Quarterly Progress Report

To the

National Cooperative Highway Research Program
(NCHRP)

On Project 22-28

CRITERIA FOR RESTORATION OF LONGITUDINAL BARRIERS, PHASE II

Limited Use Document
This Quarterly Progress Report is furnished only for review by members of the NCHRP project panel and is regarded as fully privileged. Dissemination of information included herein must be approved by NCHRP

For period
July 1 – September 31, 2014
QPR #11

From
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Introduction

The objective of this research is to develop a field guide to assist maintenance personnel in determining the extent of damage to semi-rigid longitudinal barriers that affects operational performance. The guidance may cover additional strong steel post W-beam guardrail failure modes or other types of longitudinal barriers. This research continues the work begun under NCHRP Project 22-23 and is expected to involve a combination of component testing, pendulum testing, and computer simulation. Full-scale crash testing may be considered to validate the other methods of analysis, but is not the focus of this research.

This report will describe the progress achieved in this project in the previous quarter with respect to the eight tasks identified in the work plan. The following sections will describe the task-by-task progress identifying work items accomplished and any problems encountered in the research. A section describing the contractual status of the project (i.e., funding, schedule, etc.) appears at the end of the report and the progress summary tables and plots appear in Attachment A. Research team responses to panel comments on the previous QPR are included in Attachment B.

This quarterly report and attachments as well as all future quarterly reports can be found on the World Wide Web at http://www.roadsafellc.com/NCHRP22-28/QPR/. In order to comply with the NCHRP Limited-Use document policy, all the documents on the project webpage have been password protected such that they are accessible only to the project research team and panel. All the documents are password protected PDFs and the password for all documents in this project is "fieldguide"

Task 1: Literature Review and Survey of Practice

Statement of Work

Review the work undertaken in NCHRP Project 22-23, as well as recently completed and ongoing relevant research. Survey the state and provincial transportation agencies to determine their plans for implementing NCHRP Report 656 and to identify damage modes and other system elements (e.g., wood posts, transitions, end treatments) that should be added to those covered by the report. Augment the survey results with input from the AASHTO Technical Committee on Roadside Safety; TRB Standing Committee AFB20, Roadside Safety Design; AASHTO/AGC/ARTBA Task Force 13; and the American Traffic Safety Services Association's Guardrail Committee.

Task 1a. Literature Review

This task is complete.

Task 1b. Survey of Practice

This task is complete.

Task 2. Prioritize Damage Modes and System Elements

For each damage mode and system element identified in Task 1, analyze the importance of addressing it and the research methods that could be used for evaluation. Prioritize the damage modes and system elements for inclusion in the research plan to be carried out in Task 4.

This task is complete.

Task 3. Interim Report and Panel Meeting

Within 4 months of contract execution, prepare an interim report summarizing the work performed in Tasks 1 and 2 and recommending a research plan to qualitatively and quantitatively assess the highest-priority damage modes and system elements described in Task 2. The plan should describe and estimate costs for analyses, supporting tests, and validation tests that will be used to develop metrics for assessing the operational performance of a damaged barrier (per NCHRP Report 350, Test Level 3). The research plan should provide options totaling approximately 150% of the budget for Task 4; the excess is intended to give the project oversight panel discretion in selecting the research to be conducted. The interim report should also include a preliminary outline for additions to Chapter 16, "A Field Guide for the Restoration of Longitudinal Barriers," of NCHRP Report 656.

This task is complete. Authorization to proceed with Phase II of the project was received from the program officer on May 6, 2013.

Task 4. Execute Plan

Execute the research plan for assessing damage modes and system elements as approved by the panel at the interim meeting.

This task involves evaluating the performance of common strong-post guardrail systems subjected to each damage mode or combination of damage modes identified in Task 3. The basic research approach is similar to that used in Report 656 and will involve a combination of pendulum testing and computational analyses to assess performance degradation of guardrails due to various damage modes. The level of damage for each damage mode will range from very minor to a level where unacceptable performance results. The results will be summarized and presented in a table that shows performance using both absolute and relative values of evaluation criteria for each damage-metric in much the same way that Chapter 16 of Report 656 does. Based on the results of the analyses, recommendations will be developed that clearly indicate the level of priority for repair based on quantifiable metrics, such as amount of deflection and extent of the damaged area.

The following sections present the work that was accomplished for this task during the quarter.

Task 4A. G4(2W) Strong-Wood-Post Guardrail

Task 4A-1. G4(2W) Model Development and Validation
This task is complete.

Task 4A-2. G4(2W) with Anchor Damage
This task is complete.

Task 4A-3. G4(2W) w/ Rotted or Weakened Posts
This task is complete.

Task 4A-4. G4(2W) with Rail Deflection and Rail-Post Connection/Separation
This task is complete.

Task 4A-5. G4(2W) with Splice Damage
This task was initiated in the previous quarter and continued through this quarter. The progress is documented in Attachment C of this report. The purpose of this task is to supplement the splice damage assessment criteria in Report 656 by quantifying the effects of additional damage modes. Damage involving a "cut out" of material around the lower upstream splice bolt was evaluated in Report 656. The results of full-scale crash tests indicate that a more critical location for splice rupture is at the downstream splice bolts. The evaluation for quantifying the reduction in rail capacity as a function of splice damage is being achieved through pendulum testing.

The research team was able to procure a total of 16 damaged splice specimens from Maine DOT; however, a number of those did not have sufficient damage for consideration in the test program. The samples were extracted from various crash-damaged field installations in Oxford county Maine. The damaged articles were delivered, fully-assembled, to nearby MEDOT's maintenance facilities. The research team traveled to these collection-sites to identify and measure the various damages for each specimen. A damage summary sheet was created for each damaged splice specimen (see Appendix A of Attachment C).

The basic research approach involved:

1. Identifying and measuring the visible damage modes from a number of crash-damaged splice connections from field installations,

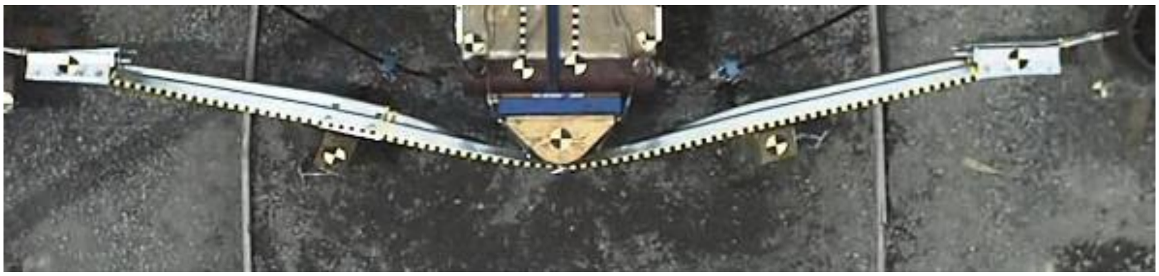
2. Correlating the measurable visible damage to the potential for crack initiation in the splice-bolt holes via disassembly and non-destructive inspection techniques (e.g., ultrasonic or magnetic particle) (those specimens selected for pendulum testing will not be disassembled),

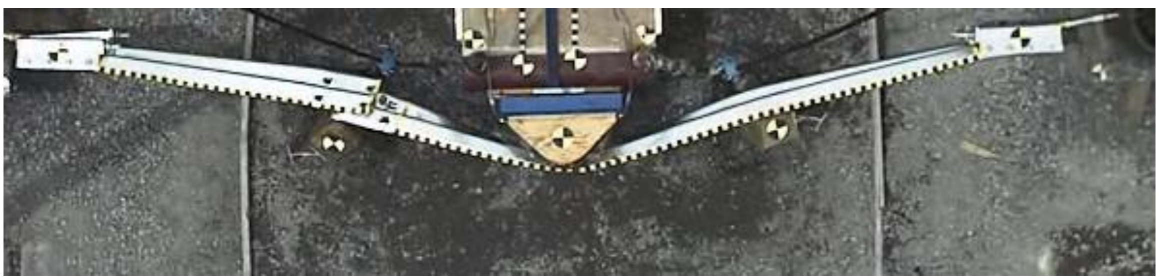
3. Use pendulum testing to measure the reduction in splice capacity due to various damage modes and levels of damage for a select number of damaged splices, and

4. Associate various splice damage modes with "priority for repair" for inclusion in a Field Guide to assist DOT maintenance personnel in making decisions about repairing damaged guardrail installations.

The second step in this research procedure was not initiated due to the low number of damaged splice specimens available for the study.

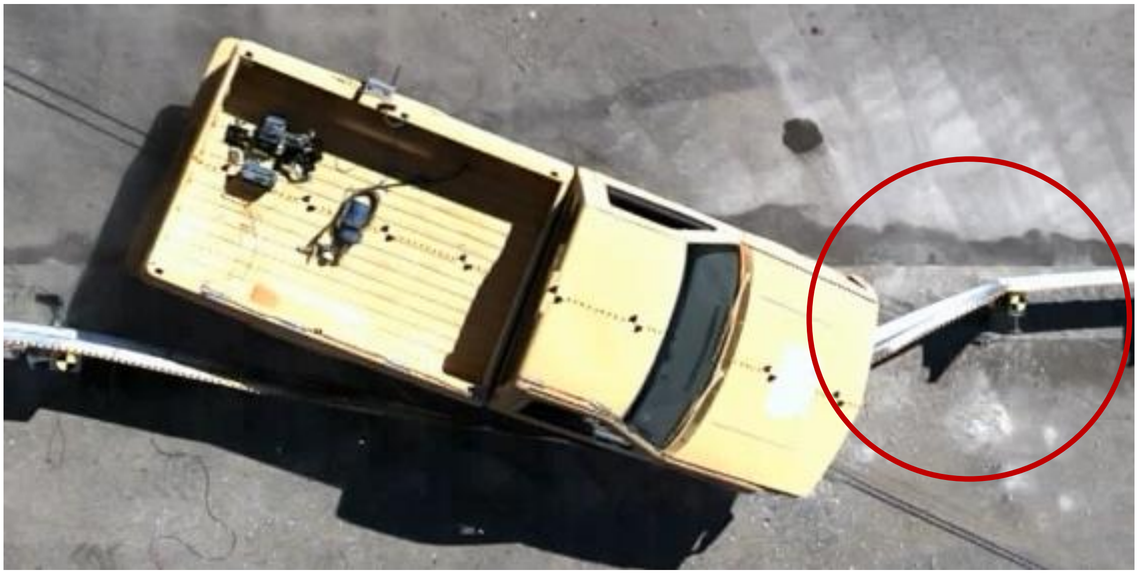
The damaged splice specimens were delivered to the FOIL on 8/11/2014. The original plan was to use the same test setup that Gabler et.al used for testing the damaged splice in Phase I. After critical review of the test video, it was determined that this test setup tended to result in the splice rupturing in pure tension, which is not generally the mode of failure in full-scale tests. Because of the short length of rail and the "rigid" constraint on the boundaries, the rail would develop very high tensile forces at relatively low rail deflections.





Unfortunately, the length of rail could not be extended beyond these limits due to the limited space at the pendulum test site. One alternative would be to design the boundary conditions to mimic the longitudinal and lateral stiffness behavior of an extended guardrail, but such an effort was beyond the scope of this study. It was therefore decided to modify the test setup such that the rail would bend at the post (typical of a normal pocket that develops in a crash event), as illustrated in the figure below. The test setup involved a single W6x16 structural steel post with wood blockout installed downstream of the impact location at the splice connection. There was no post installed upstream of the impact point in order to permit the maximum amount of deflection prior to developing full tension in the rail. The rigid W6x16 post was used to limit the amount of deflection of the post and force the bending mode of the splice around the post. More details of the test setup are documented in the Task Report.

This setup resulted in a somewhat more realistic deformation of the rail at the post prior to rupture of the splice, but the predominate failure mode was still tensile (pull-through of splice bolts).



Three damage modes are being investigated: (1) rail flattening, (2) longitudinal slip in the splice (3) splice separation (gap between panels at the downstream splice bolts). One test is also being performed to evaluate "rail crush" damage. The complete test matrix is shown below. We will not know until the testing is complete, but we are hopeful that useful information will be garnered from these limited tests for developing repair guidance. Four preliminary tests were performed using "spare" test specimens to help finalize the test setup and impact conditions. To date a total of eight tests have been performed and it is expected that the remaining seven tests will be completed in early October. A summary report for each test is documented in Appendix B of Attachment C.

Test #	Test Date	Specimen #	Damage Mode	Damage Level	Impact Velocity (mph)	Result	Max Force (kips)	Max Energy (kip/in)
14004A	8/13/2014	4A5-ME003	-	-	17.7	Boundary Failure	35.6	475
14004B	8/1482014	4A5-ME005	-	-	20.2	Boundary Failure	54.2	662
14004C	8/15/2014	4A5-ME008	-	-	18.6	Boundary Failure	48.7	605
14004D	8/19/2014	4A5-ME005	-	-	18.9	Boundary Failure	37.9	624
14004E	8/25/2014	New	Undamaged	-	20.6	Bolt Tear-Out	40.4	425
14004F	9/17/2014	4A5-ME001	Rail Flattening / Crush	68% / 14%	20.4	Splice Tear Rupture	43.2	437
14004G	9/24/2014	4A5-ME011	Rail Flattening	83%	21.2	Bolt Tear-Out	45.4	550
14004H	9/29/2014	4A5-ME014	Long. Slip	0.28 inches	20.2	Bolt Tear-Out	41.7	443
14004I		4A5-ME017	Long. Slip	0.25 inches				
14004J		4A5-ME004	Rail Crush	30.60%				
14004K		4A5-ME010	Splice Separation	0.55 inch				
14004L		4A5-ME007	Splice Separation	0.5 inch				
14004M		4A5-ME018	Splice Separation	0.5 inch				
14004N		New	Undamaged	-				
14004O		4A5-ME013	Splice Separation / Long. Slip / Flattening	0.35 inch / 0.2 inch /93.5%				

Task 4A-6. G4(2W) with Soil Eroded Away from Posts

This task was initiated in the previous quarter and completed this quarter. The updated Task Report is included as Attachment D of this report. The purpose of this task was to quantify the effects of various levels of soil loss around a post on system performance. An example of soil erosion is shown in Figure 1. In such cases, the increased deflection of the guardrail when impacted at these lower stiffness sections may result in pocketing as the vehicle approaches the stiffer downstream posts. It is important to develop a field-assessment procedure for assessing degradation of guardrail performance as a function of soil erosion around the guardrail posts to ensure proper performance of the guardrail system.

Figure 1. Example of soil erosion at a guardrail post.

The study involved: (1) performing pendulum impact tests to measure the force-deflection response of the post-soil system for various levels of "manufactured" soil erosion; (2) developing finite element models for the various soil erosion cases and calibrating/validating the models using the test data; and (3) using FEA to quantify the effects of the various degrees of soil erosion on the crash performance of the G4(2W) guardrail system under Report 350 test 3-11 impact conditions.

The pendulum tests involved a W6x16 structural steel post embedded 36 inches in the soil. The W6x16 post was used because of its rigidity, so that the energy absorption measured in the test would be attributable only to soil deformation. The erosion condition was manufactured by removing a layer of soil behind and on the side of the posts. Four erosion conditions were evaluated in the physical test program: 3 inches, 6 inches, 9 inches and 12 inches of erosion. The impact conditions involved a 2,372-lb pendulum impacting the post at 22 inches above grade at an impact speed of 20 mph. The posts were oriented in the strong direction. The results showed that the energy capacity of the post-soil system reduced as a linear function of erosion depth, in which:

$$Energy\ Capacity\ (kip - in) = 178.33 - 8.04 * (erosion\ depth)$$

Where the constant,178.33 kip-in corresponds to the energy capacity of the post at an embedment depth of 36 inches with no erosion (i.e., consistent with the post embedment depth used in full-scale crash test 471470-26 which has been used as the baseline system throughout this study.)

Finite element models for the various soil erosion cases were then developed and calibrated/validated based on comparison to the physical tests. In each soil-erosion case, the characterization of the soil model was exactly the same; that is, the same model was used in each case. The various levels of erosion were included by simply translating the soil-spring model to the appropriate erosion depth.

The finite element model of the standard G4(2W) guardrail system was then used to evaluate the effects of soil erosion around guardrail posts on the crash performance of the guardrail system. The impact conditions were set to those of full-scale crash test 471470-26 and involved the 4,568-lb C2500D pickup model impacting the guardrail at 62.6 mph (100.8 km/hr) at an angle of 24.3 degrees. The critical impact for the 6-inch erosion case was determined using FE analysis to be 45 inches (1.16 m) upstream of the w-beam rail splice connection at post 14. Due to time and budget constraints, the CIP for the 6-inch erosion case was used for all subsequent cases.

A total of six analysis cases were evaluated. These included two erosion scenarios (i.e., erosion at a single post and erosion at two consecutive posts) with three erosion depths (i.e., 6, 9 and 12 inches). The results indicated that rail deflection increased as erosion depth increased. For the baseline case (i.e., no erosion) the maximum rail deflection was 32 inches. For the case of erosion at a single post, the lateral deflection increased 7.5 percent at 9 inches erosion and 11 percent at 12 inches erosion. For the case of erosion at two posts, with erosion depths of 6, 9, and 12 inches the lateral deflection increased 11 percent, 17 percent, and 25 percent, respectively.

The analyses further indicated that the erosion does not significantly affect occupant risk measures, and in general the values were slightly lower for the erosion cases. The most critical effect of erosion was related to the potential for rupture of a rail-splice connection. For the case of erosion at a single post, the three levels of erosion (i.e., 6, 9 and 12 inches) resulted in an increase of 25 percent, 24 percent, and 33 percent increase in plastic strain levels, respectively, relative to the baseline case. Given that the G4(2W) is near its capacity under these impact conditions, the effective increase in plastic strain in the splice, indicates that the potential for rail rupture is relatively high for all cases, but particularly for the 12-inch erosion case.

For the case of erosion at two consecutive posts, the three levels of erosion resulted in an increase of 27 percent, 38 percent, and 45 percent increase in plastic strain levels, respectively, relative to the baseline case. Again, the effective increase in plastic strain indicated that the potential for rail rupture was relatively high for all three erosion levels, but particularly so for the 9-inch and 12-inch erosion cases.

As a result of this study, the research team recommends that the repair threshold for soil erosion at a single post include depths 9 inches or greater measured at the backside of the posts. For erosion depths ranging from 9 to 12 inches, the recommended priority for repair is medium. For erosion depths of 12 inches or greater, the relative priority for repair is high, based on potential for excessive pocketing and increased potential for rail rupture.

For soil erosion at two consecutive posts, the research team recommends that the repair threshold include depths 4 inches or greater measured at the backside of the posts. For erosion depths ranging from 4 to 6 inches, the recommended priority for repair is medium. The lower bound for the medium priority was based on engineering judgment, since the analysis matrix did not include erosion depths less than 6 inches. The upper bound was based on the high magnitude of strain in the splice-bolt holes for the 6-inch erosion analysis case, which was considered borderline regarding high potential for rail rupture. For erosion depths of 6 inches or greater, the relative priority for repair is considered high, based on potential for excessive pocketing and increased potential for rail rupture. A summary of the recommendations regarding soil erosion for the G4(2W) guardrail are presented in Table 1.

Table 1. Recommendations for soil erosion around guardrail posts for the G4(2W).

Damage Mode	Repair Threshold	Relative Priority
Erosion at a Single Post	Erosion depth ≥ 12 inches (erosion depth is measured at the back-face of the posts)	High
	Erosion depth > 9 inches and < 12 inches	Medium
Erosion at Two or More Consecutive Posts	Erosion depth ≥ 6 inches (erosion depth is measured at the back-face of the posts)	High
	Erosion depth > 4 inches and < 6 inches	Medium

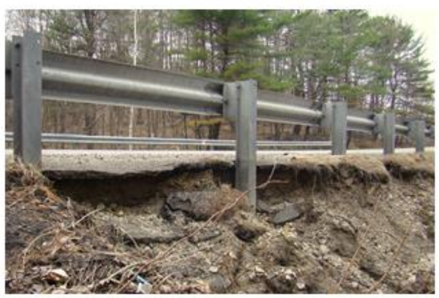
The assessment criteria as presented in the field manual are shown below.

Soil Erosion Condition

Erosion at a Single Post within a Four-Post Span:

Erosion = ≥ 12" **High** | 9 - 12" **Med**

Erosion at Multiple Posts within a Four-Post Span:



Erosion = ≥ 6" **High** | 4 - 6" **Med**

Commentary

Erosion at a Single Post within a Four-Post Span:

Erosion depth of 12 inches or greater around the post indicates high priority for repair due to increased potential for excessive pocketing and rail rupture.

Erosion depths of 9 to 12 inches were found to compromise system performance, but the guardrail should function adequately under a majority of impacts. This damage level is classified as medium.

When erosion is less than 6 inches, the guardrail is expected to remain fully functional.

Erosion at Multiple Posts within a Four-Post Span:

Soil erosion depth of 6 inches or greater at two or more posts within a four-post span indicates high priority for repair, due to increased potential for pocketing and rail rupture.

Erosion depth of 4 to 6 inches at two or more posts was found to compromise system performance, but the guardrail should function adequately under a majority of impacts at those erosion levels. The lower bound value of 4 inches was based on engineering judgment, since the study did not include erosion depths less than 6 inches. The upper bound value of 6-inches erosion was based on high magnitude strains around the splice-bolt holes in the w-beam, which were considered borderline regarding high potential for rail rupture.

When erosion is less than 4 inches, the guardrail is expected to remain fully functional.

Task 4B. Quantify Anchor Strength in Terms of Anchor Damage Modes
This task is complete.

Task 4B-1. End-Terminal with Reduced Embedment Depth
This subtask is complete.

Task 4B-2. End-Terminal with Missing Groundline Strut
This subtask is complete.

Task 4B-3. End-Terminal with Slack Anchor Cable
This subtask is complete.

Task 4B-4. End-Terminal with Rotted/Weakened Posts
This subtask was dropped from the study because rotted/weakened BCT posts could not be obtained for the study.

Task 4C-1. Simulates Test C08C3-027 to Reevaluate Cause of Test Failure
This task is complete.

Task 5. Prepare Draft Field Guide Materials

Develop additional material for the field guide for the damage modes and system elements addressed in Task 4. The material should be consistent with Chapter 16 of NCHRP Report 656.

The draft field guide materials have been presented in the "Recommendations" section of each Task Report throughout the project. These materials have also been distributed to the Panel and the field testers in three formats: (1) a cell phone application for android phones; (2) a web site; and (3) a pdf for printing to hard copy. All three versions are available on line at http://www.roadsafellc.com/password1.php. The website is password protected to comply with NCHRP procedures so to view the draft guide or download the cell phone app use the password "fieldguide" without the quotation marks. The research team has added some additional materials this quarter based on the results of Task 4 and will include the final materials as soon as Task 4A-5 (Splice damage assessment) is complete. The materials were also integrated into a draft Field Guide this quarter, which is discussed in Task 7 below.

Task 6. Field-Test Draft Field Guide Materials

Field-test and fine-tune the field guide material developed under this project with maintenance personnel from at least one state DOT approved by the panel.

Attachment E contains a status update of the Guardrail Condition Assessment (GCA) field guide. There has not been much additional activity from the field testers over what was reported last quarter. To date, the GCA has been used 10 times by people outside

Roadsafe LLC. An undetermined number of other people have downloaded the app or used the webpage but did not use an email address. Of the ten uses, only one is an actual field inspector. The rest are higher-level personnel within maintenance departments of either County or State DOT's. The research team would prefer to get the GCA into the hands of the actual inspectors but this apparently is not happening. An alternative that was suggested by one of the panel members is to share the field guide with the ATSSA Guardrail Committee and solicit feedback. Although the project is in the final stages there may still be time to get feedback from the ATSSA group before final revisions are made and the project is closed. We will contact ATSSA early in the coming quarter and ask permission to distribute the field guide to the ATSSA group.

The field guide will continue to remain available for the remainder of the project, and all parties are welcome to participate in testing and to offer comments - the guide will be revised as needed throughout the coming quarter.

Task 7. Assemble Field Guide

Prepare a field guide combining Chapter 16 of NCHRP Report 656 and the additional material from Tasks 5 and 6.

A Draft Field Guide was assembled this quarter and is included with this report as Attachment F. The evaluation procedures are presented in a graphical format to facilitate the assessment process. For each damage mode, a commentary is also provided to support the evaluation criteria. A worksheet is provided at the end of the Manual to be used in assessing guardrail condition and reporting materials to be repaired.

When reports are transmitted or downloaded the appendices often do not get included in the transmission. Since there will be many appendices in the final report, we are considering including the field guide as the final chapter in the main document to safeguard against it being separated from the main report. The format of the Field Guide chapter, however, would need to be such that the Field Guide could be extracted and viewed as a stand-alone document.

Task 8. Final Report

Submit a final report documenting the entire research effort, describing future research efforts (e.g., additional damage modes, further validation of the field guide), and including the Task 7 field guide as a stand-alone appendix. The field guide should also be provided as an independent electronic document suitable for downloading and printing by transportation agencies.

This task was initiated this quarter and is largely complete. The research team expects to submit the draft final report to the Panel at the end of October, once Task 4A-5 (splice damage assessment task) is completed.

Professional Meetings and Publications

Two papers were submitted to the Transportation Research Board for review and possible presentation/publication at the annual meeting in Washington DC, January 2015. The papers were titled:

1) Quantitative Method for Assessing Deterioration Level 2 of Wood Guardrail Posts
2) Effects of Guardrail Post Deterioration on Crash Performance of Wood Post W-3 Beam Guardrails

These are included with this report as Attachment G and Attachment H, respectively.

Contractual

A summary of the progress and fiscal status of the project is shown in Attachment A. The contract was signed on December 27, 2011 with a contract start date of January 2, 2012. Authorization to proceed with the second phase of the project was received on May 6, 2013. A contract modification to change the program officer and modify the payment schedule was executed by NCHRP on 15 October 2013. A no-cost time extension of 12 months was requested and granted such that the new contract end date is 31 December 2014. The research team expects to deliver the final report by the end of 2014. Attachment A has been revised to reflect the new contract end-date.

Sincerely,

Malcolm H. Ray, P.E., Ph.D.

Attachment A:	Fiscal and Schedule Summary
Attachment B:	Response to Panel Comments
Attachment C:	Task Report 4A-5 (Splice Damage)
Attachment D:	Task Report 4A-6 (Effects of Soil Erosion)
Attachment E:	Task 6 (Field Test Draft Materials)
Attachment F:	Task 7 (Draft Field Guide)
Attachment G:	TRB Paper: Quantitative Method for Assessing Deterioration Level 2 of Wood Guardrail Posts
Attachment H:	TRB Paper: Effects of Guardrail Post Deterioration on Crash Performance of Wood Post W-3 Beam Guardrails