/40	1.13	2	2	95	1990		0.53	0.45	0.23	0.12	2	3
78	2	79/55	1.669	6	4.166667	95	1990		0.46	0.66	0.21	0.15	2	3
79	2	40/35	2.235	5	6.533333	95	1990	y	0.57	0.76	0.27	0.15	2	3
80	2	60/40	0.9915	5	2	95	1990	y	0.54	0.63	0.19	0.14	2	3
81	2	45/40	1.626333	3	4	89	1990	y	0.45	0.54	0.22	0.09	2	3
82	2	40/35	3.903333	5	7	89	1990	y	0.71	0.7	0.34	0.2	2	3
83	2	45/40	3.444333	6	6.5	89	1990	y	0.79	0.73	0.31	0.22	2	3
84	2	45/40	2.937	4	4.5	89	1990	y	0.61	1.08	0.29	0.25	2	3

Figure 6. Candidate Test Mile Database.

After assembling and analyzing the data from the Metropolitan subdivision the test miles were chosen. The assigned upgrade and maintenance methodology for each test mile are given in Table 2. To establish the "pre-upgrade" condition of the test miles, each was visually inspected using *TieInspect™*. A tie-by-tie condition report was generated for each mile, which would become valuable in the upgrading process.

Table 2.

TEST SITE	MP	UPGRADE	MAINTENANCE
1	10	*TieInspect*	*TieInspect*
2	21	GRMS	GRMS
3	22	Conventional	Conventional
4	23	GRMS	Conventional

Task 4. Upgrades of Test Sites (2002-2003)

Two different tie gangs performed the test mile upgrades. A small tie gang partially upgraded the test miles in September 2002, while the production tie gang completed the upgrades in April 2003. All test miles upgrades were monitored by ZETA-TECH. Photographs of the tie gangs are provided in Appendix A.

GRMS Upgrades: MP 21 and MP 23

To perform an upgrade based on GRMS data it was necessary to locate specific ties based upon foot-by-foot data output. The *TieInspect™* unit gave the test mile inspector the ability to record the start and end of curves within a test mile. By overlaying the GRMS superelevation channel with the *TieInspect™* recorded curves as shown in Figure 7, a functional relationship was established between the "foot counter" of the GRMS vehicle and the *TieInspect™* tie number. This produced the plot shown in Figure 8, which displays a more useful relationship of GWR versus tie number (from the *TieInspect* data). Using a GWR upgrade threshold of 0.25 and the locating procedure described above, MPs 21 and 23 were marked using track strength data (from the CSX GRMS vehicle) exclusively.

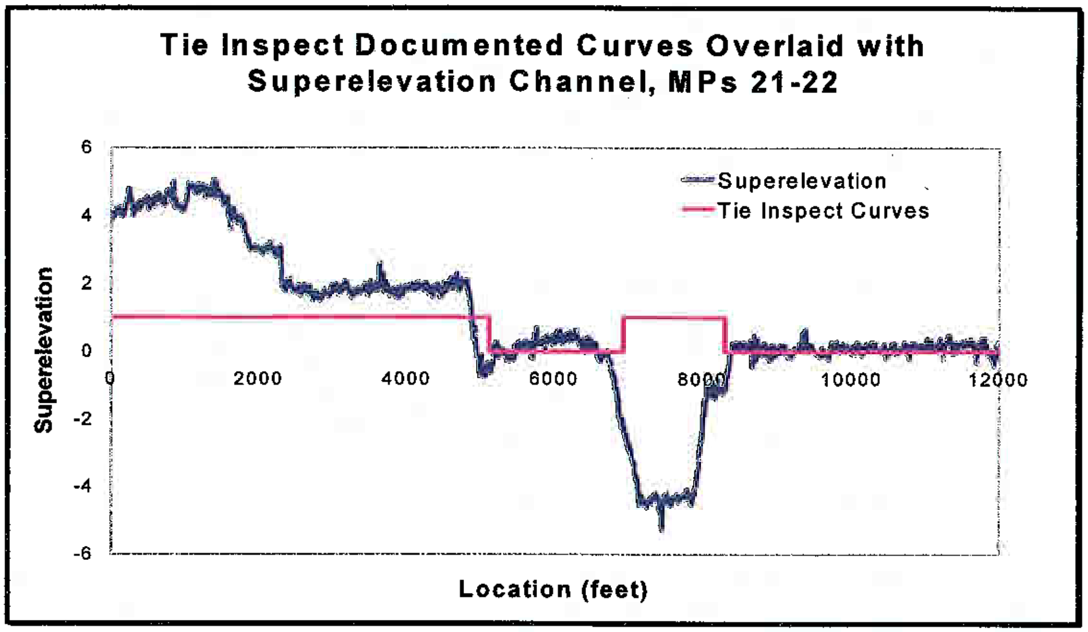


Figure 7. *TieInspect™* documented curves overlaid with superelevation channel.

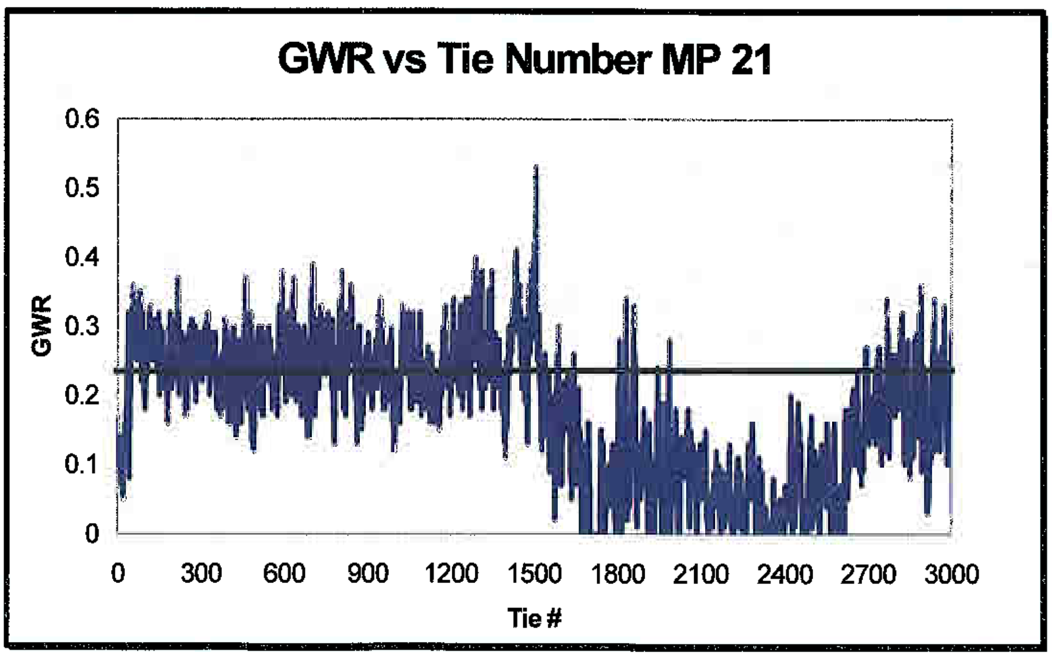


Figure 8. GWR versus tie number.

Table 3 shows the number of ties installed by both tie gangs to complete the upgrades of the GRMS test miles. The MP 23 upgrade (356 ties) is significantly smaller than CSX conventional production gang upgrades, which typically range from 1000-1200 ties. The ability to locate and remove lateral weak spots was directly based on the GRMS data and the defined upgrade threshold of 0.25.

Table 3.

MP	UPGRADE	SMALL GANG	PRODUCTION GANG	TOTAL TIES
21	GRMS	25	853	**878**
23	GRMS	79	277	**356**

Figure 9 shows the tie-by-tie replacement locations, as displayed by the *TieInspect™* host software for MP23. The red vertical dashes represent ties taken out by the production tie gang, and the yellow dashes are ties removed by the small tie gang. The ties were removed solely for lateral track strength and represent spots with GWR exceeding the threshold of 0.25.

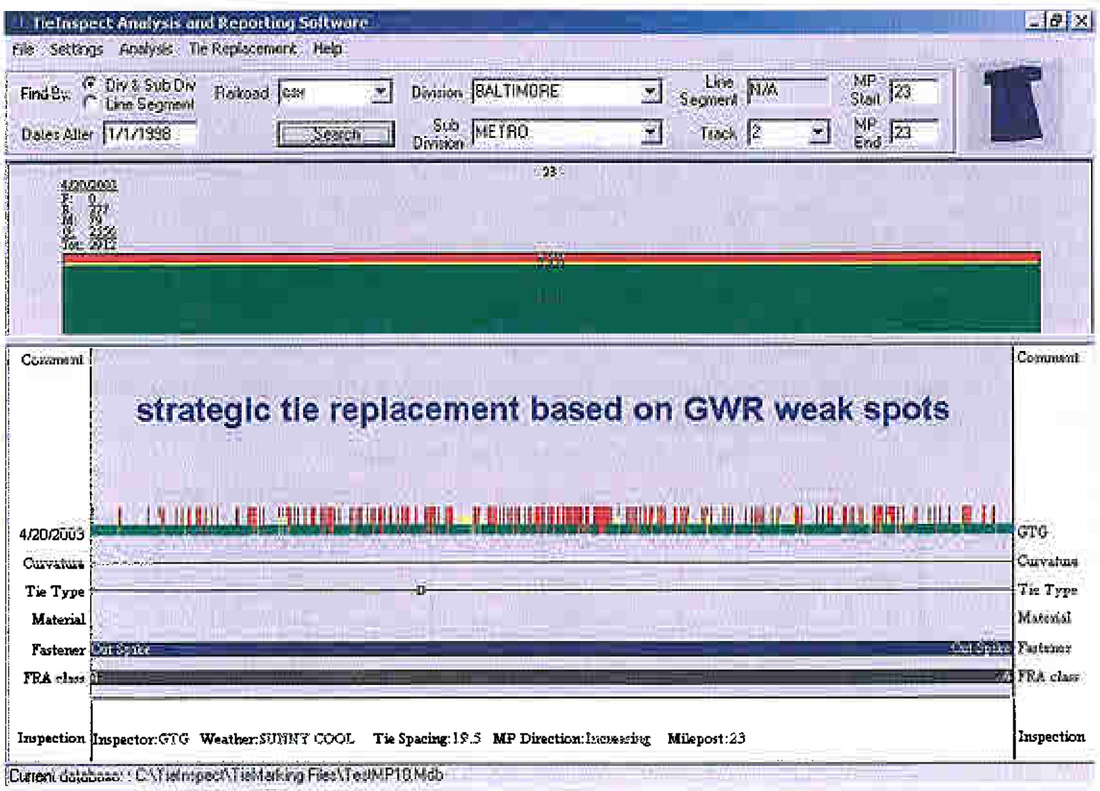


Figure 9. Location of ties removed in MP 23 for weak lateral track strength.

TieInspect™ upgrade: MP 10

The ***TieInspect™*** upgrade was based on ZETA-TECH's *TieInspect™* replacement logic, which is dependent upon track class and curvature. As previously discussed, this logic utilizes the collected data and strategically breaks up bad clusters while assuring adequate replacement in the vicinity of bridges, crossings, and turnouts (See Figure 2). Thus, not all bad ties are replaced, but only those ties required to maintain track integrity. MP 10 had been conventionally spotted by the CSX production tie gang and was originally scheduled for a **985** tie upgrade. By collecting the spotted ties, recording track curvature, and running the replacement logic, the mile was reduced to an **888** tie upgrade (9.8% decrease). ZETA-TECH's *TieMarking* software, which is housed in the *TieInspect™* unit, informs the inspector of which tie the replacement logic has selected for removal. The ties spotted by CSX in "excess" of the *TieInspect* logic's recommendations were removed with black spray paint ahead of the tie gang. MP 10 was maintained using the *TieInspect™* replacement logic, which will be applied to yearly inspections.

Conventional upgrade: MP 22

Conventional CSX production gang upgrades usually range between 1000-1200 ties. However, CSX personnel spotted MP 22, but at a lower tie total of **838**. This is largely due to the long bridge over Interstate 270 (MP 22.7), where ties were in good condition. The small tie gang installed 119 ties in September 2002, while the production gang added the remaining 719 ties in April 2003. MP 22 was maintained conventionally in this study.

Overall, a total of 2,960 upgrade ties were installed during the upgrade phase of this project in the four test miles as shown in Table 4.

Table 4. Upgrade Ties Installed.

MP	UPGRADE	MAINTENANCE	UPGRADE TIES INSTALLED
10	*TieInspect*	*TieInspect*	*888*
21	GRMS	GRMS	878
22	Conventional	Conventional	838
23	GRMS	Conventional	356

Tasks 5 and 6: Ongoing Monitoring and Analysis of Track Condition (2004)

CSX's GRMS-1

CSX's GRMS-1 vehicle operated over the test miles on May 12, 2004 from MP 75 to MP 10, from Brunswick to Silver Springs, MD. The run gathered GRMS track strength data that was used to monitor the effectiveness of the test mile upgrades performed in Spring 2003 and shown in Table 4. GRMS-1 is an independent self-propelled vehicle, which gathers track geometry as well as track strength data. By collecting the unloaded gage measurements together with loaded gage [14,000 lbs of lateral load] to measure gage spread, it calculates the delta gage and loaded gage track strength parameters (including Gage Widening Ratio or GWR) on a foot-by-foot basis. The following information was collected by GRMS-1:

1	Milepost
2	Ascending +/descending -
3	Foot offset
4	Unloaded gage
5	Crosslevel
6	Loaded gage
7	PLG24 (Projected Loaded Gage)
8	GWR (Gage Widening Ratio)
9	Profile left 62 ft
10	Profile right 62 ft
11	Alignment left
12	Alignment right
13	Curvature
14	Warp 62 ft
15	Warp 31 ft
16	Latitude
17	Longitude
18	Altitude

GRMS-1, as a single vehicle, travels at a max speed of 35 mph to allow for time for the mechanical gage widening system to perform. A picture of the vehicle is shown in Figure 10, as it awaits orders to begin testing in Brunswick, MD. Several other pictures documenting the GRMS-1 run over the test miles are included in Appendix B.

Figure 10. CSX's GRMS-1 vehicle.

The GRMS data allowed for the continuation of Tasks 5 and 6, the ongoing monitoring and analysis of track condition. The collected track strength data was used to evaluate the effectiveness of the test mile upgrades as well as current track condition.

Data Analysis (2004)

To accurately compare the pre- and post- upgrade GRMS data, the data itself underwent both aligning and calibration steps. Since mileposts are entered "on the fly" it was necessary to align the superelevation channels of both the pre-upgrade and post-upgrade runs . This ensured that the same sections of track were being compared. Figure 11 shows pre-upgrade superelevation data aligned to the post-upgrade data. Although the actual magnitudes of superelevation differ in the two runs[8], it was still possible to align the start and end of the curves accurately.

[8] Changes in magnitudes of superelevation are due to tamping and surfacing activities.

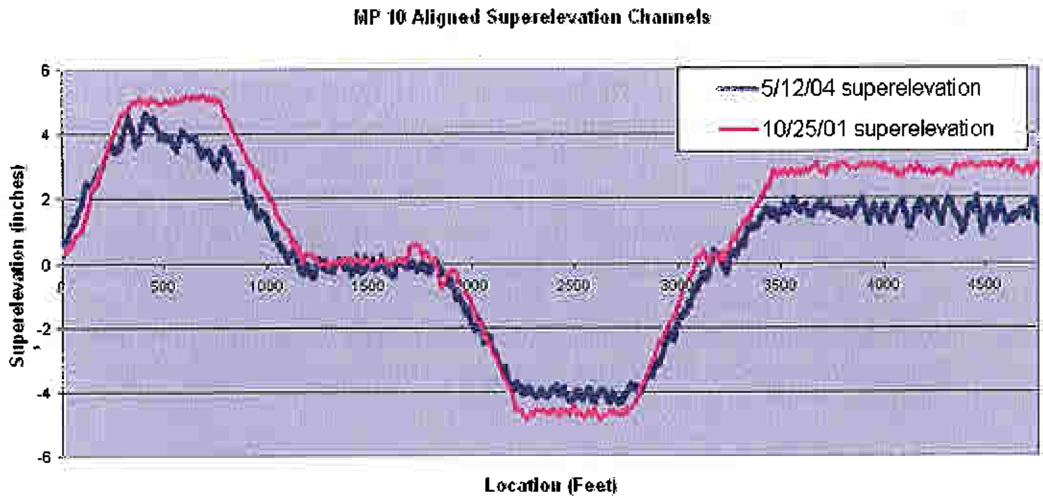


Figure 11. Aligned superelevation channels.

Close examination of the collected post-upgrade data showed significant improvement in loaded gage after the upgrades. In addition, the unloaded gage channel showed much smaller variations from standard gage. Over the entire mile it would be expected that the unloaded gage channel would show moderate improvement in deviation from standard gage (56.5 inches) in the post-upgrade run. However, the magnitude of improvement (typically 60 to 100% improvement) suggests a calibration error in the unloaded gage channel. Table 5 shows the average deviation of unloaded gage from standard gage measurements for each test mile. It is evident that the post-upgrade deviations of unloaded gage are far smaller than the pre-upgrade run. Therefore the rate of lateral track strength degradation is better observed by calibrating post-upgrade unloaded gage to the pre-upgrade values.

Table 5.

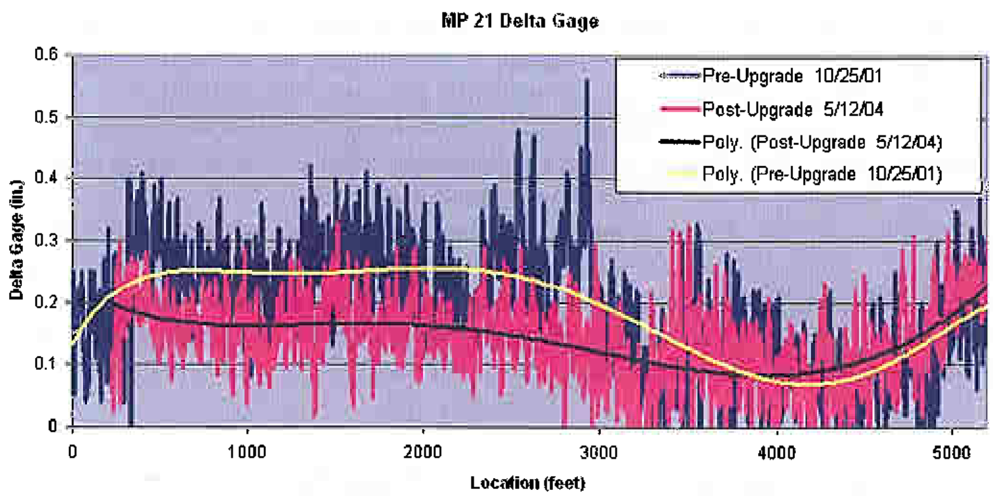
MP	AVG PRE-UPGRADE UNLOADED GAGE (DEVIATION, INCHES)	AVG POST-UPGRADE UNLOADED GAGE (DEVIATION, INCHES)	CALIBRATION FACTOR OFFSET (+)
10	0.175	0.065	0.110
21	0.044	0.001	0.043
22	0.038	-0.030	0.068
23	0.094	0.015	0.079

To specifically focus on lateral track strength and not gage improvement, each post-upgrade unloaded gage measurement was offset by the calibration factor (i.e. the difference in average pre-and post-upgrade unloaded gage for the mile) given in Table 5. For MP 10, each unloaded gage measurement was increased by 0.11, or the difference in pre- and post-upgrade average unloaded gage for the mile. Thus comparisons involving post-upgrade improvements in delta gage were derived from unloaded gage measurements calibrated to the pre-upgrade run.

Delta Gage Analysis (2004)

Figures 3 through 6 overlay the aligned pre- and post-upgrade delta gage data by test mile. Along with the "raw" data, polynomials have been fit to the data to provide an overall effectiveness measure for the mile. Figure 12 shows pre- and post-upgrade delta gage for MP 21 (GRMS upgrade), in which delta gage peaks over 0.25 were targeted[9]. Since passenger trains hit 79 mph through these miles it was the goal to invoke a tight upgrade standard. As can be seen in Figure 12, the post-upgrade delta gage response has decreased considerably in the area targeted (within the first 3000 feet of the mile). Of the 878 ties installed, 828 were located in the first 3000 feet as many locations exceeded the upgrade threshold. Noting the good track strength condition in the last 2000 feet, only 50 ties were installed throughout the rest of the mile. This test mile will undergo a GRMS maintenance cycle.

Figure 12. MP 21 Pre- vs. Post-Upgrade Delta Gage



MP 23 also utilized a GRMS upgrade designed to improve the lateral track strength of the mile with only a limited number of ties. The upgrade consisted of 356 ties targeting locations exhibiting weak lateral track strength. Examination of Figure 13 shows the average lateral track strength to be at or better than the pre-upgrade track condition with only a limited number of ties installed 15 months previously.. Thus, the integrity of the mile has been maintained with a limited upgrade. Successful reductions of some of the highest delta gage peaks are also seen throughout the mile. This mile will undergo a conventional maintenance cycle.

[9] Ties were initially spotted using a threshold of 0.25 GWR, which is delta gage normalized to a 16,000 lb lateral load. For the lateral loading of GRMS-1 (14,000 lbs) and threshold magnitude, the delta gage and GWR values are very close (0.25 GWR = 0.22 delta gage).

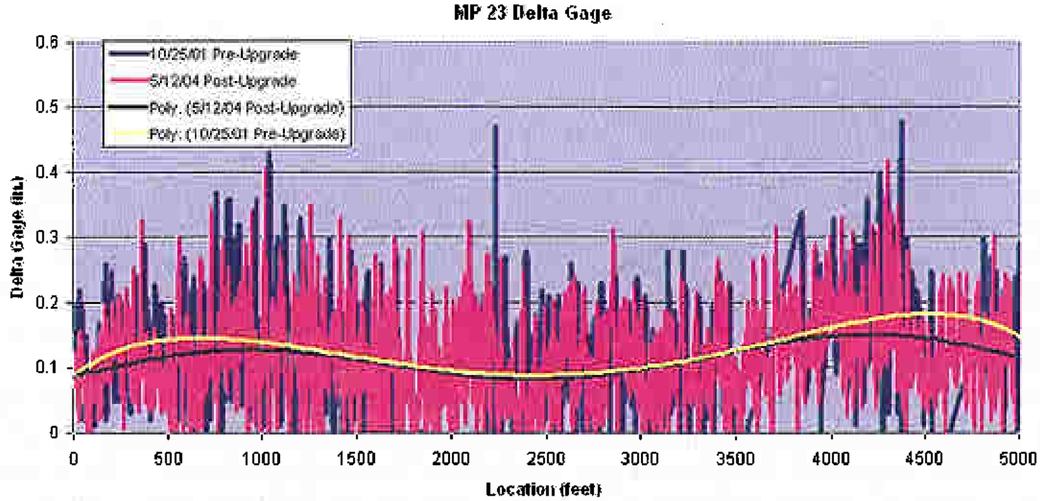


Figure 13. MP 23 Pre- vs. Post-Upgrade Delta Gage

MP 22 was conventionally spotted and upgraded by CSX personnel. The upgrade consisted of 838 ties, with the majority of the mile being a long tangent stretch. Although still in relatively good condition, Figure 14 shows a slight increase in delta gage in the first 750 feet (a 2.25-degree curve). Throughout the rest of the mile however, slight improvement in delta gage can be seen. It should be noted that this mile contains a bridge spanning from locations 4060 ft to 4500 ft, where the ties were in good condition at the time of the upgrade. Otherwise requirements could have increased to that of adjacent mile conventional CSX tie gang upgrades (1000-tie range). This test mile will undergo a conventional maintenance cycle.

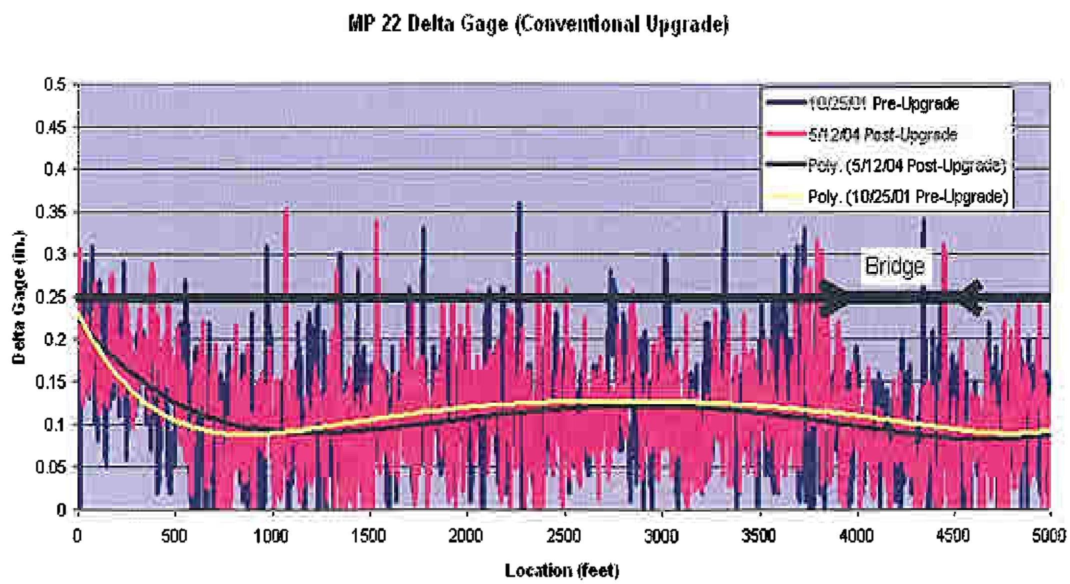


Figure 14. MP 22 Pre- vs. Post-Upgrade Delta Gage

Figure 15 shows pre- and post-upgrade delta gage for MP 10 (*TieInspect* upgrade). MP 10 had been conventionally spotted by the CSX production tie gang and was originally scheduled for a **985**-tie upgrade. By collecting the spotted ties, recording track curvature, and running the *TieInspect* replacement logic, the tie replacement requirements for the mile was reduced to an **888** tie upgrade (9.8% reduction in ties). The *TieInspect* logic, based on track class and curvature, will leave spotted ties with limited life remaining in track if an adequate number of "good" ties surround them. This logic utilizes the collected data and strategically breaks up bad clusters while assuring adequate replacement in the vicinity of bridges, crossings, and turnouts. Thus, not all bad ties are replaced, but only those ties required to maintain track integrity. The spotted ties left in track were located in the mile's only tangent stretch (located between 800 and 1800 feet) between two 3-degree curves. A reduction in delta gage is seen in this tangent stretch, where 97 spotted ties were left in track. Also the last 1500 feet of the mile saw a significant decrease in delta gage, which was within a 1.5-degree curve.

The two locations where the post-upgrade polynomial is above the pre-upgrade polynomial were within the 3-degree curves. Since rate of track degradation increases in curves and no single bad ties were left in these curves, the data suggests more ties needed to be spotted by CSX personnel. This test mile will undergo a *TieInspect* maintenance cycle.

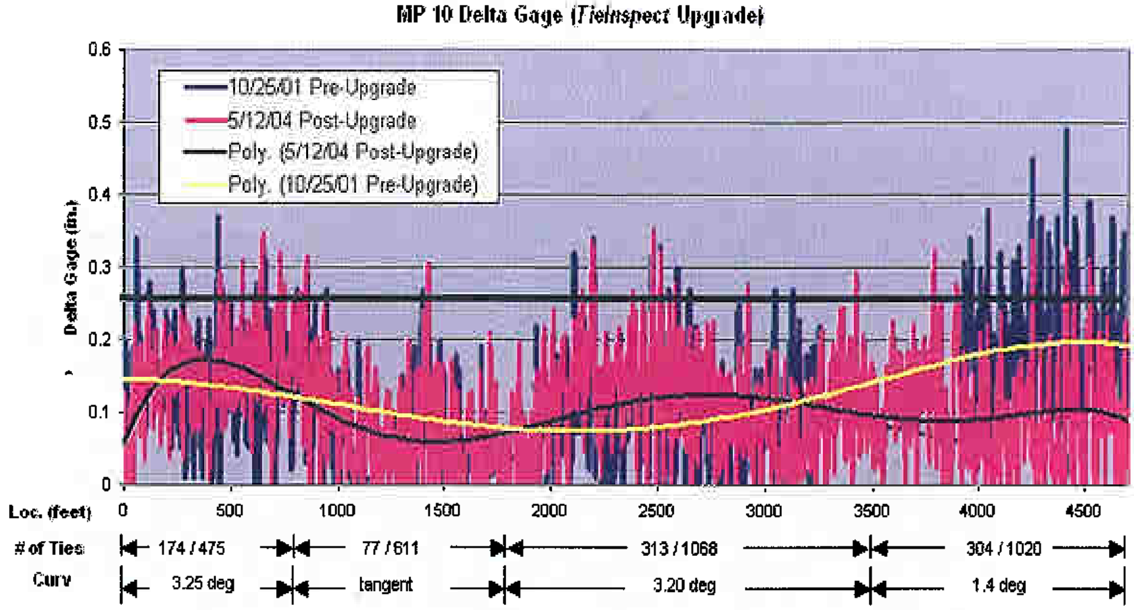


Figure 15. MP 10 Pre- vs. Post-Upgrade Delta Gage

Overall Effectiveness Index (2004)

To determine relative effectiveness of the upgrades, the Pre- and Post-upgrade delta gage 100-ft moving averages were compared. An improvement curve for each mile was created which represents the difference between the Pre- and Post-upgrade average delta gage curves, where data points above zero represent reduction in delta gage attributed to the upgrades. The overall effectiveness index is defined as the area under the improvement curve, which was used for relative comparison of upgrade success. Figure 16 shows the improvement curve for the GRMS upgrade mile at MP 21. Note that the post-upgrade curve is now completely below the dark horizontal line which represents the upgrade threshold of 0.25 delta gage. The improvement curve shows a significant improvement in delta gage over the first 3500 feet of the mile where the upgrade was concentrated. Since the last 1500 feet of the mile was in good condition to begin with, the upgrade was limited and the condition was maintained. Summing the area under the improvement curve produced by far the highest effectiveness index with a value of 243.4. It was anticipated that the GRMS upgrade, which targeted weak spots in lateral track strength, would show the greatest improvement in delta gage.

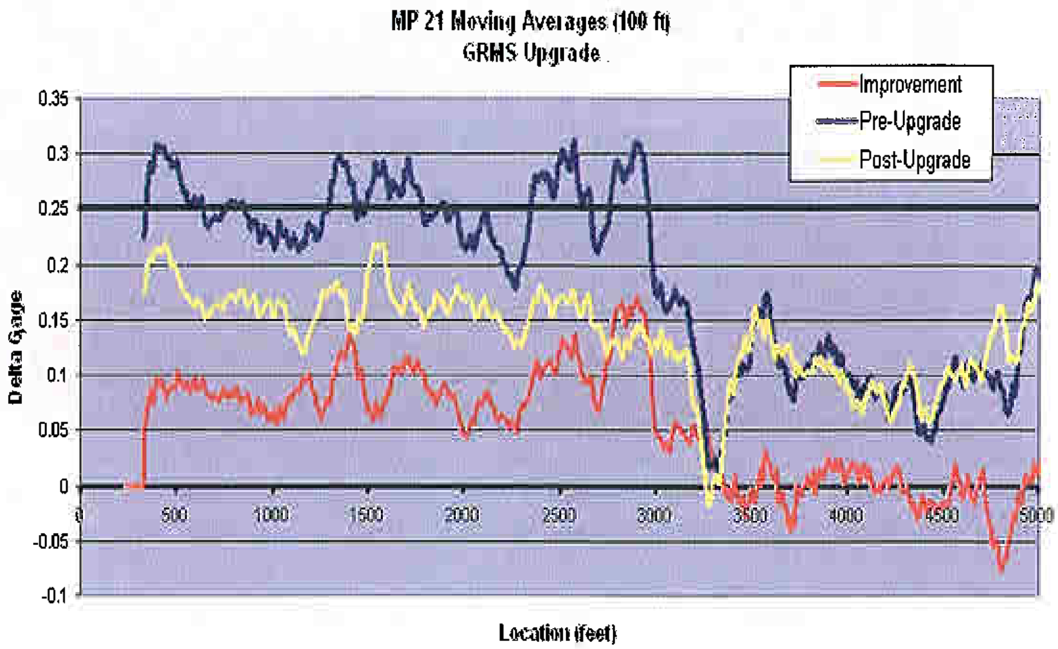


Figure 16. MP 21 Overall improvement.

The overall upgrade effectiveness for MP 23, a GRMS upgrade with limited ties, is shown in Figure 17. This mile displayed a much better initial condition than MP 21, and targeted locations with weak lateral track strength with 356 strategically located ties. As can be seen by the improvement curve, slight reductions in delta gage can be seen for the majority of the mile. Summing the area under the improvement curve produced an effectiveness index of 43.9[10], signifying slight improvement in a mile with good starting condition.

[10] Locations where the pre-and post average delta gage curves are horizontal reflect locations where the GRMS vehicle did not load the track during one run and so these areas are excluded from the summation.

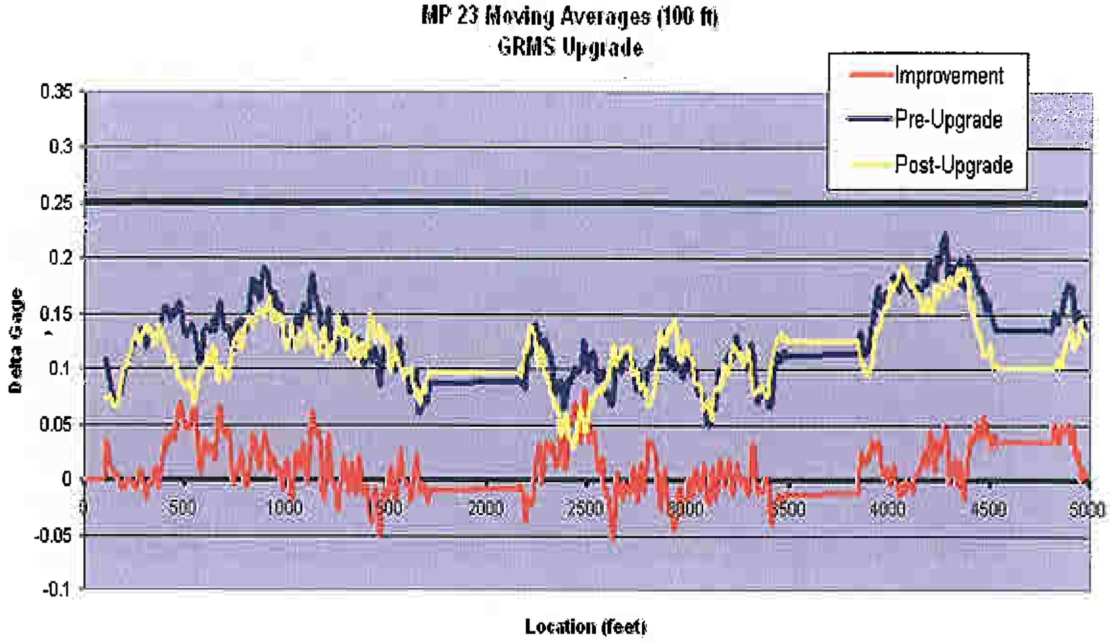


Figure 17. MP 23 Overall improvement.

The improvement in delta gage from the CSX conventional upgrade is shown in Figure 18 for MP 22. This mile had the best initial condition (average pre-upgrade delta gage of 0.114), and the post-upgrade data shows this condition to be essentially maintained, with slight improvement in some areas. Summing the area under the improvement curve produced an effectiveness index of 42.2, which is similar to the track strength improvement seen in MP 23 (GRMS upgrade) where only 42% of the ties used in this conventional mile were installed.

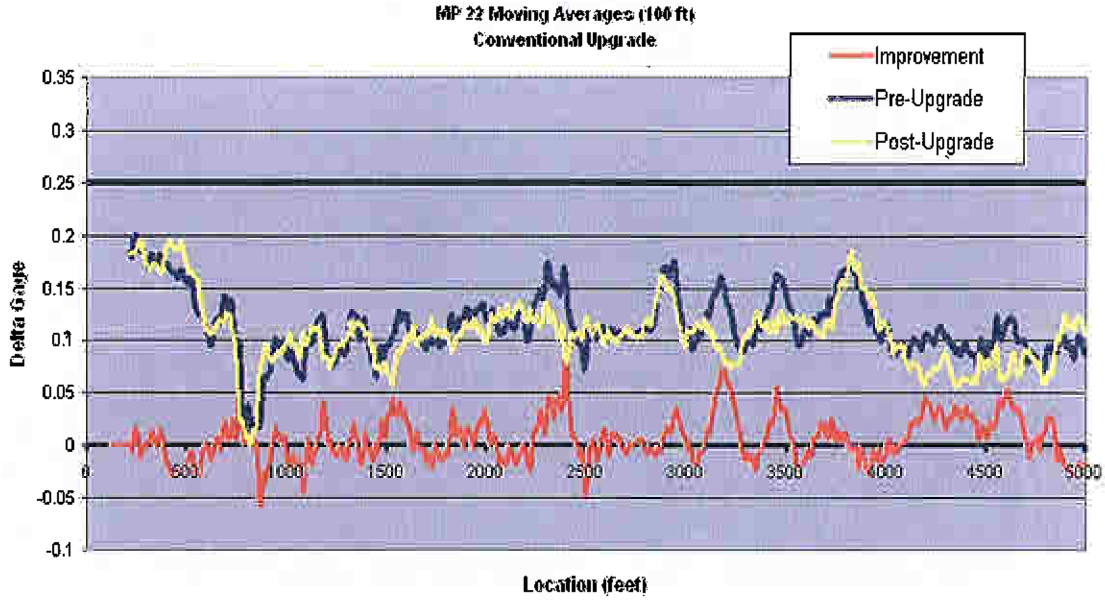


Figure 18. MP 22 Overall improvement.

Investigation into the improvement for the *TieInspect* upgrade, MP 10, once again shows slight increases in delta gage in portions of the two 3-degree curves (located from 250 ft to 750 ft and 2000 ft to 2500 ft). These average delta gage values are still well below the 0.25 in threshold used in the GRMS miles, and reflect track that is in good condition. Improvement is seen in the tangent stretch (located from 900 ft to 1750 ft) where 97 ties where strategically left in track according to *TieInspect* logic. Significant improvement in delta gage is seen at the end of the mile. Summing the area under the improvement curve produced an effectiveness index of 86.9[11], which represents the second most effective upgrade.

[11] Locations where the pre-and post average delta gage curves are horizontal reflect locations where the GRMS vehicle unloaded the track in one run and so these areas are excluded from the summation.

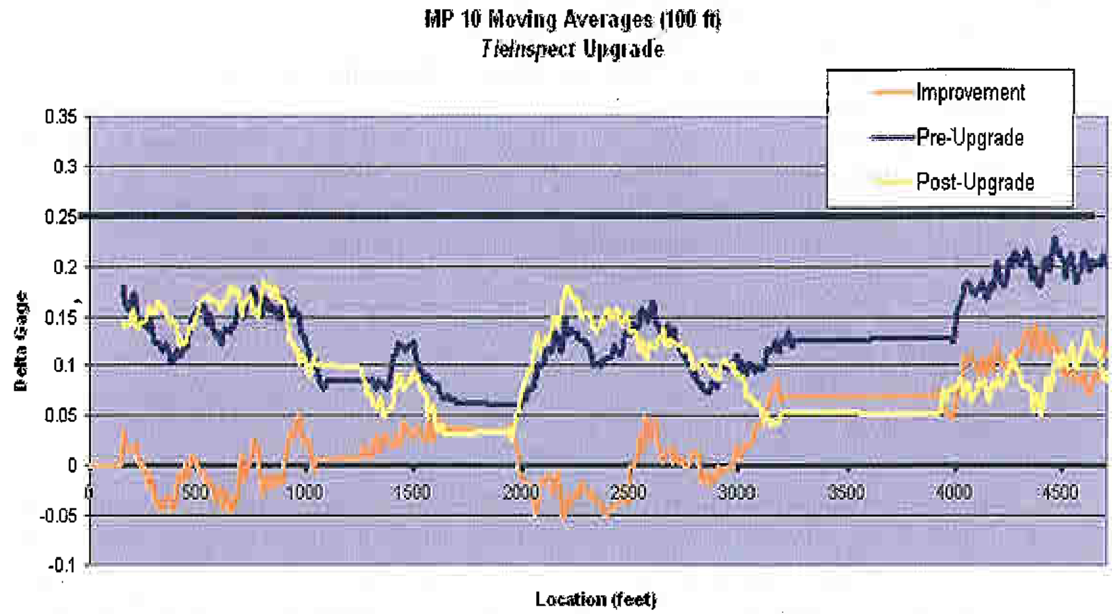


Figure 19. MP 10 Overall improvement.

Overall Upgrade Analysis (2004)

To measure overall improvement and upgrade effectiveness for each mile, Table 6 shows average initial and post-upgrade condition, the number of ties installed, the average improvement in delta gage for the entire mile, and the calculated effectiveness index. The largest improvement in delta gage can be seen in MP 21, which targeted areas exceeding 0.25 delta gage. This upgrade brought MP 21 from the worst initial condition to the best post-upgrade condition. The other GRMS upgrade mile, MP 23, saw a 9.9% average improvement in lateral track strength with only 356 ties installed in the entire mile. The effectiveness index for MP 23 is also higher than its conventional upgrade counterpart. The conventional upgrade, MP 22, saw the smallest reduction in delta gage although this mile was in the best pre-upgrade state. The *TieInspect* mile, MP 10, saw a 16.1% average reduction in delta gage for the mile, and was the second most effective upgrade.

Table 6. Overall Upgrade Improvement

MP	AVG PRE-UPGRADE Δ-GAGE	NUMBER OF TIES INSTALLED	AVG POST-UPGRADE Δ-GAGE	% IMPROVEMENT Δ-GAGE	OVERALL EFFECTIVENESS INDEX
10	0.124	888	0.104	16.1%	86.9
21	0.189	878	0.143	24.3%	243.4
22	0.114	838	0.110	3.1%	42.2
23	0.129	352	0.116	9.9%	43.9

The examination of the data from the first post-upgrade GRMS run suggested that that subsequent runs would further reveal:

-Rates of lateral track strength degradation under traffic

-Rates of lateral track strength degradation comparisons between curve and tangent segments

-Effects on degradation rates by leaving some "bad ties" surrounded by "good ties" in tangent stretches as dictated by *TieInspect* logic

-Economic implications of different upgrade/maintenance strategies versus relative effectiveness of maintaining lateral track strength integrity.

Tasks 5 and 6: Monitoring and Analysis of Test Mile Degradation Rates (2005)

CSX's GRMS Vehicle Runs

The first post-upgrade GRMS vehicle (GRMS-1) operated over the test miles on May 12, 2004 from MP 75 to MP 10, from Brunswick to Silver Springs, MD. The collected track strength data was used to monitor the effectiveness of the test mile upgrades performed in Spring 2003. In 2005, subsequent runs were made in February[12] and June by GRMS-2. GRMS runs from June 2001, May 2004, and June 2005 were used to evaluate track performance and to quantify rates of track strength degradation. These calculated rates allowed for a comparative analysis of the test miles. Forecasting (projecting) the current rates of degradation by upgrade approach provided insight into the performance implications of each upgrade approach.

Data Alignment

CSX's GRMS-1 and GRMS-2 vehicles are independent self-propelled vehicles, which gather track geometry as well as track strength data. By collecting the unloaded gage measurements together with loaded gage [14,000 lbs of lateral load] to measure gage spread, they calculate the track strength parameters (GWR and PLG24) on a foot-by-foot basis. Since mileposts are entered "on the fly" it was necessary to align the data channels for different runs. Using identifying characteristics for specific locations in the superelevation, unloaded gage, and loaded gage channels, runs on different dates were aligned on a location basis. Figure 20 shows superelevation data aligned for the June 2001, May 2004 and June 2005 runs. Although the actual magnitudes of superelevation differ in the two runs[13], it was possible to align the start and end of the curves accurately, thus allowing for accurate analysis of the relative magnitude of the measurements and the rates of degradation on a local basis.

[12] Problems were encountered with this data run, and the results have not been used in any of the analyses

[13] Changes in magnitudes of superelevation are due to tamping and surfacing activities.

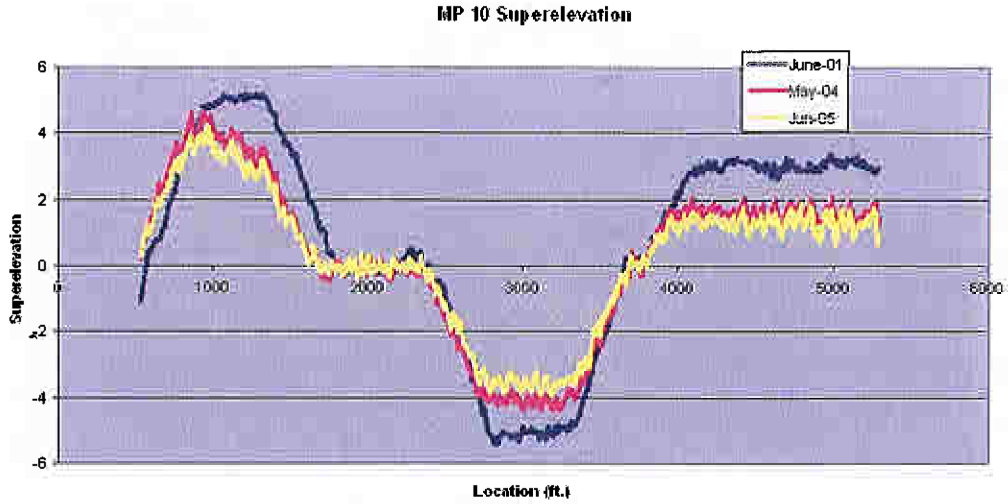


Figure 20. Aligned superelevation channels.

Once the GRMS runs were aligned on a location basis, they were then scaled to proper vertical alignment. Figure 21 shows two GRMS runs aligned horizontally but with the channel trace for the May 2004 run offset. The 6[th] order polynomials fit to the traces show similar behavior. Note, variations in instrument calibration resulted in the offset shown in Figure 3 for the unloaded gage channel.

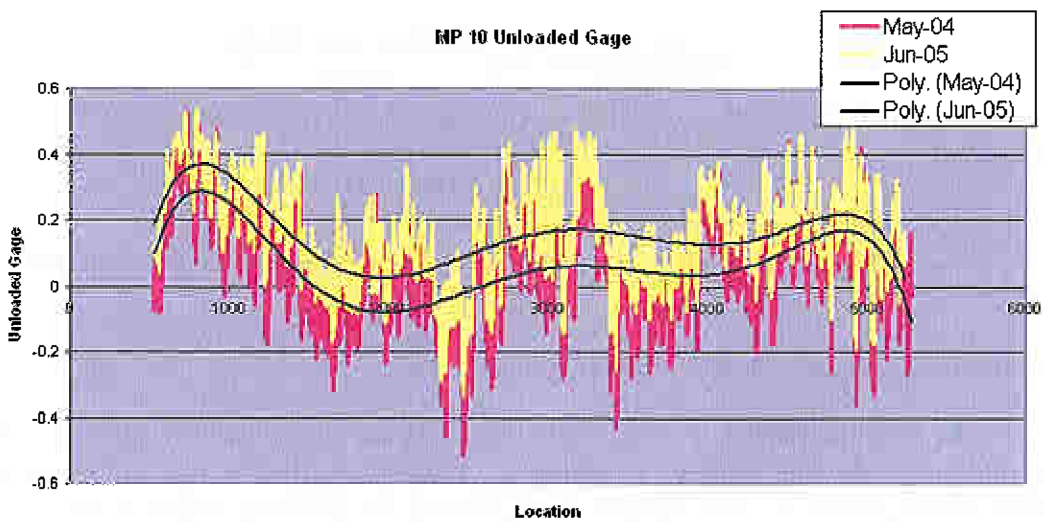


Figure 21. Unloaded gage channel horizontally aligned with vertical offset.

For comparison purposes it was necessary to recalibrate and align these channels vertically. Figure 22 shows the calibrated unloaded gage channel for these two runs. This vertical alignment process was employed on both the unloaded gage and loaded gage channels with offsets calibrated to the June 2005 run.

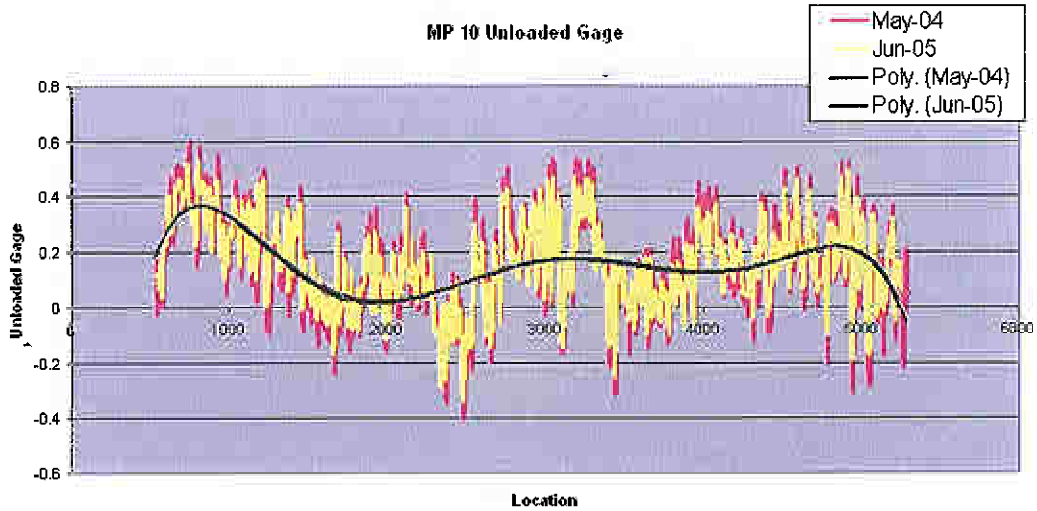


Figure 22. Unloaded gage channel horizontally and vertically aligned.

Once multiple GRMS runs were properly aligned and calibrated it is then possible to compute a recalculated gage widening ratio (GWR), which will be the variable, used for the comparative degradation analysis. Using the uncalibrated unloaded gage (UTG), uncalibrated loaded gage (LTG), and uncalibrated GWR the horizontal load applied by the GRMS vehicle can be calculated:

$$Applied\ Load\ (L) = \frac{(LTG - UTG) * 16,000}{GWR}$$

Using the calibrated LTG, UTG, and the applied load, the calibrated GWR can be computed:

$$GWR_{cal} = \frac{(LTG_{cal} - UTG_{cal}) * 16,000}{L}$$

This calibrated track strength variable is the basis for the subsequent degradation analysis.

Analysis of Upgrades Using Degradation Rates

As noted in Table 1, four test miles were studied in this activity. All four of the test miles went through a major tie replacement program, referred to here as the upgrade phase of the project. In this upgrade phase, several different approaches were used to define the number and location of ties to be installed. The focus of this study was a comparison of a GRMS based tie replacement approach as compared to the current, visual approach used by CSX (Conventional). As a supplement to this comparison, an approach using the TieInspect tie mapping system was also used on one mile. After identification of the ties to be replaced during this upgrade phase, a CSX production tie gang went through in April 2003 and installed the following numbers of ties:

MP 10 *TieInspect**	888 ties
MP 21 GRMS	878 ties
MP 22 Conventional	838 ties
MP 23 GRMS	356 ties

** Supplemental evaluation*

The following sections describe the analysis of the GRMS and Conventional upgrade miles and the evaluation of the differences between the upgrade approaches.

MP'21 GRMS Upgrade Analysis (2005)

MP 21 underwent a GRMS upgrade, in which delta gage peaks over 0.25 were targeted. Since passenger trains hit 79 mph through these miles it was the goal to invoke a tight upgrade standard. Of the 878 ties installed, 828 were located in the first 3000 feet where most of the exceedance locations were found. Figure 23 shows the 25-ft moving average GWR for the June 2001, May 2004, and June 2005 runs, noting the locations of the installed ties. Upgrade success is seen in the shift from the orange curve (June 2001) to the blue curve (May 2004). As expected a larger improvement is seen in the first 3000 feet. Overall lateral degradation for the mile is shown by the shift from the blue curve (May 2004) to the black curve (June 2005).

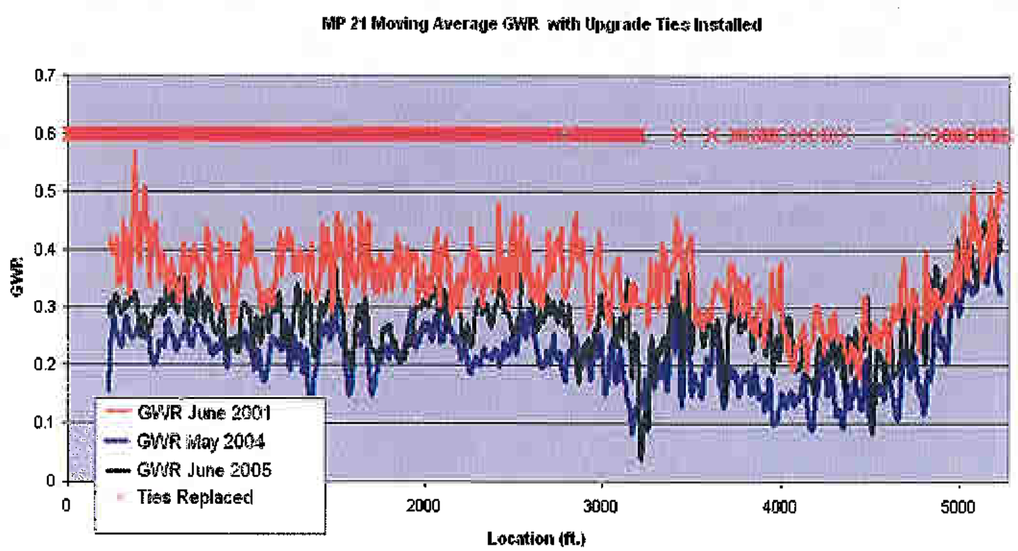


Figure 23. 25 ft Moving Average GWR for Three Runs.

To quantify overall mile condition at each run, the average or mean GWR is calculated for the entire mile and presented in Table 7. The improvement due to the upgrade tie installation can be seen by the decrease in the mean GWR from June 2001 to May 2004. Also the degradation with time (and traffic) can be seen from May 2004 to June 2005. The difference between these values can be used to calculate the degradation rate or trend. Also shown is the standard deviation (Std Dev) of each run, which shows the variation in condition for each run from the mean. Prior to the upgrade a wider variation in condition is seen (0.142 Standard Deviation for June 2001), noting the upgrade brought the mile to a more uniform, improved condition.

Table 7. Mean GWR and Standard Deviation for each run.

Date	Vehicle	Mean GWR	Std Dev
Jun-01	GRMS-1	0.352	0.142
May-04	GRMS-2	0.216	0.069
Jun-05	GRMS-2	0.275	0.072

By subtracting June 2005 and May 2004 mean GWR, and dividing by the years between the runs, an average degradation rate can be calculated (in/yr). This is shown in Table 8, where the gage widening at 16,000 lbs lateral load is seen to degrade at 0.054 inches per year.

Table 8. Calculated Degradation Rate for MP 21.

Mean GWR	May-04	Jun-05	in/yr	Upgrade Ties
MP 21	0.216	0.275	0.054	878

Using this calculated degradation rate and the assumption that the degradation is linear, both Pre-Upgrade and Post-Upgrade condition can be interpolated as shown in Figure 24. This provides a more realistic improvement in mean GWR since the pre- and post-upgrade GRMS runs where almost 2 years before and approximately 1.1 years after the upgrade respectively. This still only represents an approximation in overall upgrade success as it would be expected that the pre-upgrade degradation rate would be more aggressive for two reasons: (1) the mile was certainly starting from a worse condition than the post-upgrade condition, and (2) the upgrade targeted "weak performing areas" so these areas would now degrade more slowly, and the good performing areas would at least initially continue as such. However, this analysis improves on the accuracy of the evaluation of the upgrade success. As shown in Figure 24, MP 21 registered an approximated 0.294 improvement in mean GWR.

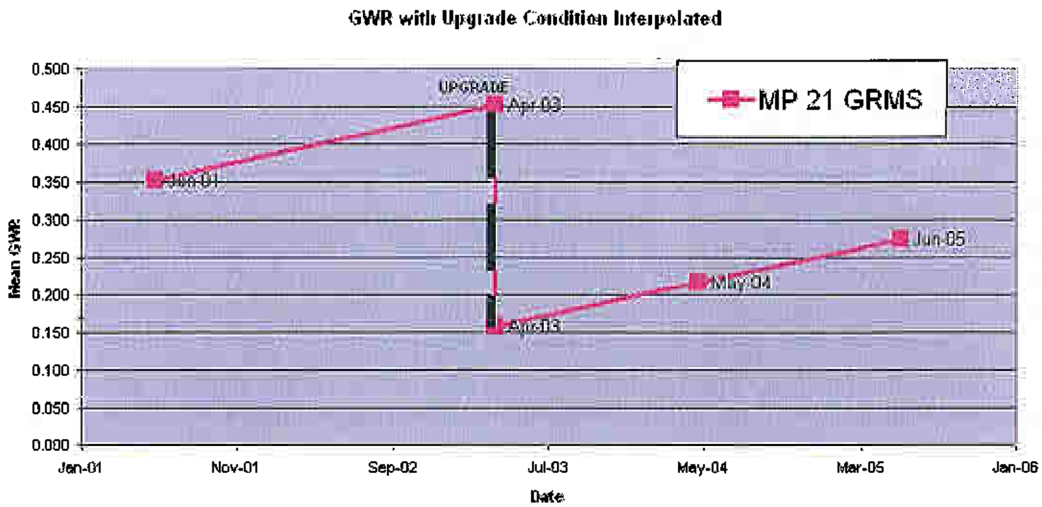


Figure 24. GWR Degradation Over Time.

Another measure of upgrade success would be the statistical distribution of GWR measurements for each of the GRMS runs. According to Figure 25, the June 2001 histogram (using 0.05 GWR increments) shows the widest scatter of measured GWR, with the curve shifted furthest to the right due to the higher mean value[14]. The effects of the upgrade are evident as the histogram shows a much narrower distribution (lower standard deviation from the mean), and the curve is shifted furthest to the left. The degradation experienced at the June 2005 run is represented by the rightward shift of the curve and widening of the histogram.

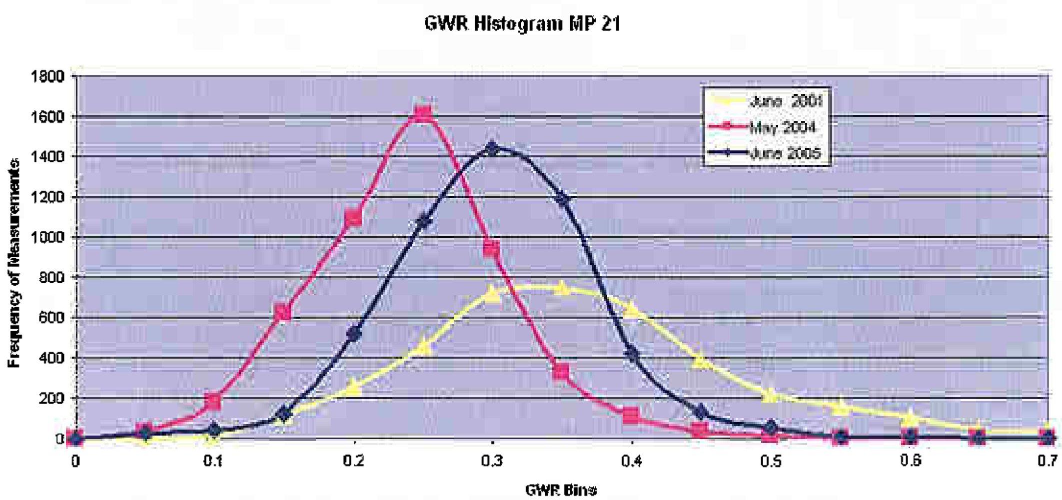


Figure 25. GWR Histogram for MP 21.

[14] Note, the finer the increment used for GWR bins, the closer the peak value will approach the sample mean value. Bin increments of 0.05 are sufficient enough to demonstrate the effects of time and the upgrade.

MP 22 Conventional Upgrade (2005)

MP 22 was spotted and subsequently upgraded according to CSX's current (conventional) practices based on visual inspection and marking by CSX tie inspectors. The upgrade consisted of 838 ties, with the majority of the mile being a long tangent stretch. It should be noted that this mile contains a bridge spanning from locations 4060 ft to 4500 ft, where the ties were in good condition at the time of the upgrade. Otherwise requirements could have increased to that of adjacent mile conventional CSX tie gang upgrades (1000-tie range). Figure 26 shows the 25-ft moving average GWR for the June 2001, May 2004, and June 2005 runs, noting the locations of the installed ties. Upgrade success is seen in the shift from the orange curve (June 2001) to the blue curve (May 2004). Moderate improvement is seen through the mile. The current calculated degradation rate is shown by the shift from the blue curve (May 2004) to the black curve (June 2005).

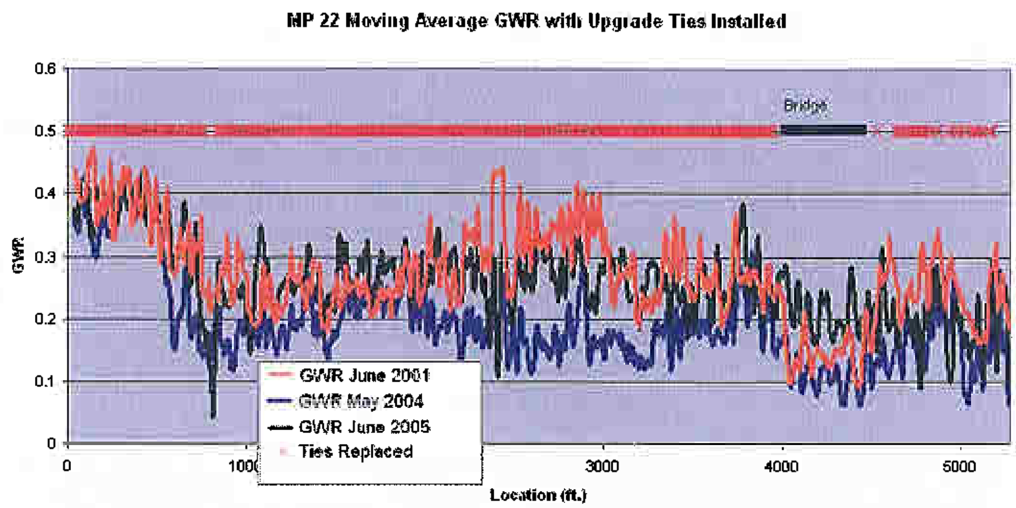


Figure 26. 25 ft Moving Average GWR for Three Runs.

To examine overall mile condition at each run, mean GWR is shown in Table 9. The upgrade improvement can be seen by the decrease in mean GWR from June 2001 to May 2004. Lateral track strength degradation can be seen in the mean GWR increase from May 2004 to June 2005. Also shown is the standard deviation of each run, which shows the variation in condition for each run from the mean. Prior to the upgrade a wider variation in condition is seen (0.107 Standard Deviation for June 2001), noting the upgrade brought the mile to a more uniform, improved condition.

Table 9. Mean GWR and Standard Deviation for each run.

Date	Vehicle	Mean GWR	Std Dev
Jun-01	GRMS-1	0.276	0.107
May-04	GRMS-2	0.195	0.086
Jun-05	GRMS-2	0.260	0.082

Once again, by subtracting June 2005 and May 2004 mean GWR, and dividing by the years between the runs, an average degradation rate can be calculated (in/yr). This is shown in Table 10, where the gage widening at 16,000 lbs lateral load is seen to degrade at a higher 0.060 inches per year.

Table 10. Calculated Degradation Rate for MP 22.

Mean GWR	May-04	Jun-05	in/yr	Upgrade Ties
MP 22	0.195	0.260	0.060	838

As shown previously, using this calculated degradation rate and the assumption that the degradation is linear, both Pre-Upgrade and Post-Upgrade condition can be interpolated as shown in Figure 26. This provides a more realistic improvement in mean GWR since the pre- and post-upgrade GRMS runs were almost 2 years before and approximately 1.1 years after the upgrade respectively. As shown in Figure 26, MP 22 registered an approximated 0.255 improvement in mean GWR.

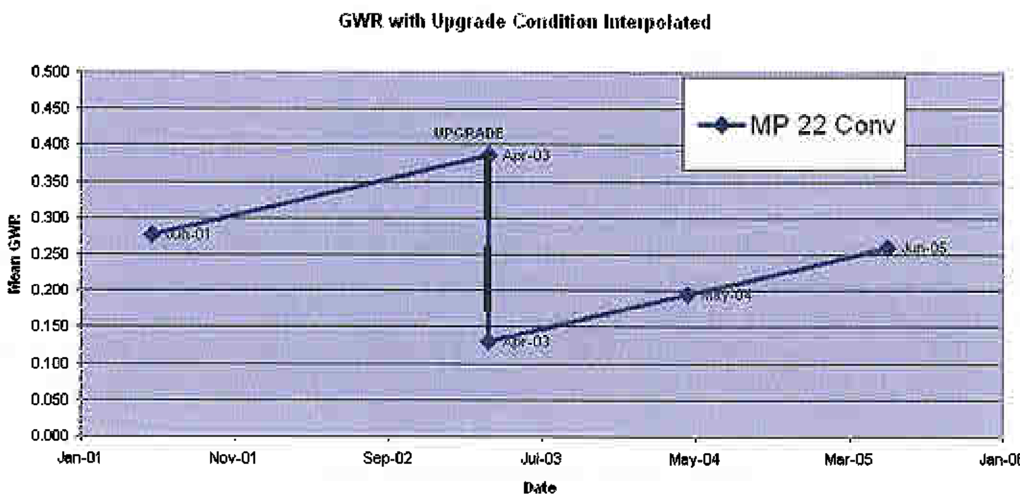


Figure 26. GWR Degradation Over Time.

Examining the statistical distribution of GWR measurements again shows the June 2001 run with the widest scatter of measured GWR, and the curve shifted furthest to the right due to the higher mean value. The effects of the upgrade are evident as the histogram shows a much narrower distribution (lower standard deviation from the mean), and the curve is shifted furthest to the left. The degradation experienced at the June 2005 run is represented by the rightward shift of the curve and slight widening of the histogram. Note the June 2005 mean is almost back to the June 2001 mean value.

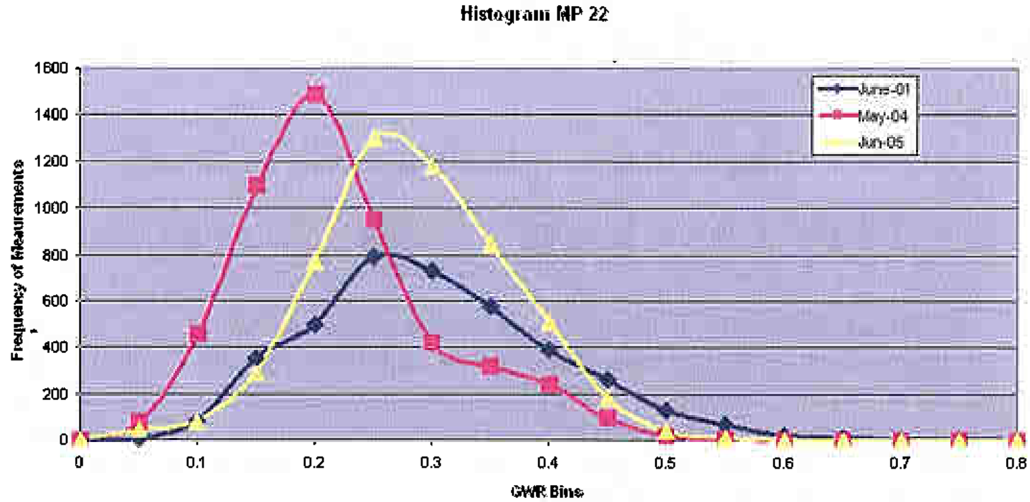


Figure 27. GWR Histogram for MP 22.

MP 23 GRMS Upgrade (2005)

MP 23 also utilized a GRMS based upgrade, which was designed to improve the lateral track strength of the mile but with only a limited number of ties. The upgrade consisted of 356 ties targeting locations with the highest GWR peaks throughout the mile. Figure 28 shows the 25-ft moving average GWR for the June 2001, May 2004, and June 2005 runs, noting the locations of the installed ties. Upgrade success is seen in the shift from the orange curve (June 2001) to the blue curve (May 2004). Improvement is most noticeable in the areas with high GWR peaks. The deterioration in lateral track strength is shown by the shift from the blue curve (May 2004) to the black curve (June 2005).

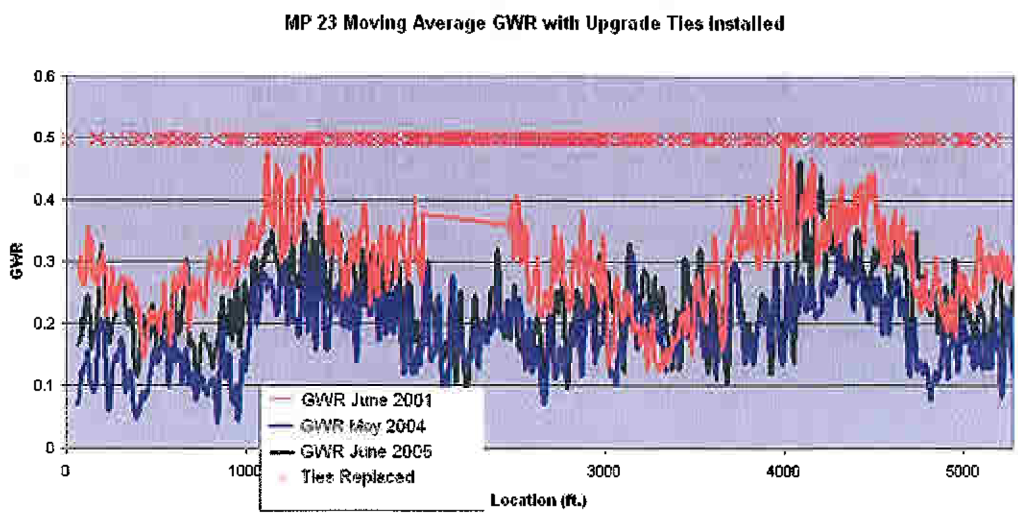


Figure 28. 25 ft Moving Average GWR for Three Runs.

For comparison purposes, mean GWR for each run is shown in Table 11. The upgrade improvement can be seen by the decrease in mean GWR from June 2001 to May 2004. Lateral track strength degradation can be seen in the mean GWR increase from May 2004 to June 2005. Also shown is the standard deviation of each run, which shows the variation in condition for each run from the mean. Prior to the upgrade a wider variation in condition is seen (0.132 Standard Deviation for June 2001), noting the upgrade brought the mile to a more uniform, improved condition.

Table 11. MP 23 Mean GWR and Standard Deviation for each run.

Date	Vehicle	Mean GWR	Std Dev
Jun-01	GRMS-1	0.299	0.132
May-04	GRMS-2	0.184	0.082
Jun-05	GRMS-2	0.237	0.087

Once again, by subtracting June 2005 and May 2004 mean GWR, and dividing by the years between the runs, an average degradation rate can be calculated (in/yr). This is shown in Table 12, where the gage widening at 16,000 lbs lateral load is seen to degrade at a much improved 0.049 inches per year with only a limited number of ties strategically located.

Table 12. Calculated Degradation Rate for MP 23.

Mean GWR	May-04	Jun-05	in/yr	Upgrade Ties
MP 23	0.184	0.237	0.049	356

As shown previously, using this calculated degradation rate and the assumption that the degradation is linear, both Pre-Upgrade and Post-Upgrade condition can be interpolated as shown in Figure 29. According to Figure 2, MP 23 registered an approximated 0.256 improvement in mean GWR, which approximately equals the improvement seen in MP 22 using 58% less crossties.

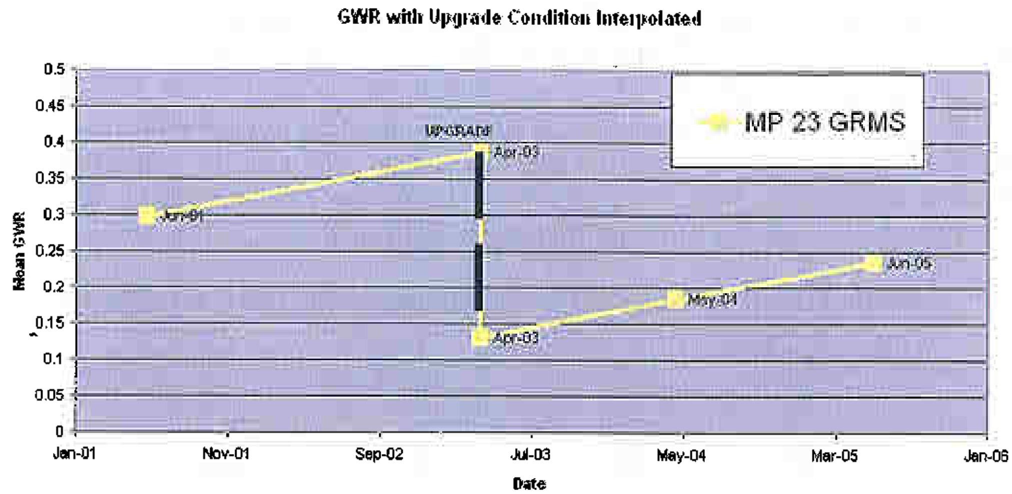
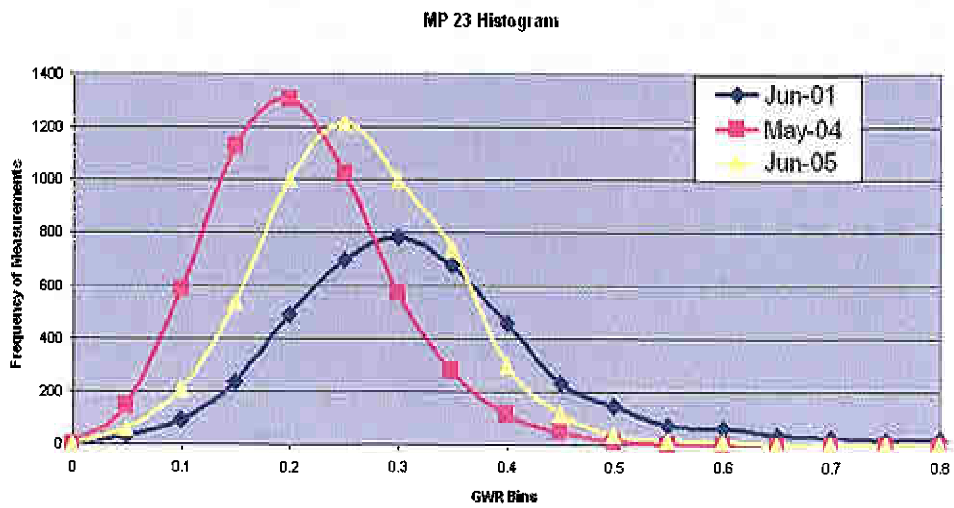


Figure 29. GWR Degradation Over Time.

Examining the statistical distribution of GWR measurements for MP 23 shows the June 2001 run with the widest scatter of measured GWR, and the curve shifted furthest to the right due to the higher mean value. The effects of the upgrade are evident as the histogram shows a much narrower distribution (lower standard deviation from the mean), and the curve is shifted furthest to the left in May 2004. The degradation experienced at the June 2005 run is represented by the rightward shift of the curve and widening of the histogram. Note the rightward shift of the June 2005 curve is the smallest of all the miles.

Figure 30. GWR Histogram for MP 23.



Comparisons GRMS vs. Conventional

As shown in Table 12A below, the GRMS miles outperformed the conventional mile in the effectiveness of the tie replacement/upgrade as defined by the corresponding mean GWR degradation rate. In fact, the lowest degradation rate corresponds to the GRMS upgrade mile (Mile 23) with the lowest number of ties installed; 356 vs. 838 for the conventional mile. In addition, examination of the GWR standard deviation (Tables 7, 9, and 11) show that the GRMS miles had higher pre-upgrade standard deviations, which indicates a wider scatter of tie condition, but ended up with lower standard deviations (less scatter) after the upgrade. This highlights the ability of the GRMS upgrade methodology to provide a more uniform, superior condition, based on the gage strength of the track.

TABLE 12A: Summary of GWR Degradation Rates

	Mean GWR (in.)		Degradation Rate	
MP (Upgrade)	May-04	Jun-05	in/yr	Upgrade Ties
21 (GRMS)	0.216	0.275	0.054	878
22 (Conv)	0.195	0.260	0.060	838
23 (GRMS)	0.184	0.237	0.049	356

Figure 31 presents the relative behavior of the three test miles graphically. As can be seen in this Figure, the conventionally upgraded mile (Mile 22) started off (pre-upgrade) with the best gage strength, as defined by mean , but was outperformed by the GWR miles, particularly MP 23. This is in spite of the fact that MP 23 installed 58% fewer crossties. The other GRMS mile, MP 21 (GRMS), registered the largest improvement in mean GWR again due to successful targeting of weak spots..

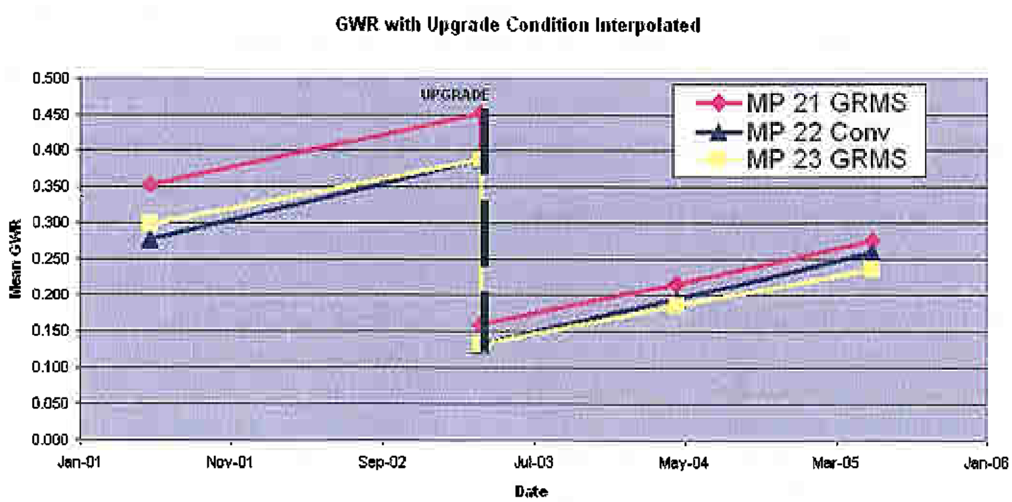


Figure 31. Upgrade Effectiveness and Degradation Rates of Test Miles.

The effects of these relative degradation rates on the time it takes for the track to reach the GWR threshold levels[15] was calculated and presented in the Table below. Note, the 2nd or maintenance level used is 0.75 inches. A GWR value between 0.75 and 1 inch represents a second level exception and track speed must be set at the maximum for class 3 track (*FRA Track Safety Standards Part 213 pg 38*). A GWR reading of 1 inch or more represents a first level exception and track speed is to be reduced to 10 mph (*FRA Track Safety Standards Part 213 pg 37*). Noting the above, the conventional mile on average reaches a second level exception 1.4 years earlier than the worst performing GRMS mile. This is a direct function of the higher degradation rate shown in Table 12A. Likewise it reaches a first level exception 1.8 years earlier. Based on this study and using the second level exception threshold, the GRMS upgrade philosophy provides an additional 2.1 years to reach the threshold. Extending this improvement to overall tie life, and noting average tie life for this location is 23 years[16], this would represent a 9.1% extension in tie life.

Table 18. Average Time to GRMS Exception Thresholds.

		From Perfect Condition		
MP	Upgrade	Deg Rate	2nd level (Yrs)	1st level (Yrs)
21	GRMS	0.054	13.9	18.5
22	Conv	0.060	12.5	16.7
23	GRMS	0.049	15.3	20.4

MP 10 TieInspect Upgrade Performance

As noted above, a supplemental evaluation of tie replacement using the TieInspect inspection and analysis system was performed at MP 10. In this activity, MP 10 was inspected by CSX personnel noting all tie failure mechanisms including the ties ability to hold line and surface, splitting, breaks, plate cutting, plate movement, wheel cuts, decay or hollowness, and the ability to hold cut spikes. This mile was originally scheduled for a **985**-tie upgrade. However, the *TieInspect* replacement logic, based on actual tie condition, tie location, curvature and other factors, defined a requirement for **888** ties, a 9.8% reduction in ties required. That is because not all bad ties are replaced, but only those ties required to maintain track integrity.

The spotted ties left in track were located in the mile's only tangent stretch (located between 800 and 1800 feet) between two 3-degree curves. Figure 32 shows the 25-ft moving average GWR for the June 2001, May 2004, and June 2005 runs, noting the locations of the installed ties. Upgrade success is seen in the shift from the orange curve (June 2001) to the blue curve (May 2004). The area where the spotted ties were left in track continues to perform well as location 750 ft to 1250 ft saw good improvement, and 1500 ft to 1800 ft is part of the best performing stretch of the mile. The deterioration in

[15] Time to reach GRMS 1st and 2nd level exceptions is less than average tie life due to the expected nonlinear tie life behavior.
[16] Average tie life was calculated using the RTA SelecTie Model II, for the track and operating conditions of the Metropolitan Sub.

lateral track strength is shown by the shift from the blue curve (May 2004) to the black curve (June 2005).

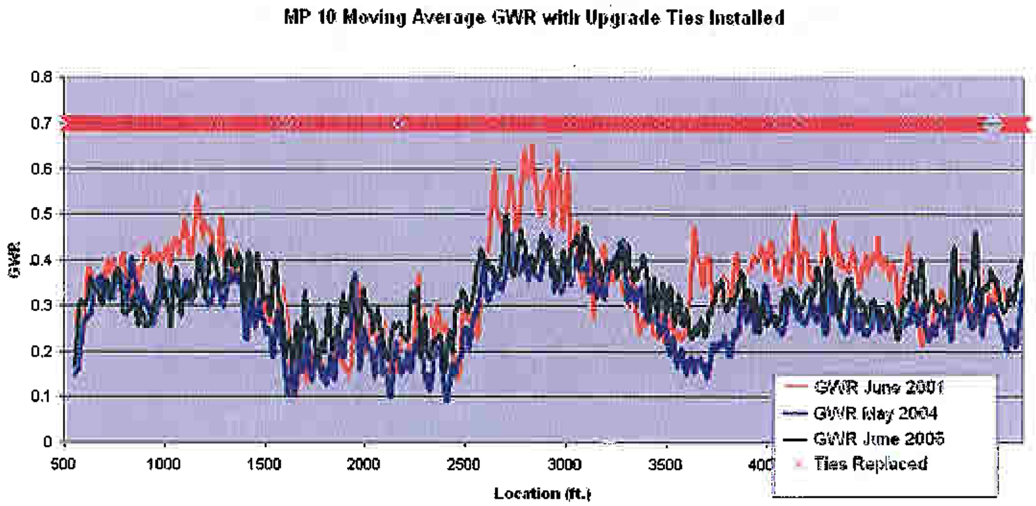


Figure 32. 25 ft Moving Average GWR for Three Runs.

Similar trends as previously discussed are seen in mean GWR for each run, which is shown in Table 14. Prior to the upgrade a wider variation in condition is also seen (0.125 Standard Deviation for June 2001).

Table 14. MP 10 Mean GWR and Standard Deviation for each run.

Date	Vehicle	Mean GWR	Std Dev
Jun-01	GRMS-1	0.353	0.125
May-04	GRMS-2	0.275	0.092
Jun-05	GRMS-2	0.321	0.082

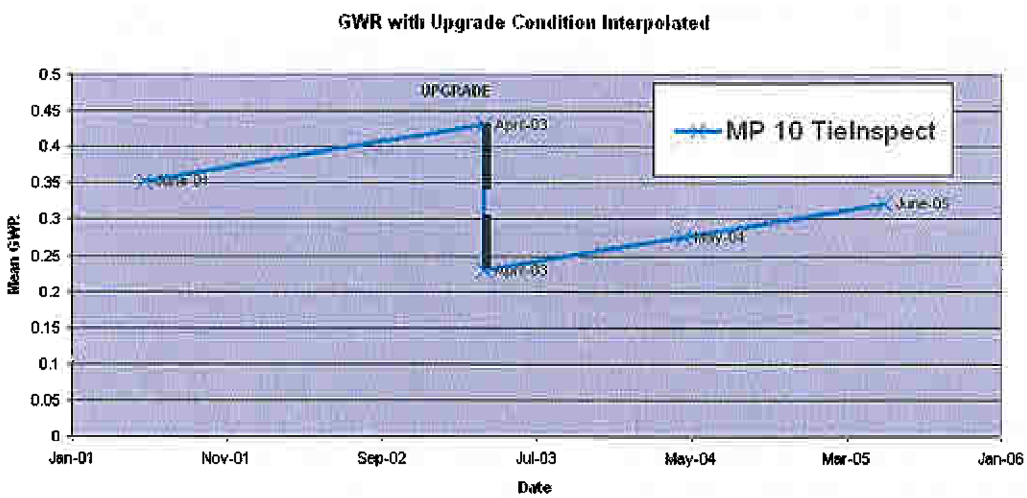
The average GWR degradation rate is shown in Table 15, where the gage widening at 16,000 lbs lateral load is seen to degrade at a 0.042 inches per year. This is, in fact, a lower degradation rate than that obtained by the GRMS and Conventional techniques. However, the mean values were generally higher.

Table 15. Calculated Degradation Rate for MP 10.

Mean GWR	May-04	Jun-05	in/yr	Upgrade Ties
MP 10	0.275	0.321	0.042	888

As shown previously, using this calculated degradation rate and the assumption that the degradation is linear, both Pre-Upgrade and Post-Upgrade condition can be interpolated as shown in Figure 33. According to Figure 33, MP 10 started with the worst initial condition and registered an approximated 0.2 improvement in mean GWR.

Figure 33. TieInspect Degradation Over Time.



The statistical distributions of TieInspect measurements for each run are given in Figure 34. Similar trends hold true as the June 2001 histogram shows the highest mean condition (right-most shift), and a wide scatter due to large variations in pre-upgrade condition.

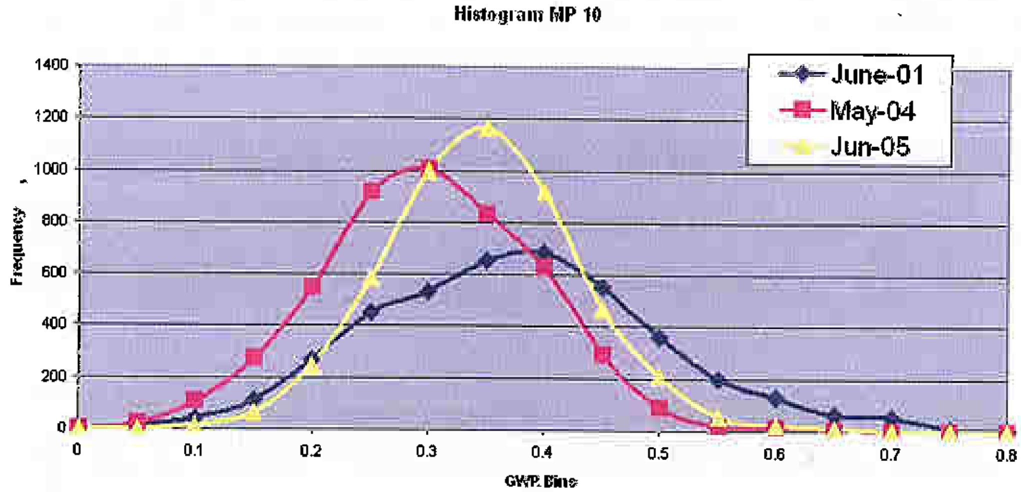


Figure 34. GWR Histogram for MP 10.

Tie Selection and Spotting for Maintenance Cycle

To further investigate tie requirements for each replacement methodology, the test miles underwent a maintenance cycle based on the philosophies given in Table 16.

Table 16. Maintenance Philosophies

TEST SITE	MP	MAINTENANCE
1	10	*TieInspect*
2	21	GRMS
3	22	Conventional
4	23	Conventional

Implementation of Tie Spotting Methodologies

The selection of maintenance ties, which can be referred to as tie spotting for the different test miles were as follows.

MP 10 (*TieInspect* Maintenance Cycle): This mile underwent a tie-by-tie inspection by the CSX Roadmaster. Each tie was graded on the *TieInspect* condition classification: Good, Marginal, Bad, or Failed. Figure 35 shows the *TieInspect* condition map provided by the host software with black and red lines representing failed or bad ties respectively. The total mile summary is provided at the top, noting the inspection revealed 164 bad ties, and 39 failed ties (203 total ties in bad condition). This mile continues to exhibit good tie condition as 2,549 good ties and 412 marginal ties were graded.

After tie condition data was collected, the *TieInspect* replacement logic was then employed and specific ties were identified for removal. By analyzing the stored tie condition and location data, the software strategically broke up bad clusters. Although 203 ties in bad condition were identified, surrounding condition dictated that only 184 ties be replaced. The *TieInspect* logic reduced the requirements by 9.4% as 19 bad ties (not failed), which had excellent surrounding tie condition were left in the tangent stretch of track.

Figure 35. *TieInspect* Condition Map for MP 10.

MP 21 (GRMS Maintenance Cycle): To perform tie replacement based on GRMS data it is necessary to locate specific ties based upon foot-by-foot data output. The *TieInspect™* unit gave the test mile inspector the ability to record the start and end of curves within a test mile. By overlaying the June 2005 GRMS superelevation channel with the *TieInspect™* recorded curves as shown in Figure 36, a functional relationship was established between the "foot counter" of the GRMS vehicle and the *TieInspect™* tie number. This produced the plot shown in Figure 37, which displays a more useful relationship of GWR versus tie number. Using a GWR maintenance threshold of 0.4 and the locating procedure described above, MP 21 was marked using track strength data exclusively. In total 162 ties were spotted in this mile.

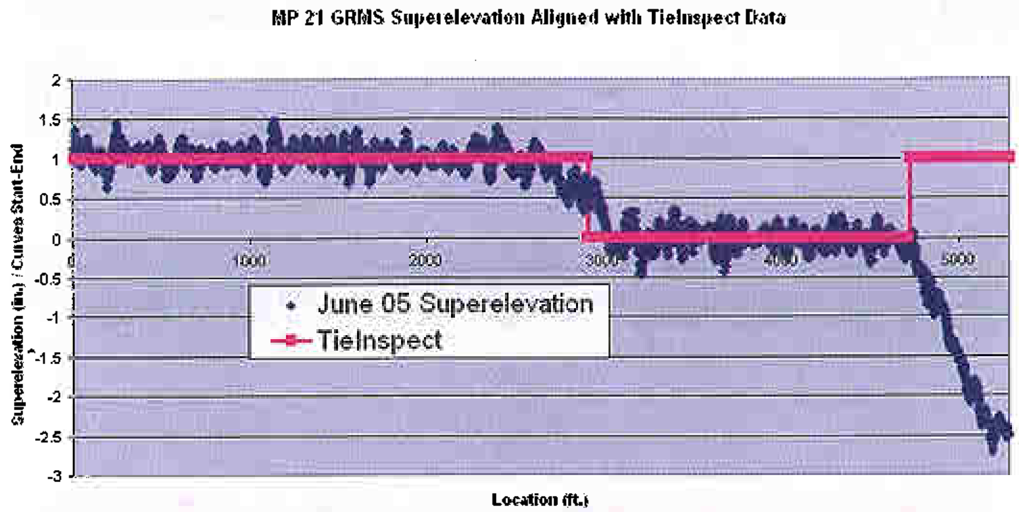


Figure 36. Superelevation Channel Aligned with Start and End of Curves Collected with *TieInspect* Unit.

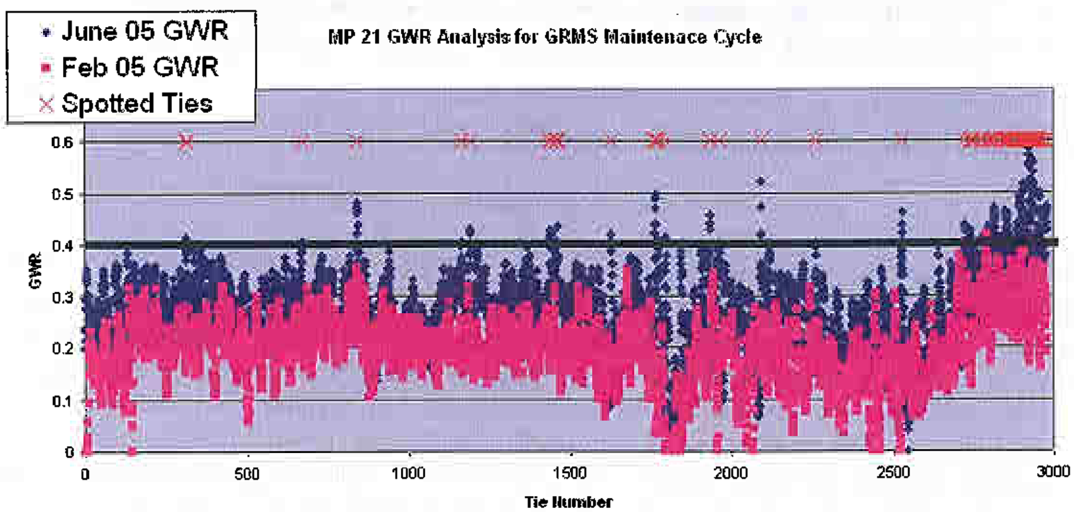


Figure 37. GWR versus Tie Number Showing 0.4 GWR Maintenance Threshold.

MP 22 (Conventional Maintenance Cycle): This mile was conventionally spotted by the CSX Roadmaster, who identified 352 ties for replacement. Figure 38 shows locations of the spotted ties that were collected with the TieInspect Unit and marked as "Bad."

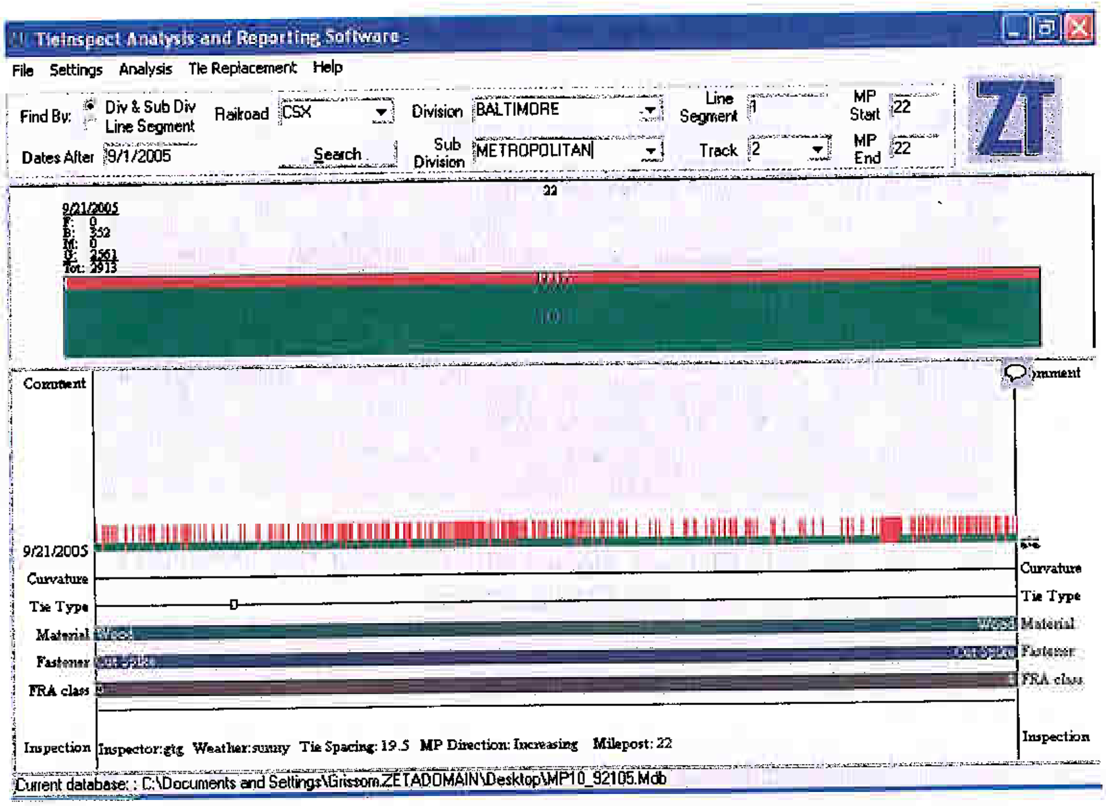


Figure 38. ***TieInspect*** **Condition Map for MP 22.**

MP 23 (Conventional Maintenance Cycle): MP 23 received a 356 tie GRMS-based upgrade by the production tie gang in April 2003. As a result, a conventional maintenance philosophy generated a higher maintenance tie count. Although this mile was successful at targeting lateral weak spots with minimal ties during the upgrade, conventional spotting targeted all bad ties regardless of surrounding condition and lateral performance. This mile was conventionally spotted by the CSX Roadmaster, who identified 551 ties for replacement. The total tie count (upgrade plus maintenance, 907 ties) brings this mile near the conventional mile upgrade totals. . Figure 39 shows locations of the spotted ties that were collected with the TieInspect Unit and marked as "Bad."

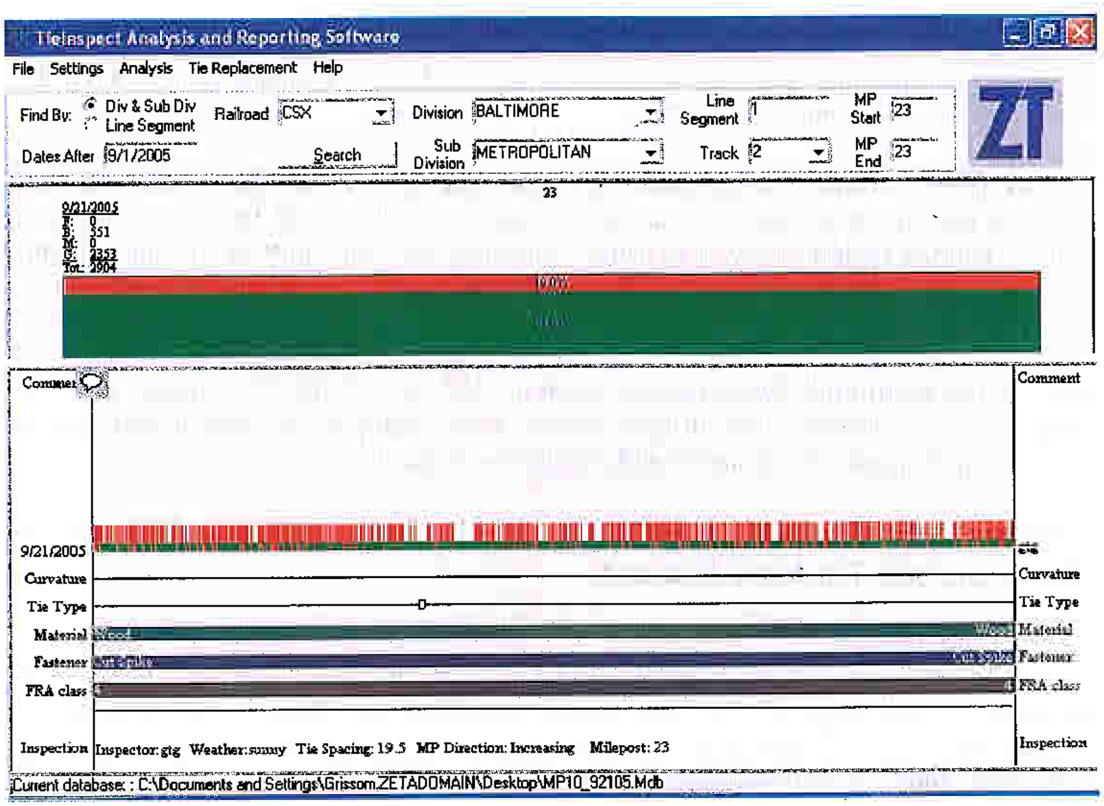


Figure 39. *TieInspect* Condition Map for MP 23.

Installation of Maintenance Ties

Based on the tie count from the spotting exercise, the Railway Tie Association coordinated the shipment of 1,250 crossties to Brunswick, MD. A full-mechanized tie gang (CSX TA tie gang) installed approximately 1,200 of the maintenance ties spotted on the 9/21/05 trip. Prior to the gang's arrival, ballast was dumped and the new ties were spread along the test miles. The gang was made up of approximately 20 machines, including ballast regulator, gaging equipment, spike pullers, tie removers/inserters, tie cranes, magnetic spike collector, and complete surfacing equipment (see photos in Appendix B). The gang installed 184 ties in MP 10, 149 ties in MP 21, 332 ties in MP 22, and 532 ties in MP 23. The gang was unable to put ties in some platform locations (MP 21 and 23), due to both clearance limitations (i.e. pedestrian crossings) and lifting of the track in platforms. Also there were ties left on the west side of the MP 22.7 Bridge, since the gang can only replace seven consecutive ties in a row. As such 9 ties were left to hold the rail together while replacing these consecutive ties. The ties left in track were installed with a backhoe by local forces.

MP 10 (*TieInspect* Maintenance Cycle): 184 ties were installed, with no problems reported.

MP 21 (GRMS Maintenance Cycle): 149 ties of the 162 spotted ties were installed due to pedestrian crossings and clearance limitations in the Gaithersburg station area. The ties left in track were installed with a backhoe by local forces.

MP 22 (Conventional Maintenance Cycle): 332 ties of the 352 spotted ties were installed due to the consecutive ties spotted on the west side of the MP 22.7 bridge. Gangs can only replace seven consecutive ties, since the gage must be maintained while replacing ties. Also some ties in the vicinity of a grade crossing where left due to clearance concerns. The ties left in track were installed with a backhoe by local forces.

MP-23 (Conventional Maintenance Cycle): 532 ties of the 551 spotted ties were installed due to clearance and surfacing issues at the Metropolitan Grove MARC station. The ties left in track were installed with a backhoe by local forces.

Tasks 5 and 6 (2006) April 2006 GRMS Run – GRMS Analysis of Maintenance Tie Installations.

GRMS Data Analysis

The first post-maintenance GRMS vehicle (GRMS-2) operated over the test miles on April 17, 2006 from MP 75 to MP 2, from Brunswick to F-Tower. The collected track strength data was used to evaluate the effectiveness of the maintenance cycle performed in October 2005. The maintenance gang installed 1,249 ties as shown in Table 17.

Table 17. Maintenance Tie Installations

MP	MAINTENANCE	MAINTENANCE TIES INSTALLED
10	*TieInspect*	184
21	GRMS	162
22	Conventional	352
23	Conventional	551

For the individual tie selection process refer to *Implementation of Tie Spotting Methodologies.*

MP 21 GRMS Maintenance Evaluation

MP 21 was the only mile to undergo a GRMS based maintenance cycle. Figure 18 shows the pre- and post-maintenance GRMS runs along with the locations of the ties installed. It is evident that GWR peaks exceeding 0.4 were successfully targeted using the June 2005 run by the reduction in the highest GWR peaks. MP 21 outperformed both conventional maintenance cycles (MP 22, 23), by reducing average GWR by 0.046 inches with significantly less ties.

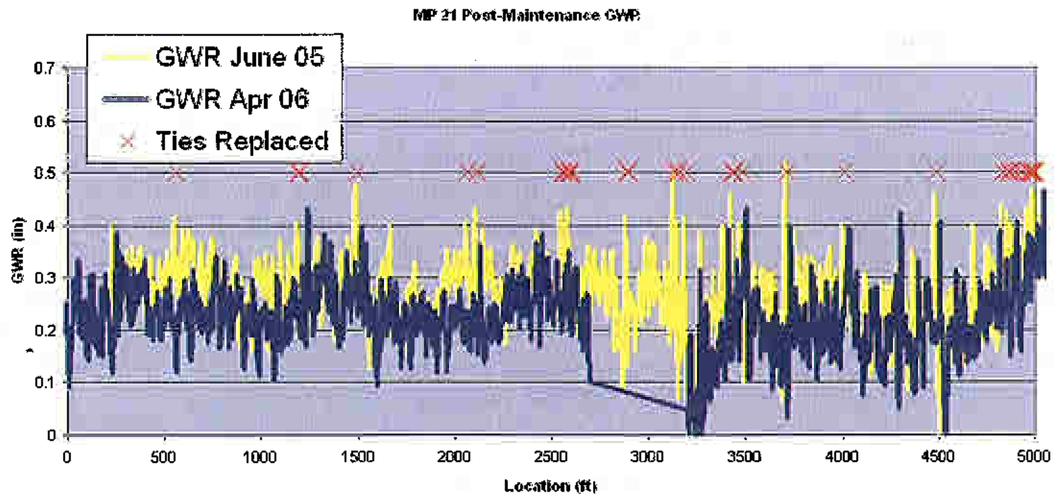


Figure 18. MP 21 Post-Maintenance GRMS run.

One issue with GRMS maintenance is the effect on track profile, as tie replacement is based on lateral track performance. To investigate this, Figure 19 plots the 62 ft chord left profile[17] for MP 21. For most of the mile, a smaller deviation from zero profile can be seen in the April 2006 run, despite tie replacement focusing on lateral performance. The spike seen in this plot occurs at a grade crossing with an abrupt change in profile.

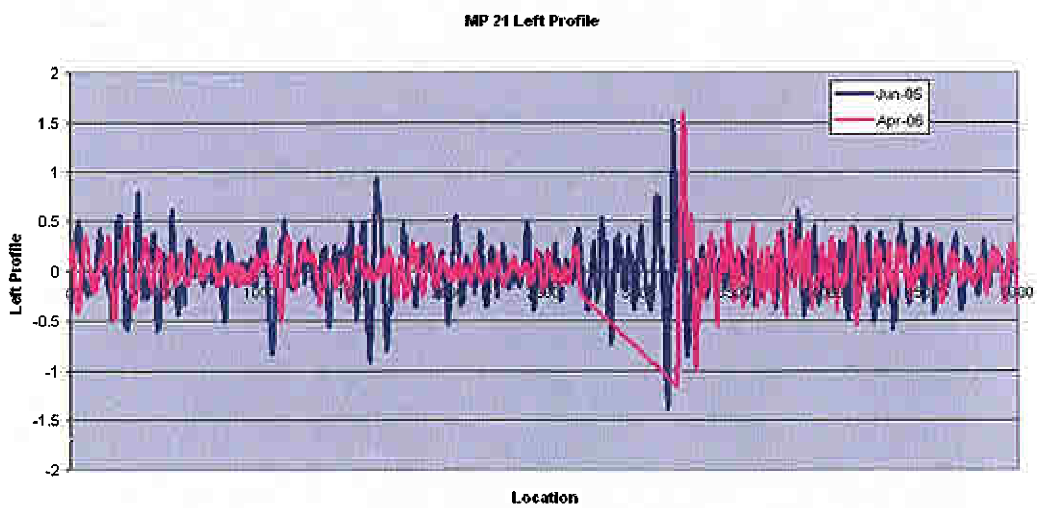


Figure 19. Left Profile for MP 21

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[17] Investigation into left and right profile (62' chord) showed similar results.

MP 22 Conventional Maintenance Evaluation

MP 22, the control mile, underwent a conventional upgrade in which 352 ties were spotted and installed. Replaced ties were identified visually without using lateral track performance data. As can be seen from Figure 20, the conventional philosophy resulted in increased maintenance tie requirements while showing a slight reduction in GWR. The average GWR was reduced 0.03 inches from the pre-upgrade condition using twice as many ties as the GRMS mile. As shown in Figures 20 and 21, a GWR peak of over 0.6 inches was measured, although this was not identified by the June 2005 run. This represents abnormal deterioration and may be a data anomaly. This location is well within FRA compliance for GWR but should undergo further monitoring.

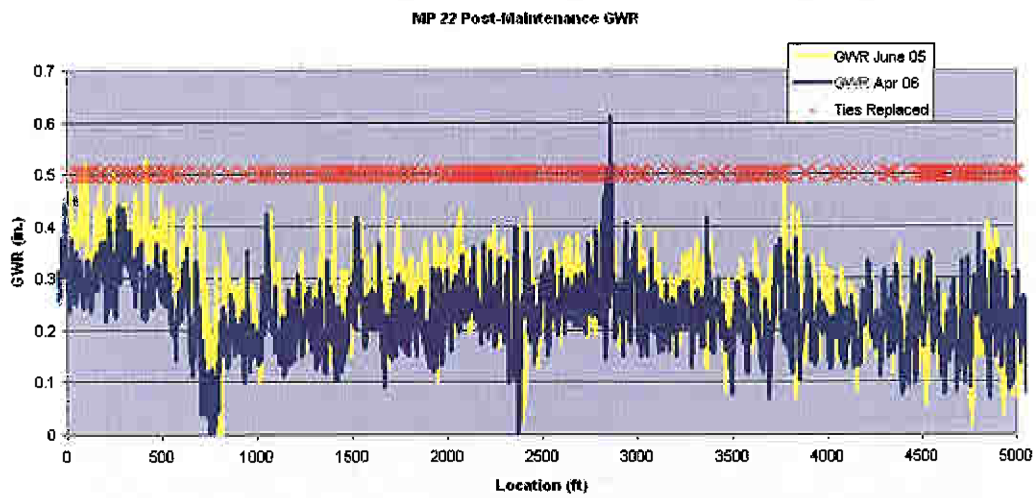

Figure 20. MP 22 Post-Maintenance GRMS run

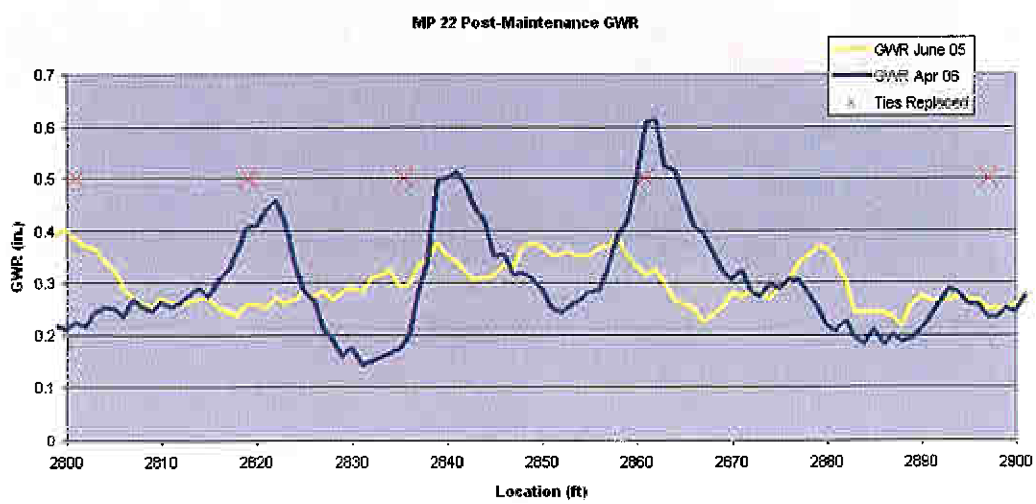

Figure 21. Investigation of GWR Peak.

MP 23 Conventional Maintenance Evaluation

MP 23 received a 356 tie GRMS-based upgrade by the production tie gang in April 2003. As a result, a conventional maintenance philosophy generated a higher maintenance tie count. Although this mile was successful at targeting lateral weak spots with minimal ties during the upgrade, conventional spotting targeted all bad ties regardless of surrounding condition and lateral performance. This mile was conventionally spotted by the CSX Roadmaster, who identified 551 ties for replacement. Figure 22 shows the distribution of ties installed along with the effect on GWR. GWR actually increased the first 1000 ft of the mile despite the tie installations. Even with the highest tie count, this mile showed only a 0.019 inch improvement in average GWR. Figure 23 demonstrates that tie maintenance that does not utilize lateral track strength data leaves behind GWR peaks above the maintenance threshold. The selected ties for replacement missed this peak, and as such lateral deterioration will continue for several years to come.

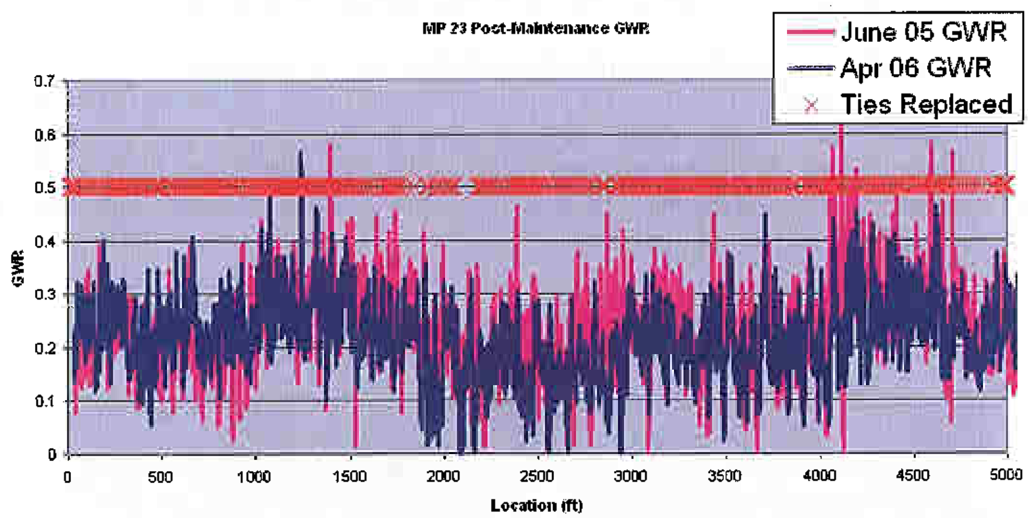

Figure 22. MP 23 Post-Maintenance GRMS Run.

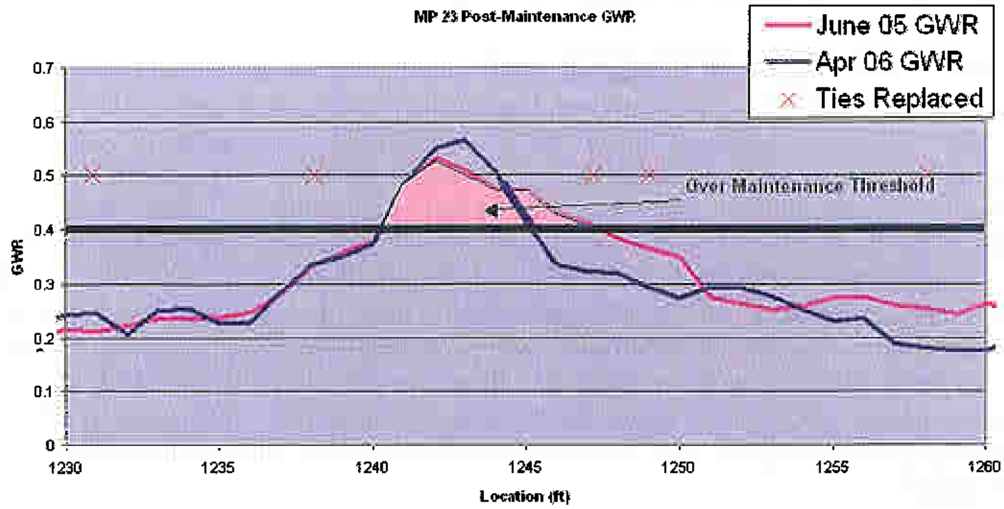

Figure 23. Conventional Spotting Missed GWR peak.

Figure 24 examines the left profile for MP 23 noting the strategic 356-tie upgrade performed in April 2003. The June 2005 run shows three areas of surface variations at the middle to end of the mile, which were alleviated by the conventional maintenance cycle. This highlights the need to analyze track profile when performing limited GRMS based upgrades. By overlaying GWR and profile data, a targeted complete tie replacement strategy can be implemented.

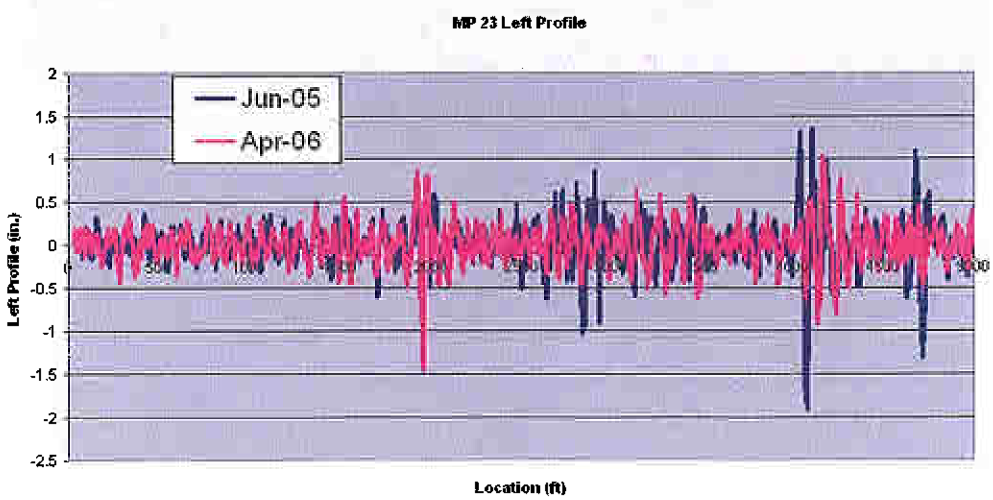

Figure 24. Left Profile Data for MP 23.

GRMS vs. Conventional Maintenance

The GRMS maintenance mile outperformed the conventional maintenance miles in average GWR improvement, with much fewer ties installed. Table 18 shows the direct comparison of average GWR and the number of ties installed. The GRMS replacement methodology was once again successful in targeting and reducing GWR peaks.

Table 18.

MP	Maint	Avg. GWR Improvement	Ties
21	GRMS	0.046	162
22	Conv	0.030	352
23	Conv	0.019	551

To calculate the new degradation rates one more GRMS run is needed. It is recommended that further monitoring continue at these sites to quantify new degradation rates based on the various maintenance methodologies.

MP 10 TieInspect Maintenance Evaluation

This mile underwent a tie-by-tie inspection by the CSX Roadmaster. Each tie was graded on the *TieInspect* condition classification: Good, Marginal, Bad, or Failed. After tie condition data was collected, the *TieInspect* replacement logic was then employed and specific ties were identified for removal. By analyzing the stored tie condition and location data, the software strategically broke up bad clusters. Although 203 ties in bad condition were identified, surrounding condition dictated that only 184 ties be replaced. The *TieInspect* logic reduced the requirements by 9.4% as 19 bad ties (not failed), which had excellent surrounding tie condition were left in the tangent stretch of track.

Figure 25 shows significant improvement in GWR even in the tangent stretch where ties were strategically left (location 800 to 1600 ft). As shown in Table 19, the *TieInspect* mile generated the largest improvement in average GWR, while using only 184 ties.

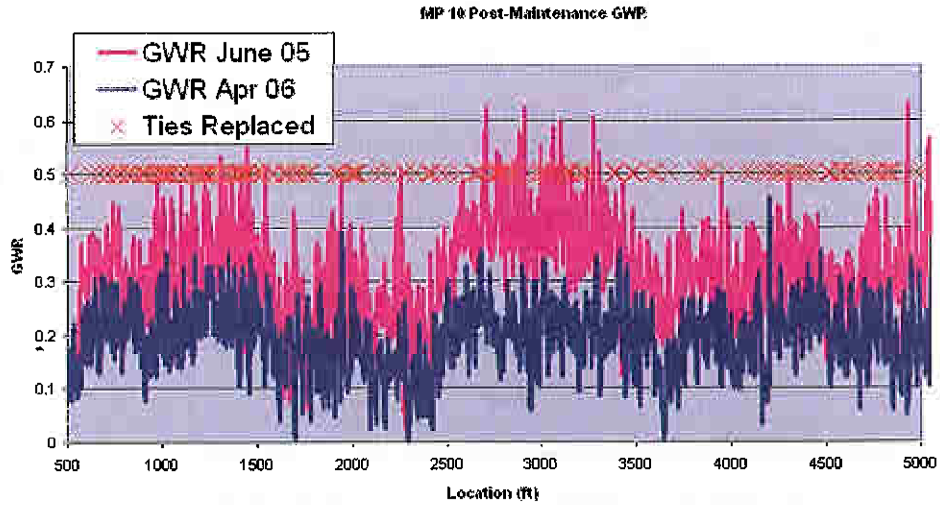

Figure 25. MP 10 Post-Maitenance GRMS Run

Table 19. *TieInspect* GWR Improvement.

MP	Maint	Avg. GWR Improvement	Ties
10	TieInspect	0.052	184

Task 7 Total Tie Requirements / Economic Analysis

Total Tie Requirements

The total number of ties installed, by test mile, is presented in Table 20. In total, 4,209 crossties were installed in this study. MP 22, the test mile where only conventional CSX replacement practices were employed saw 1,190 ties spotted and installed. Tie requirements for the other miles will be compared to conventional practices in an effort to optimize replacement strategies.

MP 23 underwent a targeted GRMS upgrade, followed by a conventional maintenance cycle, which required 23.8% less ties than the adjacent conventional test mile (MP 22). As shown in the previous section this mile showed comparable upgrade improvement in average GWR compared to the conventional mile but with fewer ties. This validated the effectiveness of targeting lateral weak spots exceeding 0.25 GWR. It should be noted that replacement philosophies targeting lateral performance neglect other tie failure mechanisms, i.e. vertical performance, ability to hold surface, etc. However, inspection of this mile showed no evidence of plate cutting and showed the ties to be performing well in all aspects of tie functionality. It should also be noted that the low GRMS upgrade tie requirements, was followed by a relatively high conventional tie maintenance cycle, but the combined total ties inserted was still 24% less than a comparable adjacent mile maintained using the conventional upgrade and maintenance approach.

MP 21's tie requirements were completely based on GRMS data for the entire study, to include both the upgrade and maintenance cycle. While this mile required more ties than the other GRMS upgrade mile (MP 23), it still reduced tie requirements by 12.6% over the conventional mile (MP 22) and furthermore showed the largest upgrade improvement in terms of mean GWR. Field inspections revealed good tie functionality in both laterally and vertically for this mile.

MP 10 employed the *TieInspect* replacement logic (applied to conventional CSX inspections) for both the upgrade and maintenance cycle. Inspectors looked for all tie failure mechanisms including the ties ability to hold line and surface, splitting, breaks, plate cutting, plate movement, wheel cuts, decay or hollowness, and the ability to hold cut spikes. The inspections provided a full condition map and allowed for strategic tie replacement. As such tie requirements were reduced by 9.9% compared to conventional practices.

Table 20. Total Test Mile Installations

MP	UPGRADE	MAINTENANCE	UPGRADE TIES INSTALLED	MAINTENANCE TIES INSTALLED	TOTAL TIES
10	*TieInspect*	*TieInspect*	888	184	1072
21	GRMS	GRMS	878	162	1040
22	Conventional	Conventional	838	352	1190
23	GRMS	Conventional	356	551	907

Life Cycle Costing Analysis

To investigate the relative tie costs associated with each replacement philosophy an economic analysis was conducted using the total tie requirements. Prior to the study, the test location was previously tied in 1993, and was upgraded in 2003, giving a tie gang cycle of ten years. The maintenance cycle occurred two years after the tie upgrade. From this information the number of failed ties per year can be calculated for each mile by the following equation:

$$Failed\,Ties\,/\,yr = \frac{Upgrade\ Ties + Maintenance\ Ties}{12\ \ years}$$

As such the number of ties failing per year for each mile is as follows:

MP 10=(888+184)/12=89 ties/yr

MP 21=(878+162)/12=87 ties/yr

MP 22=(838+352)/12=99 ties/yr (control mile)

MP 23=(356+551)/12=76 ties/yr

Using the Railway Tie Association's *SelecTie II* model[18], the average Class 1 replacement cost of a wood crosstie was calculated to be $90 per tie installed. This cost encompasses all installation costs including equipment, labor costs and expenses, hardwood tie cost, fuel, etc.

Based on the failure rates calculated above, the average tie requirements for a typical ten year cycle would be:

MP 10 TieInspect/TieInspect: 890 ties

MP 21 GRMS/GRMS: 870 ties

MP 22: Conv/Conv: 990 ties (control mile)

MP 23: GRMS/Conv: 760 ties

Comparing each philosophy to the conventionally upgraded and maintained control mile (MP 22) a total savings/mile/cycle can be calculated:

MP 10 TieInspect/TieInspect: 100 ties*$90/tie=$9,000/mile/cycle

MP 21 GRMS/GRMS: 120 ties *$90/tie=$10,800/mile/cycle

MP 23: GRMS/Conv: 230 ties *$90/tie=$20,700/mile/cycle

If the GRMS savings is the average of MP 21 and MP 23, this would represent a $15,750/mile/cycle savings. Noting that CSX installs 2.75 million wood ties annually, which translates into approximately 2,778 wood tie miles per year[19], the GRMS and *TieInspect* philosophies would generate annual savings of:

GRMS: $15,750/mile*2,778 miles/yr = $43.78 million/year
***TieInspect*: $9,000/mile*2,778 miles/year = $25 million/year**

Thus, using a targeted tie replacement philosophy based on track strength measurements (GRMS) or tie condition mapping (*TieInspect*) the results of this study suggest that a strategic tie replacement can reduce tie costs on the order of $25 to $44 million annually.

CSX Current Practices

CSX currently uses GRMS data in several ways:

Many subdivisions make direct use of the CFR Title 49 Part 213.110 to determine compliance with FRA crosstie and fastener requirements. On these subdivisions Part 213.110 First and Second Level Exceptions levels for UTG, LTG, PLG24 and GWR are used. On other subdivisions, the CFR 49 Part 213.110 levels for PLG24 and GWR are used with the Part 213.53 (Gage) limits, which are more restrictive, for UTG and LTG.

[18] The model parameters were updated in 2006, making this cost estimation very current.
[19] Based on an average of 990 ties per mile based on conventional CSX practice.

In addition, UTG, LTG, PG24 and GWR measurements are input into CSX's Track Management Program (TMP) where they are available in the TMP analysis package to plan maintenance activities.

This study has described the additional value in analyzing GRMS measured track strength distributions and degradation trends for use in tie replacement decisions. Based on the extension in tie life and corresponding economic savings, GRMS data provides valuable information in addition to FRA exception based analyses.

Other Lateral Track Strength Studies

Lateral track strength degradation rates have been quantified on the FAST Loop at TTCI for wood tie / cut spike zones[20] under heavy axle loads. Measurements were taken using a lateral track loading fixture (LTLF) with a 9 kip lateral load. It was reported that delta gage degradation ranges from 0.13 in/100 MGT to 0.16 in/ 100 MGT, under heavy axle loadings. The degradation rates provided in the current study (in/yr) represent GWR degradation over 64 MGT (the annual tonnage of the line). Converting these rates to *in/100 MGT* gives:

MP 10 = 0.042 *in/64MGT*100 MGT* = **0.066** ***in/100 MGT (GWR)***
MP 21 = 0.054 *in/64MGT*100 MGT* = **0.084** ***in/100 MGT (GWR)***
MP 22 = 0.06 *in/64MGT*100 MGT* = **0.094** ***in/100 MGT (GWR)***
MP 23 = 0.049 *in/64MGT*100 MGT* = **0.077** ***in/100 MGT (GWR)***

Noting GWR is delta gage normalized to a 16,000 lb lateral load, the degradation rates in terms of delta gage (at 9 kips) are:

MP 10 =(0.066 *in/100 MGT**9,000 lbs)/16,000 lbs= **0.037** ***in/100 MGT (delta gage)***
MP 21 = (0.084 *in/100 MGT**9,000 lbs)/16,000 lbs= **0.047** ***in/100 MGT (delta gage)***
MP 22 = (0.094 *in/100 MGT**9,000 lbs)/16,000 lbs= **0.053** ***in/100 MGT (delta gage)***
MP 23 = (0.077 *in/100 MGT**9,000 lbs)/16,000 lbs= **0.043** ***in/100 MGT (delta gage)***

The current study showed a *delta gage* degradation range of 0.037 to 0.053 *in/100 MGT* for the replacement methodologies investigated, noting the test bed was Class 4 (79 mph passenger speed), predominantly tangent track. These numbers are the interpolated track response at a 9 kip loading. This degradation rate is lower than that measured at FAST which is consistent with the difference in service environment and loading. FAST track degradation rates were measured on a 6-degree curve under 39 ton axle load (315,000 lb cars) unit train traffic. This is significantly more severe service than the traffic and track curvature at the test sites and thus the more severe track strength degradation rate is to be expected.

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[20] RS 05-009 "Long-term Performance Testing of Wood Ties and Fastening Systems at FAST"
TD 05-029 "Wood Ties and Fastening Systems Performance at FAST (1995-2004)"

Conclusion

The focus of this study was to compare tie replacement strategies based on conventional, visual inspection to one based on track strength measurements taken from Gage Restraint Measurement System (GRMS) inspection data. As a secondary objective, a third set of replacement strategies, based on the TieInspect data collection and analysis system was also examined. This report presented the results of a full-scale field demonstration allowing for a side-by-side comparison of alternate **upgrade** approaches (GRMS, CSX Conventional and *TieInspect™*) and **maintenance** approaches (GRMS, CSX Conventional and *TieInspect™*,) approaches. The study consisted of four test miles, each with a unique upgrade and maintenance combination as shown in Table 21.

Table 21: Upgrade and Maintenance Summary

MP	UPGRADE	UPGRADE TIES INSTALLED	MAINTENANCE	MAINTENANCE TIES INSTALLED
10	*TieInspect*	*888*	*TieInspect*	184
21	GRMS	878	GRMS	162
22	Conventional	838	Conventional	352
23	GRMS	356	Conventional	551

Analysis of the strength of the track, as measured by CSX's GRMS inspection car and defined by the Gage Widening Ratio (GWR), showed that the average or mean GWR is representative of the track strength across the each test zone (of one mile each) and formed the basis for evaluation of tie replacement performance.

This study showed a GWR degradation range of 0.066 to 0.094 *in/100 MGT*[21] for the replacement methodologies investigated, noting the test bed was Class 4 (79 mph passenger speed), predominantly tangent track.

The GRMS miles outperformed the conventional mile in the effectiveness of the tie replacement/upgrade as defined by the corresponding mean GWR degradation rate. The lowest degradation rate corresponded to the GRMS upgrade mile (Mile 23) with the lowest number of upgrade ties installed; 356 vs. 838 for the conventional mile as well as the lowest total ties (upgrade plus maintenance) installed (907 vs. 1190). In addition, examination of the GWR standard deviation show that the GRMS miles had higher pre-upgrade standard deviations, which indicates a wider scatter of tie condition, but ended up with lower standard deviations (less scatter) after the upgrade. This highlights the ability of the GRMS upgrade methodology to provide a more uniform, superior condition, based on the gage strength of the track.

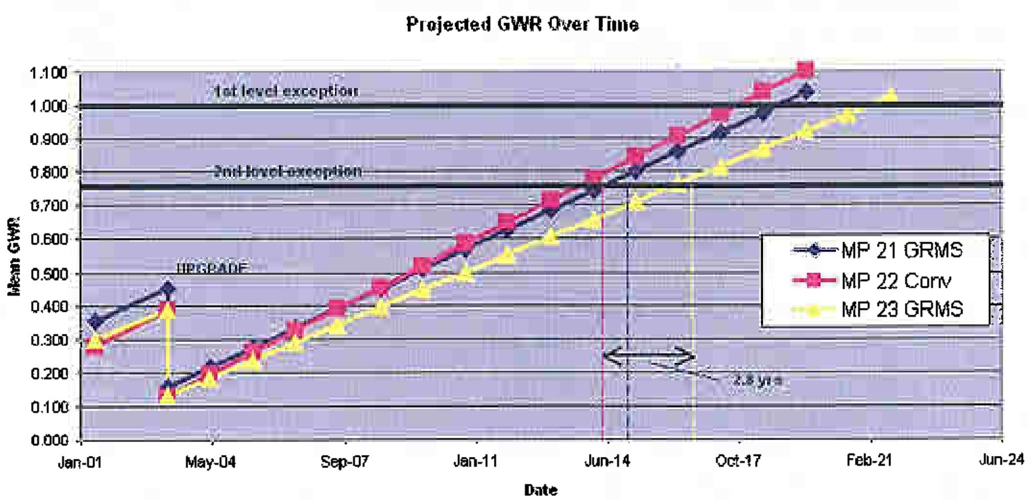
The conventionally upgraded mile (Mile 22) started off (pre-upgrade) with the best gage strength, as defined by mean, but was outperformed by the GWR miles, particularly MP 23. This is in spite of the fact that MP 23 had 58% fewer crossties

[21] This corresponds to a *delta gage* degradation range of 0.037 to 0.053 *in/100 MGT.*

installed during the upgrade (and 14% fewer in total: upgrade plus maintenance). The other GRMS mile, MP 21 (GRMS), registered the largest improvement in mean GWR again due to successful targeting of weak spots, again with fewer ties installed overall (upgrade plus maintenance).

The effects of these relative degradation rates on the time it takes for the track to reach the GWR threshold levels[22] was calculated and presented in Figure 26 below. Note, the 2nd or maintenance level used as the replacement threshold is 0.75 inches of GWR. A GWR value between 0.75 and 1 inch represents a second level exception and track speed must be set at the maximum for class 3 track (*FRA Track Safety Standards Part 213 pg 38*). A GWR reading of 1 inch or more represents a first level exception and track speed is to be reduced to 10 mph (*FRA Track Safety Standards Part 213 pg 37*). Noting the above, the conventional mile, on average, reaches a second level exception 2.8 years earlier than the best performing GRMS mile. This is a direct function of the higher degradation rate shown above. By averaging the two GRMS mile degradation rates and using the second level exception threshold, it can be shown that the GRMS upgrade philosophy provides an additional 2.1 years to reach the threshold. Extending this improvement to overall tie life, and noting average tie life for this location is 23 years[23], this would represent a 9.1% extension in tie life.

Figure 26: Projected GWR Degradation Rates



In addition to the GRMS vs. conventional tie installation comparison, MP 10 employed the *TieInspect* system and replacement logic for both the upgrade and maintenance cycle. Inspectors looked for all tie failure mechanisms including the ties ability to hold line and surface, splitting, breaks, plate cutting, plate movement, wheel

[22] Time to reach GRMS 1st and 2nd level exceptions is less than average tie life due to the expected nonlinear tie life behavior.
[23] Average tie life was calculated using the RTA SelecTie Model II, for the track and operating conditions of the Metropolitan Sub.

cuts, decay or hollowness, and the ability to hold cut spikes. The inspections provided a full condition map and allowed for strategic tie replacement. Comparing this approach to the conventional CSX approach, tie requirements were reduced by 9.8% using the TieInspect system and replacement logic.

Results for the upgrade portion of this study showed that GRMS based tie replacement generated a stronger track structure, with a lower rate of track strength degradation than conventional techniques, while using fewer ties. That is because targeted tie replacement resulted in superior lateral track strength, and decreased lateral degradation rates with an overall extension in the time to GRMS thresholds.

Maintenance ties were installed in October 2005 with a post-maintenance GRMS run conducted in April 2006. Similar to the upgrade findings, the GRMS maintenance mile outperformed the conventional maintenance miles in average GWR improvement, with much fewer ties installed. Table 22 below shows the direct comparison of average GWR improvement (From June 2005 to April 2006) and the number of ties installed for the maintenance cycle. The GRMS replacement methodology was once again successful in targeting and reducing GWR peaks.

Table 22: GWR Improvements by Test Mile

MP	Maint	Avg. GWR Improvement	Ties
21	GRMS	0.046	162
22	Conv	0.030	352
23	Conv	0.019	551

As shown above, the conventional mile with the most ties installed saw the smallest GWR improvement from the maintenance cycle. This is largely because of instances were GWR peaks were missed, as noted previously.

Another issue investigated with the GRMS maintenance miles was the track profile (surface) effect, since GRMS based tie replacement is based on lateral (not vertical) track performance. Examining the 62 ft chord left profile[24] for GRMS MP 21 showed good improvement in profile deviations (post-upgrade and post-maintenance), even though the tie replacement focused on lateral performance.

For MP 23, noting the very limited 356-tie upgrade performed in April 2003, the June 2005 run showed three areas of surface variations at the middle to end of the mile, which were alleviated by the follow up conventional maintenance cycle. This highlights the need to analyze track profile when performing GRMS based upgrades with greatly reduced tie insertions. By overlaying GWR and profile data, a complete tie replacement strategy can be implemented. However, in this case as well, overall tie insertions (upgrade plus maintenance) were significantly (14%) less than that for the conventional mile.

[24] Investigation into left and right profile (62' chord) showed similar results.

In total, 4,209 crossties were installed in this study. MP 22 had 1,190 ties spotted and installed based on current (conventional) CSX practices. Total tie requirements for the other miles were in all cases less than the conventional MP 22.

To investigate the relative savings associated with each replacement philosophy an economic analysis was conducted using the total tie requirements. **This analysis has shown that strategic tie replacement can reduce tie costs on the order of $25 to $44 million annually.**

The current study was conducted over a 5-year period with post-upgrade GRMS monitoring spanning 3 years. Noting tie life can range from 20 to 30 years in this area, it is recommended that this study be continued and further GRMS monitoring be performed to obtain a more complete picture of track degradation.

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Appendix A Tie Gang Upgrade Photographs

Small Tie Gang Upgrades September 2002


TRW 9418

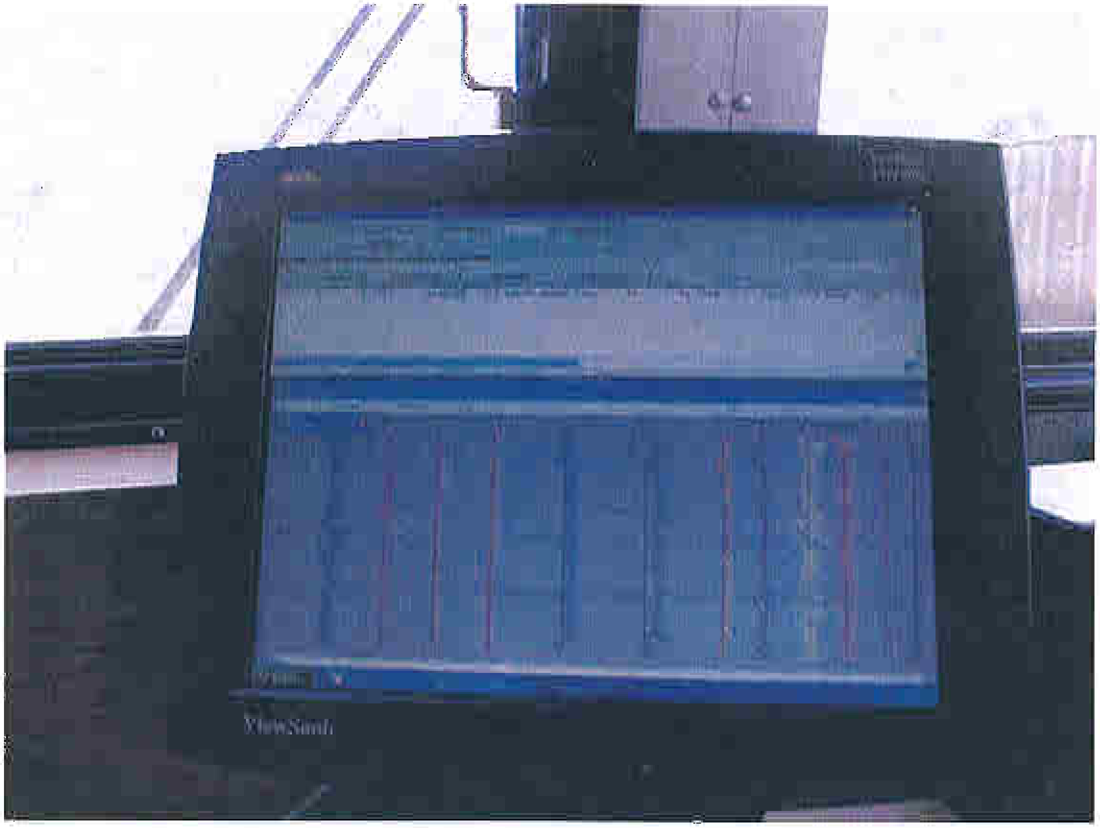
Production Tie Gang Upgrades 4/2003


CSX


CSX


10

Appendix B GRMS-1 Run 5/12/2004



Appendix C GRMS-2 Run

GRMS-2 Vehicle Pictures


CSX EM-GRMS2 WELCOME TO

Appendix D. Maintenance Tie Installation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