PORTABLE CONCRETE BARRIER CONDITION AND TRANSITION PLAN SYNTHESIS

FHWA/MT-12-002/8117-41

Final Report

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THE STATE OF MONTANA
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June 2012

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RESEARCH PROGRAMS

MDT

Portable Concrete Barrier Condition and Transition Plan Synthesis

Final Report

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16. Abstract

Precast (or portable) Concrete Barrier (PCB) is a guardrail system that is intended to contain and redirect a vehicle that has left the travel lane. Barrier connections are typically formed using steel wire or bar to form loops which are joined by a steel pin. While the materials used in connection systems are quite strong, exposure to the elements and winter maintenance chemicals can, over time, lead to corrosion and loss of effectiveness. The identification of such corrosion was a concern to the Montana Department of Transportation (MDT), which decided that additional research should be done on this issue to determine what, if any, past research has been done regarding PCB in general, PCB connection corrosion, the maintenance of barrier connection systems, and approaches to address corrosion on existing and future installations. The research would also identify approaches that may be taken in developing and implementing a transition plan for replacing PCB if needed.

This report presents a synthesis of information from past published research and reports, as well as information from a survey of transportation agencies conducted as part of this project, regarding precast concrete barriers, the corrosion of their connection systems, approaches to rating/ranking this corrosion, and current state DOT practices for their maintenance and replacement. Potential strategies for prioritizing barrier replacement are identified and discussed.

17. Key Words

Portable Concrete Barrier Corrosion, Connection System, median barrier, deterioration, maintenance practices, transition plan, and structural connection

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EXECUTIVE SUMMARY

Precast (or portable) Concrete Barrier (PCB) is a guardrail system that, when placed along a roadway (either along the median, or in some cases, along the shoulder to protect fixed objects), is intended to contain and redirect a vehicle which has left the travel lane. In doing so, PCB can reduce the severity of an accident by preventing a vehicle from crossing over into oncoming traffic or striking a more substantial fixed object. Since the 1990's, the Montana Department of Transportation (MDT) has used PCB in areas where little or no barrier displacement was allowable during vehicle contact, such as between opposing lanes of traffic on selected interstate segments.

While undertaking the Taft-West repaving project (located in western Montana on I-90 near the Montana-Idaho border), it was found the wire strand loops forming the connection between barriers had corroded to a point of no longer being effective. This is a concern because such corrosion was not expected and may be present in other locations where PCB is used. Consequently, the decision was made by MDT to remove all two loop PCB barrier segments moved as part of any federal aid project and replace it with a three loop system. It was further decided additional research should be done on this issue to determine the extent of the corrosion problem and what, if any, past research has been done regarding PCB connection corrosion, PCB in general, the maintenance of PCB connection systems, and approaches to address corrosion of existing and future PCB installations. The research would also identify approaches that may be taken in developing and implementing a transition plan for replacing PCB that may not otherwise be replaced via federal aid projects.

In this resulting project, information was synthesized from past published research and reports, as well as from a survey of transportation agencies conducted as part of the project, on precast concrete barriers, the corrosion of connection systems, approaches to rating/ranking corrosion, and current state DOT practices regarding PCB maintenance and replacement, The literature review found that while a wide body of general literature discussing PCB exists, with a particular focus on crashworthiness/testing, information specifically on maintenance, connection corrosion issues and replacement is relatively sparse.

The survey of agency experience with PCB found only 11 agencies had experienced corrosion issues with PCB connections. Where corrosion was identified as an issue, spot replacement, the use of additional strengthening and prioritized replacement were the strategies used to address the problem. In no case did an agency remove corroded connections and replace them with new materials, reusing the existing barrier. Instead, barriers were replaced in their entirety. When corrosion had occurred, it was primarily thought to be caused by the use of winter maintenance materials, specifically salt. Smooth steel bar, wire rope and rebar were all identified as having experienced corrosion.

The primary conclusion from the survey is that most agencies have not experienced corrosion with their PCB connection systems. Whether this is because states simply have not yet encountered any such issues, or the materials and treatments being used in PCB connections are proving effective in preventing corrosion, is not entirely clear. Most respondents indicated that no special approaches or treatments were being used to prevent corrosion, so it may be more likely that corrosion issues have not yet been encountered, but the potential for them to occur (or already exist) is present.

When considering approaches to replacement of PCB, whether to address corrosion issues or to meet NCHRP 350/MASH criteria, a number of options are available. Spot replacement can be used to address issues pertaining to specific sections of PCB, although this approach does not address replacement in a systemic manner. A worst-first approach can be taken, whereby segments of PCB that have the most severe connection system corrosion present or are thought to be least crashworthy under NCHRP 350/MASH criteria are replaced. Retrofitting could also be employed, adding a third loop to each barrier section and eliminating the cost of replacing a full section. However, as this approach has not been employed by any agency to date, it would require field testing to determine NCHRP 350/MASH compliance. Prioritized replacement is another potential approach, relying on quantified data to rank sites requiring replacement. Finally, a hybrid replacement approach could be followed which combines various aspects of the other approaches. Using some form of weighting strategy, such an approach would consider several factors in arriving at an average ranking for each site/segment of PCB, such as barrier condition, functional classification of the route it is located on, and safety conditions at that location (e.g., via a metric such as crash rate). The segments requiring the most urgent replacement would be those ranked the highest by the weighting function.

Relative to choosing a replacement strategy, ideally all potentially compromised PCB would simply and systematically be replaced immediately. More pragmatically, available resources should be directed first to the most critical situations, which probably are best identified using a hybrid approach.

1. INTRODUCTION

1.1. Background – Precast (or portable) Concrete Barrier (PCB)

Precast (or portable) Concrete Barrier (PCB) is a guardrail system that, when placed along a roadway (either along the median, or in some cases, along the shoulder to protect fixed objects), is intended to contain and redirect a vehicle which has left the travel lane. In doing so, PCB can reduce the severity of an accident by preventing a vehicle from crossing over into oncoming traffic or striking a more substantial fixed object. PCB are free-standing, precast concrete segments approximately 8 to 30 feet in length, a height of between 32 and 50 inches, and a mass of approximately 4,500 and 16,500 pounds (American Association of State Highway Transportation Officials [AASHTO], 2006). The 32 inch height of PCB dates back to the development of the New Jersey shape barrier in the late 1940s (Lisle and Hargroves, 1980). When developed by New Jersey highway officials, the barrier height was 18 inches. However, it was found vehicles climbed the barrier at this height, and so the present 32 inch height was developed. This 32 inch height has remained in use over time and has continually found to be effective in crash testing. Newer applications of PCB have been developed which have resulted in the so called "tall wall" design, which ranges between 42 and 50 inches in height. Similarly, different lengths of PCB have been developed over time to meet different needs and applications.

As the name and length implies, PCB is portable and can be moved/placed with heavy machinery. PCB is used for different purposes and for different durations along highways. In many cases, it is used temporarily in work zones to shield traffic from the construction area, channelize traffic, separate it from opposing traffic streams and/or protect construction workers. In other cases, some states use PCB in long-term applications as a median barrier, to shield roadside obstructions, and/or as bridge rail. Regardless of its use (temporary or long-term), PCB must be connected together in some manner to form a continuous barrier section. The connections provide strength and rigidity to the overall PCB system by joining adjacent barrier segments into a continuous system.

Connection systems come in many designs, but the most commonly used is the pin and loop, where loops embedded into opposing segments of barrier are joined by a pin passing vertically through them. The number of loops incorporated into the connection varies depending on the requirements and specifications of an agency. In general, the loop and pin system, as well as other connection designs, offer resistance to torsion and other forces when a barrier segment is struck. However, depending on the amount of exposure to the elements (e.g., rain and snow), chemicals (e.g., salt) and other factors, connection systems may be susceptible to corrosion given their metallic construction. Additionally, increasingly stringent crashworthiness criteria and improved connection designs may render some older connection designs obsolete. In both of these cases, it may be necessary to transition to new barrier segments.

1.2. Montana PCB Usage

Since the 1990's, the Montana Department of Transportation (MDT) has been using PCB in areas where little or no barrier displacement was allowable during vehicle contact, such as between opposing lanes of traffic on some interstate segments. The PCB sections used are shaped barriers approximately 10 feet long and joined together by pin and loop connections using two wire rope loops cast in each end of each barrier (Buth et al., 2003). An example is presented in Figure 1. Different sizes of PCB are used, including standard wall, which as mentioned above, is approximately three feet tall, and tall wall, which can extend up to approximately four feet in height. According to MDT records, Montana has approximately 140 miles of PCB in place at the time of this report. A majority of PCB is located along Interstate highways, either in the median, along the shoulder (e.g., rock slide shielding), along both together, or as protection against fixed roadside objects (e.g., bridge piers).

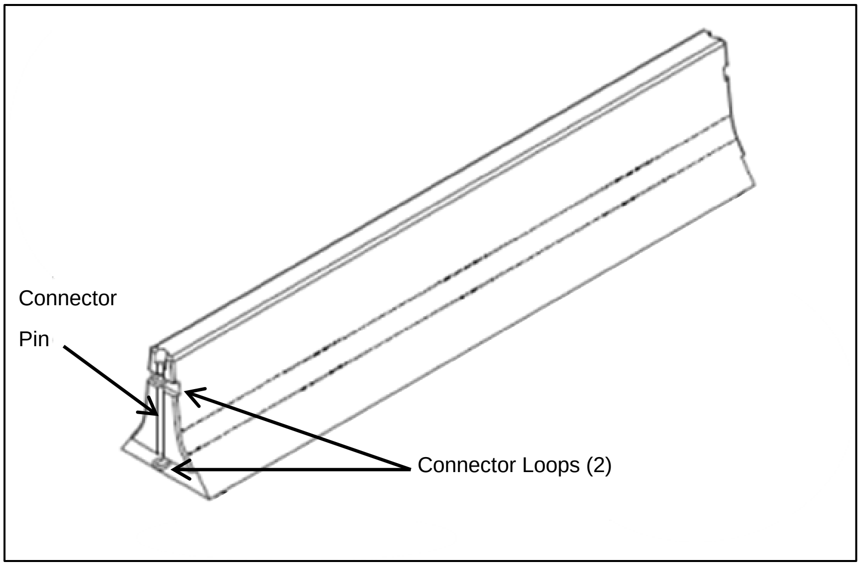


Figure 1: Portable concrete barrier example

While undertaking the Taft-West repaving project (located in western Montana on I-90 near the Montana-Idaho border), a contractor tasked with removing and resetting PCB found the wire strand loops forming the connection between barriers had corroded to a point of no longer being effective. This is a concern because such corrosion was not expected and may be present in other locations where PCB is used. Consequently, the decision was made by MDT to remove all two loop PCB barrier segments moved as part of any federal aid project and replace it with a three loop system. It was further decided additional research should be done on this issue to determine the extent of the corrosion problem and what, if any, past research has been done regarding PCB connection corrosion, on PCB in general, the maintenance of PCB connection systems, and approaches to address corrosion on existing and future PCB installations. The research would also identify approaches that may be taken in developing and implementing a transition plan for replacing PCB which may not otherwise be replaced via federal aid projects.

In looking at this potential PCB performance issue, it is important to note MDT has already been working with FHWA to replace two loop PCB across the state on a project by project basis, based on relatively new information available regarding PCB crash performance. Beginning in 1998, the Federal Highway Administration (FHWA) and the American Association of State Highway Transportation Officials (AASHTO) agreed to implement the procedures outlined in National Cooperative Highway Research Program (NCHRP) Report 350 for evaluating the safety performance of different highway features (Ross et al., 1993). Although no specific tests have found to date which conclusively indicate it, traditional two loop PCB may not be compliant under NCHRP Report 350 tests.

A significant amount of MDT PCB is connected using two pairs of 1 inch diameter wire rope loops connected by a 26 inch long, 1 inch diameter pin which is not restrained at the bottom. This combined system has a low probability of complying with NCHRP 350 guidelines. Consequently, MDT had an evaluation done of alternative connection systems using computer simulations. The first alternative consists of a modified pin and loop system using a 1.25 inch diameter steel pin inserted into three sets of 0.75 inch diameter steel bar loops (Buth et al., 2003). A schematic of this system is presented in Figure 2. The second design is a lapped plate system with two sets of vertical plates lapped and bolted through recesses cast horizontally across the ends of the barrier (Buth et al., 2003). Simulation indicated both designs should meet NCHRP 350 criteria Crash testing confirmed this, with the modified pin and loop system producing a deflection of 4.2 feet and the lapped plate system producing a deflection of 3.6 feet. These results met the criteria of NCHRP 350 test 3-11, making them acceptable for use.

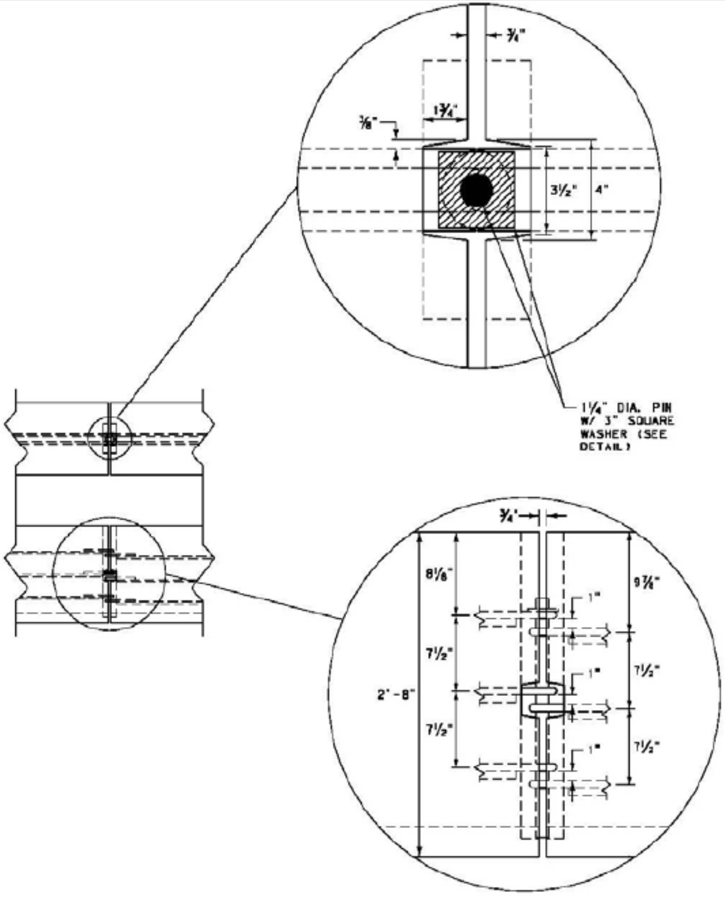


Figure 2: Montana 3 by 2 loop and pin connection (Montana DOT, 2008)

In any event, replacement of the existing two loop PCB on a project by project basis is a lengthy process, since a number of years may pass before a particular segment of roadway is in need of rehabilitation, reconstruction, etc. Consequently, in light of the issues identified above, alternative replacement approaches focused solely on replacing PCB outside of the scope of larger projects need to be identified and considered for use in Montana. Additionally, an inventory of the existing condition of PCB was determined necessary and was completed in the

Spring of 2012. This inventory found only 0.5 miles of barrier was in a deteriorated or sever condition (missing concrete, corroded connection(s), etc.). While a low amount of PCB requires immediate attention, future replacement needs remain a concern. Indeed, the PCB inventory identified 47.1 miles of barrier which, while in functional condition at present, is showing signs of deterioration combined with a connection system that is not NCHRP 350/MASH compliant.

1.3. Research Objective and Scope

The objective of this research was to prepare a synthesis of available information on precast concrete barriers, with a specific focus on the corrosion of link-pin and other connection systems, approaches to rating/ranking this corrosion, and any current state DOT practices regarding PCB maintenance and replacement. As part of this work, a survey was conducted of state departments of transportation (DOTs) regarding their experience with PCB and with these issues. Potential transition approaches for the replacing barrier were identified, aside from completing this work as part of ongoing federal aid projects.

1.4. Report Overview

This report is organized in 4 chapters. Chapter 1 (this chapter) presents an introduction to the project, including background, objectives and scope. Chapter 2 presents the results of a literature review that was conducted summarizing information available related to various aspects of PCB, with a specific focus on literature which discusses PCB in general, PCB connection systems specifically (including corrosion), metal corrosion, PCB maintenance, and transition/replacement plans (specific to PCB or similar infrastructure). Chapter 3 presents the results of a survey of state DOTs conducted to obtain information on their experience with PCB connection system corrosion, whether materials had been employed to address or prevent corrosion, maintenance practices employed, whether retrofit or transition plans or programs had been used to address any existing connection system corrosion issue, and what agencies did with barrier segments that had been removed from service. Chapter 4 summarizes the findings of the work and presents recommended approaches to handle the transitional replacement of PCB segments throughout the state.

2. LITERATURE REVIEW

This literature review summarizes the knowledge and state of the practice relative to PCB, as presented in the published literature. The focus of this review was on connection systems, and as such includes information which may not specifically discuss PCB but does have applicability to the issues facing MDT (connection system corrosion and PCB replacement/retrofit). Information is included on PCB in general, PCB connection systems specifically (including corrosion), metal corrosion, PCB maintenance, and transition/replacement plans specific to PCB or similar infrastructure.

This review employed a comprehensive literature search through sources such as the Transport Research International Documentation (TRID) database, the EI Compendex database, Federal Highway Administration (FHWA) websites, Transportation Research Board (TRB) websites, Institute of Transportation Engineers (ITE) websites, American Association of State Highway and Transportation Officials (AASHTO) websites, state DOT websites, and other databases (e.g., Google Scholar).

2.1. General PCB Literature

Before examining literature pertaining to specific aspects of PCB such as connection systems, a general literature review was completed. This review examines the development of different types of PCB, including profiles and dimensions, general aspects of connection systems, past results of state surveys regarding PCB use, reports on in-service performance, and advanced approaches to design and modeling of performance.

2.1.1. NCHRP 20-07/Task 257 (2010)

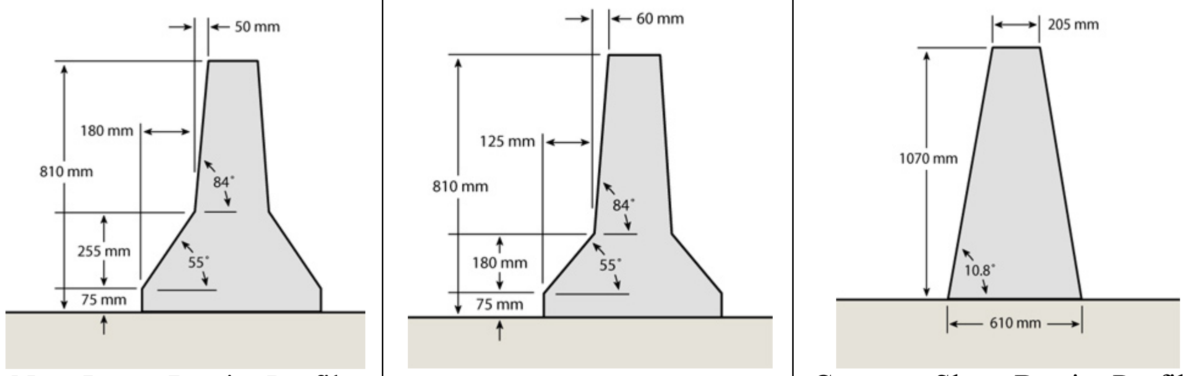
A significant source of general and specific information on PCB is the report on National Cooperative Highway Research Program (NCHRP) Project 20-07, completed in 2010 (McGinnis, 2010). The report discusses a variety of general aspects of PCB, including types and uses, crash test guidelines, FHWA-accepted designs, a survey of states and their designs and uses of PCB, and a summary of findings and recommendations from all their work. Of interest to the current project is the discussion of different connection systems (designs and crash test performance), as well as the “state of the practice” among different states. Despite the comprehensive coverage of the subject, one aspect of PCB that is not discussed in the report is corrosion, particularly of connection systems. Indeed, the closest the report comes to discussing the topic (the word corrosion itself does not appear in the report) is a discussion of grout deterioration when used as a barrier underlay. Still, the overall coverage of PCB makes this document a central reference in the discussion of general aspects of PCB which is presented in the following paragraphs. Note that information on specific aspects of PCB from this report appear in other sections of this synthesis (e.g., in later and specific discussion of PCB Connection Systems).

2.1.1.1. Design and Crashworthiness

The first topic covered by NCHRP 20-07 was crash test guidelines and FHWA-approved designs. In general, three types of PCB designs are used in the United States: the New Jersey shape, the F-shape and the single slope. Examples of each of these shapes are presented in

Figure 3. The specific dimensions (length, height, and cross-section), connection systems, reinforcement, materials and other features differ from state to state.

Regardless of design specifics, barriers must meet crashworthiness guidelines. These guidelines have evolved over time, resulting in barriers needing to meet the guidelines of NCHRP Report 350 and updated by NCHRP Project 22-14(2) which resulted in the Manual for Assessing Safety Hardware (MASH) in terms of crashworthiness (AASHTO, 2009). AASHTO adopted the MASH guidance in June of 2009 and agreed on an implementation plan for this guidance with FHWA at that time (McGinnis, 2010). Safety equipment which already met NCHRP 350 guidelines, including PCB, could continue to be manufactured, installed and used following that time. However, hardware developed after October 15, 2009 would need to meet MASH guidelines (excluding hardware already in development on that date).



New Jersey Barrier Profile

F-Shape Barrier Profile

Constant Slope Barrier Profile

Figure 3: Common portable concrete barrier shapes and general dimensions (Easi-Set Industries, 2011)

Based on these guidelines, the FHWA reviews crash test results for safety hardware submitted by manufacturers, state DOTs and crash test organizations and issues “acceptance letters” if satisfied that the hardware has been shown to be crashworthy. Acceptance letters issued by the FHWA pertaining to PCB and/or connection systems are presented in Table 1 and can also be found at: http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/listing.cfm. In addition, NCHRP 20-07/Task 257 presents a similar summary of published acceptance letters, as well as those which are not posted to the FHWA website (Table 2 and 3 of that respective document) (McGinnis, 2010). Note the information provided by the NCHRP document does not cover letters pertaining to acceptance letters for connection systems.

Table 1: FHWA acceptance letters for PCB and/or connection systems

Date	Test (350/Mash)	Manufacturer	Device Description
1/12/2010	350	EASI	Vocan New Hinge
3/31/2009	MASH	Bexar Concrete	CTB with Quick Bolt Connection
7/17/2008	MASH	Hill and Smith	Zoneguard MASH
4/16/2008	350	Colorado DOT	F-Shaped CMB
9/14/2009	350	South Carolina Department of Transportation	Temporary Concrete Barrier Wall and Anchorage TL-3
2/20/2009	350	South Carolina Department of Transportation	Temporary Concrete Barrier Wall and Anchorage
1/24/2008	350	Easi-Set Industries	JJ Hooks on 20 ft Kentucky CMB
10/30/2007	350	Barrier Connection LLC	F-Shape portable concrete barrier wall
3/27/2008	350	Permatile Concrete Prod	Revision of FHWA acceptance to Include shorter segments of TCB
5/19/2006	350	Battelle Memorial Institute	50-inch tall NJ barrier @ TL-3
10/2/2003	350	Midwest Roadside Safety Facility	Bolt-down System for F-shape on bridge deck @ TL-3
3/14/2003	350	Midwest Roadside Safety Facility	Steel strap tie-down system for PCB on bridge decks @ TL-3
7/3/2002	350	John Carlo, Inc.	Conditional Acceptance: 20' NJ-shape TCB @ TL-3
5/10/2002	350	North Carolina Department of Transportation	10-ft NJ barrier w/ triple loops and drop-in pin @ TL-3
1/24/2002	350	NY DOT	20-ft NJ barrier w/ I-beam connection @ TL-3
1/8/2002	350	OH DOT	10' NJ shape barrier w/ pin and loop connections @ TL-3
8/24/2001	350	CalTrans	4-m long single-slope barrier with double pin&loop connection @ TL-3
11/21/2001	350	OR DOT	42-inch tall F-shape @ TL-4
8/17/2001	350	Daniel J. MacDonald, Oregon DOT	12.5 ft F-shape precast concrete barrier w/a pin and loop connection @ TL-3
1/24/2002	350	IN DOT	10-ft F-shape barrier w/pin&loop connection @ TL-3
12/18/2000	350	Gary L. Hoffman, Pennsylvania DOT	12.5' F-shape temporary barrier (w/ plate connection) @ TL-3
7/17/2000	350	State of Idaho Transportation Department	20ft long NJ barrier (pin and loop connection)
3/22/2005	350	Barrier Systems, Incorporated	limited deflection RTS-QMB
3/30/2000	350	Georgia Department of Transportation	Temporary Concrete Barrier
1/5/2000	350	Barrier Systems, Inc.	Quickchange Moveable Barrier (QMB)
12/13/1999	350	Gunnar Prefab AB	GPLINK pre-cast Temporary Concrete Barrier
11/22/1999	350	Rich Peter, California DOT	K-rail (NJ Barrier) for Semi-permanent Installations
5/18/1999	350	Roberto Fonseca-Martinez	Virginia DOT (VDOT) temp.conc.barrier (F-shape)
12/8/2000	350	Easi-Set Industries	20 ft segments
3/26/1999	350	Easi-Set Industries	J-J Hooks temp. conc. barrier (NJ & F-shapes)
2/20/2009	350	Rockingham precast	Permits 18 and 20 ft long segments
10/20/1997	350	M. Budd, Rockingham Precast	Temporary cmb - F shape w/ slotted tube/T-bar Connection
10/10/1997	350	D. Sicking, U of NebraskA	Temporary cmb - F shape w/ pin & loop conn.

The report also summarized the results of 18 crash tests conducted on 32 inch (standard wall) PCBs using pin and loop connections conducted at NCHRP Test Level 3 (TL-3). Of the 18 tests, only eight were classified as a pass. Seven tests produced marginal performance results, while 3 failed to meet NCHRP 350 criteria. Only three of ten New Jersey shape barriers passed crash tests, while five of eight F-shaped barriers passed. The data available was not sufficient to establish whether longer barrier segments performed better than shorter ones.

Finally, NCHRP 20-07 reported on tests for other types of wall heights and PCB that was anchored. Three tall wall designs (two Oregon and one Ohio) with pin and loop connectors (2 by 3 and 2 by 4) had been tested as of 2010, with all of them passing NCHRP 350 criteria. Tests of standard height anchored temporary barriers were limited (four total), with Kansas, K-Rail (Idaho) and Oregon systems found acceptable (a Washington design failed). No crash tests of permanent applications of temporary PCB were found by NCHRP 20-07.

2.1.1.2. State Survey

NCHRP 20-07/Task 257 included a survey of states on barrier practices, which covered a variety of topics. The survey included information on the barrier systems approved for use in each state, the collection of anchor and connection systems used and design drawings (discussed in a later section of this report), the extent of barrier use in each state, and the in-service performance of different barriers.

States responding to the survey indicated barrier was used in both temporary and permanent applications, and were typically New Jersey or F-shaped. The Kansas (Iowa) F-shape was the most commonly used among the responding states, both in short and tall wall installations. At the time of the report, it appeared PCB used in Connecticut, Maine, Massachusetts, Michigan, Rhode Island, Vermont, and West Virginia did not meet NCHRP 350 requirements. The height of PCB was typically 32 inches, although "tall wall" (42-50 inches) was also used. Approximately 45 states indicated using pin and loop connectors to join PCB sections (this specific topic will be discussed in greater detail in a later section of this report).

Six states reported using PCB in permanent installations (shoulders, medians, bridge pier shield), while seven states reported they do not use PCB for permanent applications. All remaining states only provided information on temporary PCB uses and did not indicate if it was used in permanent applications. When used in permanent applications, barrier was reported as being "keyed" by pavement to provide anchorage and to reduce impact deflections (McGinnis, 2010).

2.1.1.3. In-Use Performance

As part of the previously discussed survey, states were asked to provide information on in-service evaluations of PCB. No state had done a structured study of such performance to date (as of 2010). Most states indicated they had not heard of any problems with their PCB from the field, and as a result, it must be working fine. However, as McGinnis points out, the performance of PCB can also be considered from the perspective of motorists and construction workers.

From a motorist's perspective, PCBs that have passed NCHRP 350 TL-3 tests should perform adequately, as tests have shown vehicles remain stable when they strike the barrier, which should lower occupant risk. However, information obtained directly from motorists, either from a survey or other mechanism, had not been collected at the time of NCHRP 20-07.

From a construction worker perspective, PCB does offer protection, although that protection may not be as significant as it first appears. PCB tests have often shown varying barrier deflections when struck, which may encroach on work areas occupied by construction workers when a crash occurs. Many states specify a minimum clearance behind a barrier which is less than the deflection observed during tests. Furthermore, current crash test criteria do not address the safety of people working behind the barrier. This includes consideration of the potential for flying barrier debris. Consequently, while PCB does offer construction workers some measure of protection, it is difficult to say to what extent protection exists. Once again, information obtained directly from construction workers or from crash reports had not been collected or reported at the time of NCHRP 20-07.

2.1.1.4. NCHRP 20-07/Task 257 Conclusions and Recommendations

McGinnis concluded that based on the work of NCHRP 20-07, five states (Connecticut, Maine, Rhode Island, Vermont, and West Virginia) used PCB which had not been crash tested or accepted as NCHRP 350 worthy, while Michigan PCB had failed to meet NCHRP 350 criteria. The author noted barrier performance heavily depended on the inter-segment connection, including its capacity to transfer tension and moment, its tightness, the gap between barriers, and the physical condition of the concrete on the segment ends. Interestingly, despite citing concrete condition, the physical condition of the connection system steel (e.g., presence of corrosion) was not mentioned as a critical component of functionality.

Based on the work of NCHRP 20-07, a number of recommendations were developed. Of particular interest to this work are the following:

- Temporary PCBs currently in service that do not meet NCHRP Report 350 requirements or do not meet AASHTO's requirement for a positive connection that can transfer tension and moment across the joint should be removed from service (McGinnis, 2010). [Note that no guidance for an approach to completing this removal is provided.]
- Additional research should investigate whether the pin and loop connection is the optimum design for temporary PCBs. If so, how can its design be improved to reduce barrier rotation and deflection during impacts (McGinnis, 2010)? [Note that design is of concern, but corrosion is not identified as affecting the connection system or its performance.]

While a thorough and detailed synthesis, nowhere within NCHRP 20-07 is corrosion and its potential impact on connection performance discussed. Given the stated importance of the connections in creating an integrated barrier system, this is surprising. It also indicates the clear need for the investigation being done by the present work.

2.1.2. Roadside Design Guide (2011)

The 4th edition of AASHTO's *Roadside Design Guide* (RSDG) discusses PCB in Chapter 9 (AASHTO, 2011). This discussion covers a variety of different topics, including uses, design dimensions, and types (shapes and connections) of PCB which are available. The types of PCB covered include:

- Iowa Temporary Concrete Barrier
- Rockingham Precast Concrete Barrier
- J-J Hooks Portable Concrete Barrier
- Modified Virginia DOT Portable Concrete Barrier
- California K-Rail Portable Concrete Barrier for Semi-Permanent Installations
- GPLINK® Pre-Cast Temporary Concrete Barrier
- Georgia Temporary Concrete Barrier
- Idaho 6.1-m [20-ft] New Jersey Portable Barrier
- Oregon Pin-and-Loop Barrier
- Ohio DOT 3-m [10-ft] Long New Jersey Profile Temporary Concrete Barrier
- New York DOT Portable Concrete Barrier
- Iowa DOT Tie-Down Steel H-Section Temporary Barrier
- Quick-Bolt F-Shaped Concrete Safety Barrier
- Texas X-Bolt F-Shaped Concrete Safety Barrier
- Texas Single Slope Concrete Barrier (SSCB)
- Quickchange® Barrier System
- Low-Profile Barrier System
- Florida Low-Profile Barrier System (AASHTO, 2011)

In discussing the different types of PCB, information is also presented on crash performance, primarily maximum deflections observed during crash tests. Criteria to consider when deploying PCB at restricted sites where crash angles may exceed 25 degrees is also covered. These criteria included locations where speeds were 40 mph or less, ensuring all sections of PCB were connected together, adequately anchoring end sections, providing adequate clearance between the barrier and the work area to allow for barrier sliding (and use of anchoring if sufficient clearance is not available), and preventions taken to avoid PCB caving into an excavation.

While the 4th Edition of the RSDG presents a significant amount of information on different types of PCB, one significant change from the previous edition is the absence of a specific discussion of tested and operational connection systems. Such a discussion was present in the 3rd Edition, and the contents of that discussion will be presented in a later section of this document.

2.1.3. Marzougui et al. (2007 and 2008)

Marzougui et al. evaluated the safety performance of general PCB designs using finite element simulation, validating the results against previously conducted crash tests (Marzougui et al, 2007; Marzougui et al, 2008). The simulations were set up to match NCHRP 350 TL-3 guidelines. PCB shapes included New Jersey, F, Single Slope, Vertical (i.e. rectangular shape), and Inverted (i.e. upside down Single Slope). All of the simulated tests used pin and loop connections with close and far spacing. While only example results were presented for demonstration purposes in this paper, these results compared well to crash tests which had been completed in the field. This indicates finite element simulation provides an approach to estimating the performance of a barrier design and connection system prior to field tests.

2.1.4. McDevitt (2000)

McDevitt discussed general aspects of PCB, including design shapes and the connection system (McDevitt, 2000). A summary of PCB shapes included those most commonly used (New Jersey and F-shape), as well as other designs such as the single slope and low-profile (20 inch height) (McDevitt, 2000). The discussion also included a brief piece on connection systems, focusing on loop and pin connections. The author stated such systems were widely used because they could accommodate changes in horizontal curvature and vertical grade. It was stressed a washer or cotter pin at the bottom of the steel pin was needed to keep the pin from jumping out on impact. With respect to loops, reinforcing bars were cited as being better for use than wire rope because of their resistance to torsional rotation at the joint when struck.

2.1.5. Bronstad et al. (1976)

In one of the earliest discussions and evaluations of PCB (termed concrete median barriers by the researchers), Bronstad et al. synthesized the existing state of the practice and evaluated the performance of barrier designs in crashes, both through crash testing and through a review of accident data (Bronstad et al., 1976a; Bronstad et al., 1976b). At the time, two types of barrier shapes were used by agencies: the New Jersey shape and the General Motors (GM) shape. Evaluation of accident data from the field indicated that in general, concrete barriers were effective in reducing accident severity (predominantly property damage only crashes were observed in the data). However, the GM shape[1] produced greater observations of vehicle rollovers and mounting of the barrier. Crash tests following the procedures of NCHRP Report 153 (then in effect) found similar results. In crash tests of the New Jersey shape, the GM shape and the F-shape (developed by the project using a mathematical crash simulation program), it

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[1] The GM shape of barrier was similar to the New Jersey barrier with differing dimensions (ex. different slope degrees and heights).

was found the GM barrier produced greater vehicle roll angles than other shapes for a subcompact car (a standardized car and bus were also tested) (Bronstad et al., 1976a; Bronstad et al., 1976b). Based on this finding, the report predicted future vehicle rollovers if the GM shape remained in use. As history can attest, this barrier design is no longer employed, in part because of this tendency.

The work also included a survey of agencies to determine the current state of the practice that was employed. The survey obtained information on the total miles, shapes used, dimensions, warrants for use, applications, anchorage (into the pavement/earth), construction methods, and reinforcing steel (internal to the barrier) used on barriers by agencies. Note the work did not inquire about the connection systems of PCB. This stemmed from the nature of the work, which tended to focus more on continuous barrier formed by slipformed production, with only a limited discussion of precast barrier made throughout the document. In much of the text, the focus when discussing PCB was on anchorage into the pavement/earth and the bedding (grout) such barrier should be set in.

Specific to connection systems, joint requirements (i.e. connection systems) are cited as a disadvantage of precast barrier. However, specific drawbacks to joints, such as corrosion, are not cited in support of this statement. Also of interest is the mention of designs which used a steel joint have costs associated with each joint, although once again, what those costs were was not specified. The statement is made that the tongue and groove connection design (molded concrete tongue and groove as opposed to a steel channel) was acceptable from an operations and cost perspective. In using jointed PCB, “joints should be designed to minimize permissible movement during impact…movement of barrier with respect to the mating barrier during impact could produce extraneous local dynamic forces, thus requiring additional joint strength” (Bronstad et al., 1976b). Only in the appendices presenting the design plans of PCB used by different agencies were specific types of connection systems (aside from tongue and groove) presented in any manner.

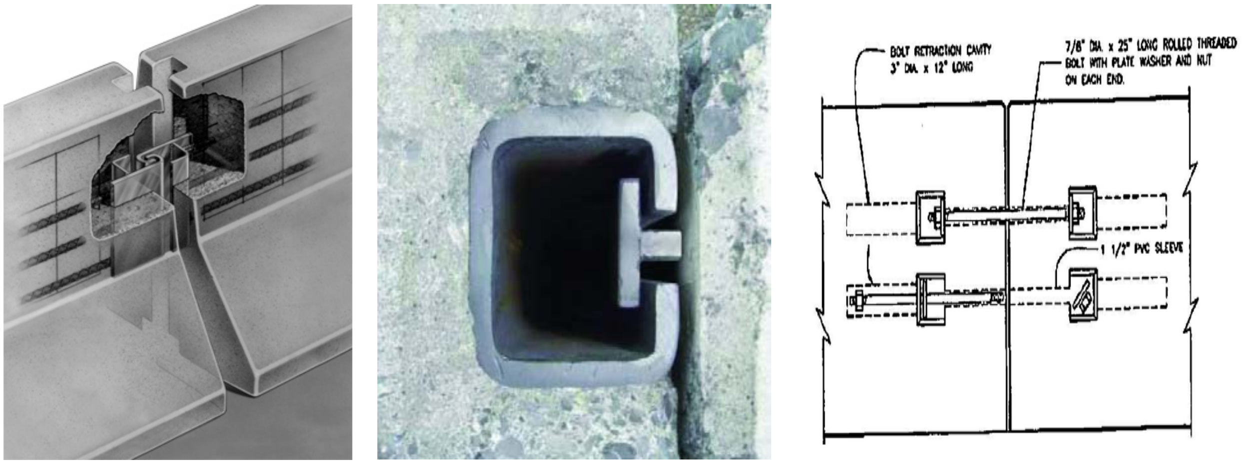
2.2. PCB Connection Systems

Despite their central role in joining PCB and helping to reduce deflection in a crash, surprisingly little literature is available that specifically discusses connection systems. Typically connection systems are discussed in general terms as part of crash testing documents (type, dimensions, materials, performance), but outside of these discussions, in only a few cases is the topic more specifically addressed.

2.2.1. NCHRP 20-07/Task 257 (2010)

McGinnis noted the primary function of the connection system is to limit the movement and rotation of barrier segments and to absorb some of the impact energy experienced in a crash (McGinnis, 2010). The design of connections appears to be independent of barrier profile and varies by the number of loops, their shape, the materials used, the diameter and length of pin used, the method of securing the pin, and the anchoring used with the connecting loops.

Part of the survey conducted by NCHRP 20-07/Task 257 specifically obtained information on the connection systems (and drawings) used with PCB in different states. Survey results indicated most states (45) used pin and loop connections with two configurations of loops (2 loops by 2 loops or 2 loops by 3 loops [2]). Texas reported using X-bolts for connections, while New York used an H-beam system. Interestingly, Pennsylvania reported not using any connection between PCB segments. In addition, some states indicated the use of proprietary connection systems, including J-J hooks (Easi-Set Industries), T-LOC (Rockingham Precast), and Quick-Bolt (Bexar Concrete Works) (McGinnis, 2010). Examples of these are presented in Figure 4.



J-J Hooks (Easi-Set Industries, 2011)

T-LOC (Saferoads, 2009)

Quick-Bolt (aka. Cross Bolt) (FHWA, 2009)

Figure 4: Proprietary connection systems

When tall wall was used, pin and loop connections were once again most frequently employed (2 by 3 and 2 by 4 loops used). I-beam, plate and rebar grids were also used by some states for connection systems.

In terms of materials, most states over time have moved away from the use of rebar and/or wire rope for loops, instead using smooth steel bars. This has been done for structural performance reasons rather than other factors (e.g., corrosion). Of the loop systems used, the Kansas system was the most widely used as identified by NCHRP 20-07 (see Figure 5 for a schematic of this system). This is the result of its structural capacity as well as lower cost compared to other systems of comparable strength (McGinnis, 2010).

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[2] Regarding the number of loops, the first number in the configuration designation refers to the number of connection points from one side of a joint, while the second number refers to the number of loops overlaid at each connection point from the opposite side of the joint.

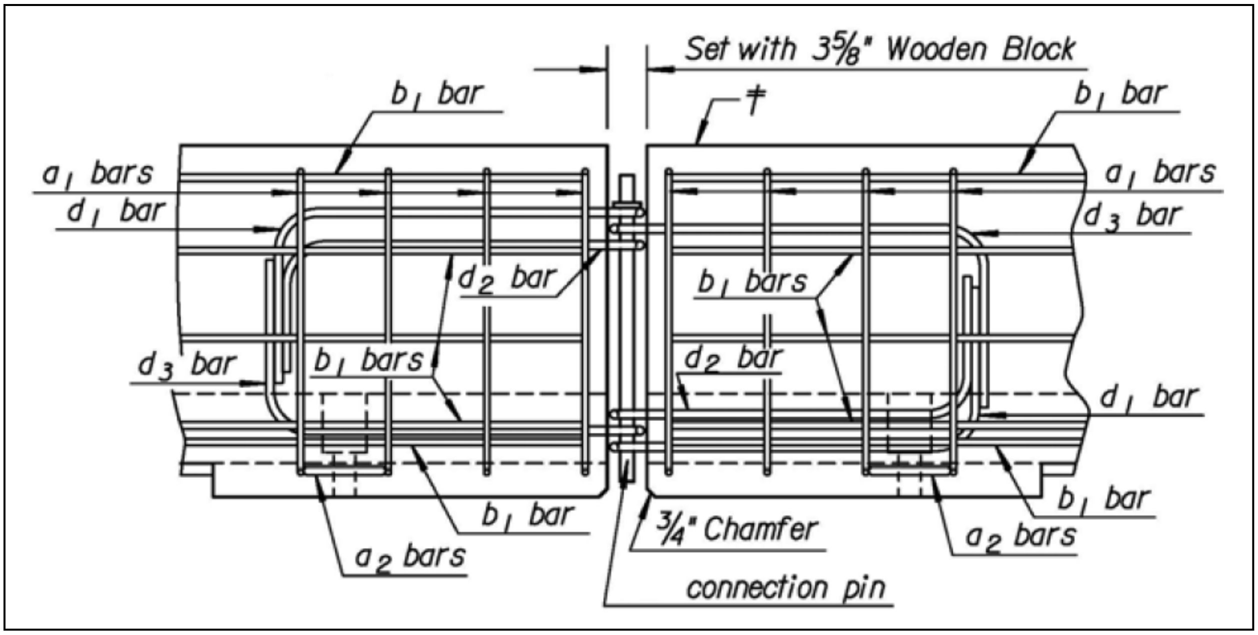


Figure 5: Kansas 2 by 3 loop and pin connection (McGinnis, 2010)

Of specific interest to this work, NCHRP 20-07 documented Montana's three by two pin and loop system, which is the only 32 inch standard wall barrier with a connection design having three loops. This system is presented in Figure 2, found in Chapter 1. Montana also has a 46 inch (tall wall) barrier using this same connection system.

NCHRP 20-07 found 41 states used ¾ inch smooth steel rods or rebar to form their loops. Five of the remaining seven states which responded to the survey used 5/8 inch smooth steel rods or rebar, while the remaining two states used wire rope of 5/8 inch (Washington) to ½ inch (Michigan) diameter. Fourteen states specify A-36 or A 709 grade 36 steel be used, while seven states specified grade 60 (McGinnis, 2010). Michigan, the state using ½ inch wire rope, reported it was in the process of transitioning to barriers with 5/8 inch wire rope. The wire rope used by Washington was specified as A-603, while Michigan specified A-1023 (McGinnis, 2010).

For the pins employed in connection systems, sixteen states specified some variation of A-36 steel, while seven states specified A-449 or A-325. Finally, two states specified AASHTO M-314 steel for connecting pins (McGinnis, 2010).

As indicated previously, the topic of corrosion to connection systems was not discussed as part of the work done by NCHRP 20-07/Task 257.

2.2.2. Graham et al. (1987)

One of the more notable discussions which focused specifically on barrier connection systems was the 1987 work completed by Graham et al. for the FHWA (Graham et al., 1987; Loumiet et al., 1988). This work sought to determine the optimum design of pin and loop connection systems and included not only a design analysis, but also a survey of states to determine the different kinds of connection systems then in use. Forty four agencies indicated they were using pin and loop connection systems, with these systems comprised of rebar in 27 states, wire in 14 states, eyebolts in 2 states and pin and plate in 1 state. Based on these results, pin and loop types of connection systems became the focus of the work.

At the time of the research, there was contradiction among existing information and reports regarding connector static strengths. Given that connection strength had a direct impact on barrier performance, it was important to complete an analytical determination of this strength. To do so, calculations were done of tensile, moment, shear and torsion capacity for each connection system for several failure states (Graham et al., 1987; Loumiet et al. 1988). Based on the research, a number of recommendations were developed, including:

1.) Inserted loops (loops of one barrier placed above and below the loops of the other barrier) were preferable to staggered loops (loops of one barrier placed on top of the loops of the other barrier) to resist torsional overturning of barriers.
2.) Pins should be anchored at both ends of a barrier segment with nuts and bolts.
3.) Wire rope was preferable to rebar for forming loops.
4.) States should only use connection systems which have been structurally analyzed and crash tested.
5.) Connectors should be designed to match the strength of all components in the connector (Graham et al., 1987; Loumiet et al., 1988).

While this work provided a comprehensive analysis and summary of the strengths of connection systems, it did not touch upon the potential for that strength to be lost over time, particularly due to corrosion. It also did not discuss measures to mitigate potential strength loss over time, such as use of corrosion resistant materials and treatments.

2.2.3. Roadside Design Guide (2006)

The 3rd Edition of AASHTO's *Roadside Design Guide* included a discussion of tested and operational PCB connection systems (AASHTO, 2006). This section of the RSDG covered connection systems which had been tested under the then applicable NCHRP 350 criteria. These included pin and loop connectors, channel splice joints, vertical I-beam joints, lapped joints and J-J hooks. While much of the information presented on these connections was descriptive in nature, more detailed information was presented on pin and loop connections than other systems. This included a high level summary of materials, including smooth or deformed bars, steel eyebolts, and cable or wire rope, noting the then-current trend was to use steel bars to obtain more consistent fracture toughness (AASHTO, 2006).

Perhaps the most notable portion of the discussion of pin and loop connections comes from the discussion of securing the pins themselves when installed. The RSDG recommends drilling a hole and inserting a cotter pin below the upper loops to prevent the pin from dislodging on impacts (AASHTO, 2006). The RSDG continues by saying a nut or washer can also be used to prevent the pin from being dislodged, but this can be difficult to install when the segments are in place *and salt corrosion can make them difficult to remove* [emphasis added] (AASHTO, 2006). This mention of salt corrosion is notable, as it suggests some agencies have encountered the issue. However, a further discussion of such corrosion and its other impacts on PCB (e.g., loss of strength) does not occur.

The section concludes by discussing problems encountered when using pin and loop connectors. These include the pin not remaining in place after installation (including removal by vandals), loops not being structurally adequate because of design deficiencies or previous damage, and pin and loop connectors being too close to allow for pin installation (especially on curves), weakening the connection. Notable in its absence is any mention of the potential for corrosion to occur, especially in light of the subject being mentioned in a prior paragraph of the RSDG text.

2.2.4. Bligh et al. (2006)

Bligh et al. discussed the development of a new cross bolt connection made in conjunction with work to develop a low deflection concrete barrier (discussed in Bligh et al., 2005b). One efficient way to reduce deflection is through the use of a strong, tight connection (Bligh et al. 2006). A cross bolted connection system which uses two threaded steel rods placed in different horizontal planes to form an X across the joint of adjacent barriers can provide such a connection. This system was perceived to offer the potential for easier installation, inspection and repair, although, while the researchers do not note this, the accessibility and exposure of system components could make them more susceptible to corrosion (see Figure 6). When crash tested, the PCB segments using cross bolt connections produced deflections between 19 and 27 inches, depending on barrier length (10 to 30 feet). These results met NCHRP 350 criteria and made the barrier acceptable for use in restricted work areas (Bligh et al. 2006).

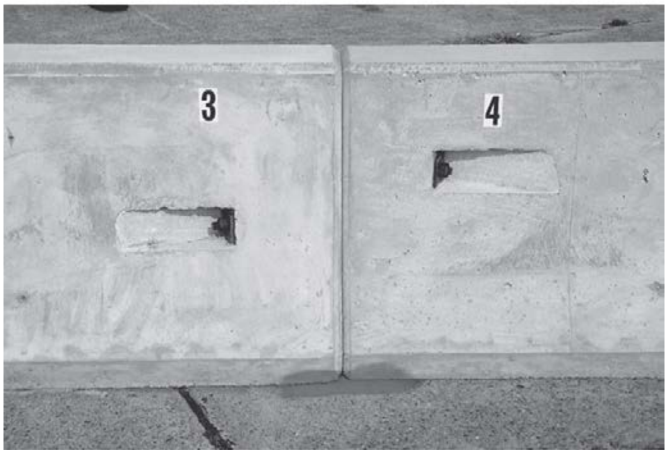


Figure 6: Cross bolt system (Bligh, 2006)

2.2.5. Ivey et al. (1980)

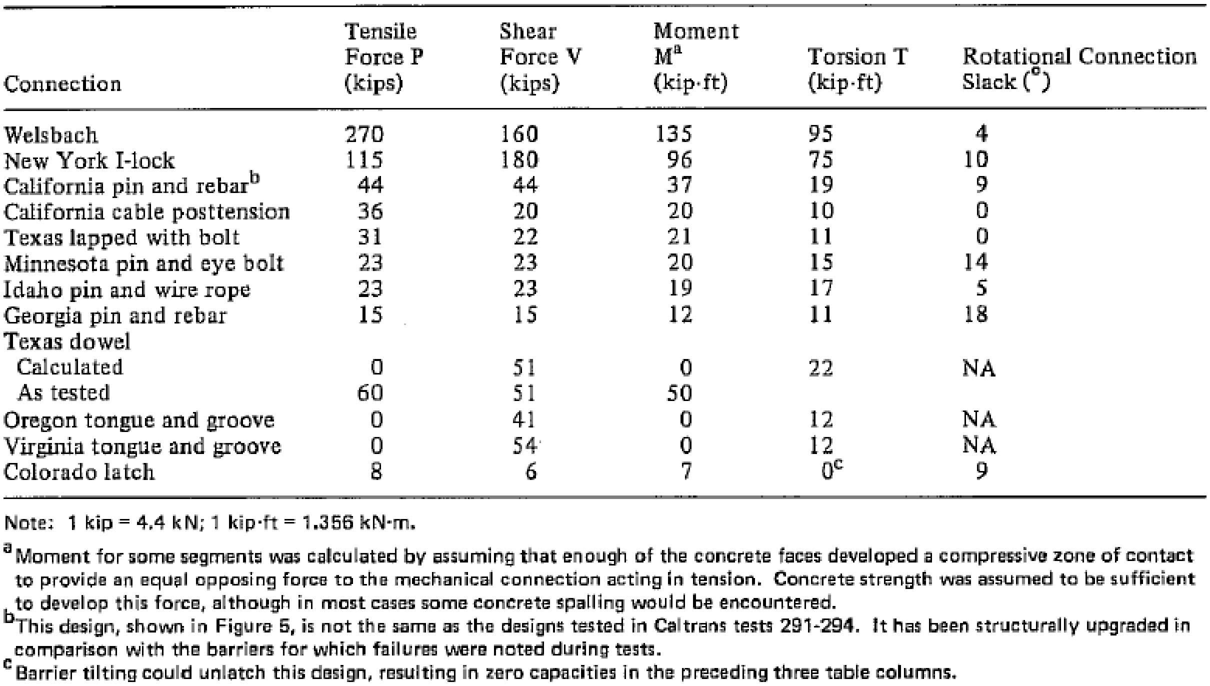
Ivey et al. discussed the structural design and dynamic performance of PCB (Ivey et al., 1980). This included an analysis of twelve end-connection designs to estimate resistance to loads in four test conditions: simple tension, shear, yaw moment and torsion (Ivey et al., 1980). End connection designs included:

- Welsbach interlock
- New York H pin
- California pin and rebar
- California cable post tension
- Texas lapped with bolt
- Minnesota pin and eye bolt
- Idaho pin and wire rope
- Georgia pin and rebar
- Texas dowel

- Oregon tongue and groove
- Virginia tongue and groove
- Colorado latch (Ivey et al., 1980)

The results of nine crash tests previously performed by different agencies were analyzed, with this information used to complete a parametric study of barrier characteristics. The structural characteristics of PCB connections developed from this work are presented in Table 2. The primary conclusion from this work was that some PCBs exhibited restricted performance capacity, but in general, PCBs and their connection systems could be designed to resist high-intensity impacts. As the work completed by Ivey et al. was a numerical analysis, no field observation of the condition of PCB end connections or the potential impacts of deterioration of connections on in-service performance, was made or discussed as part of this work.

Table 2: Structural characteristics of PCB connections (Ivey et al., 1980)



Connection	Tensile Force P (kips)	Shear Force V (kips)	Moment M^a (kip·ft)	Torsion T (kip·ft)	Rotational Connection Slack (°)
Welsbach	270	160	135	95	4
New York I-lock	115	180	96	75	10
California pin and rebar[b]	44	44	37	19	9
California cable posttension	36	20	20	10	0
Texas lapped with bolt	31	22	21	11	0
Minnesota pin and eye bolt	23	23	20	15	14
Idaho pin and wire rope	23	23	19	17	5
Georgia pin and rebar	15	15	12	11	18
Texas dowel					
Calculated	0	51	0	22	NA
As tested	60	51	50		
Oregon tongue and groove	0	41	0	12	NA
Virginia tongue and groove	0	54	0	12	NA
Colorado latch	8	6	7	0[c]	9

Note: 1 kip = 4.4 kN; 1 kip·ft = 1.356 kN·m.

[a] Moment for some segments was calculated by assuming that enough of the concrete faces developed a compressive zone of contact to provide an equal opposing force to the mechanical connection acting in tension. Concrete strength was assumed to be sufficient to develop this force, although in most cases some concrete spalling would be encountered.

[b] This design, shown in Figure 5, is not the same as the designs tested in Caltrans tests 291-294. It has been structurally upgraded in comparison with the barriers for which failures were noted during tests.

[c] Barrier tilting could unlatch this design, resulting in zero capacities in the preceding three table columns.

2.2.6. Connection Systems and Crash Tests

Given the number of different PCB design shapes which have been developed, it stands to reason those shapes have also undergone extensive crash testing in the field. Therefore, in addition to literature which specifically covered different aspects of PCB connection systems, a literature search was conducted for crash test results that discussed the performance of PCB designs incorporating different types of connection systems. Note that the discussions of this section include only reports and documents which include a discussion (i.e. at least a general description) of the connection system and the performance of the barrier system during the course of crash tests. This information may be of use to MDT in the future should alternative barrier and/or connection system designs be pursued.

2.2.6.1. Williams and Menges (2010)

Williams and Menges discussed the results of MASH Test 3-11 on Type 2 PCB in conjunction with steel strap connection plates and a sign support assembly (Williams and Menges, 2010). Steel strap plates are a type of connection using a steel plate to span the joint between barrier sections, with two bolts anchored through the plate into each section. The combination of Type 2 PCB and steel strap plates had been successfully tested under NCHRP 350 criteria in 2001. The results of MASH Test 3-11 found the barrier passed all criteria, with the maximum deflection observed being 3.9 feet (Williams and Menges, 2010).

2.2.6.2. Sheikh et al. (2008)

Sheikh et al. evaluated F-shaped barrier for use on slopes in Texas (Sheikh et al. 2008). Based on the research, it was determined that PCB using cross bolts (a connection design discussed earlier) was acceptable for use on roadside or median foreslopes of 6:1 or less (Sheikh et al. 2008). During crash tests, the maximum deflection observed was 1.15 feet, which met NCHRP 350 criteria.

2.2.6.3. Kennedy et al. (2006)

Kennedy et al. developed and crash tested a 50 inch (tall wall) New Jersey shape PCB for the Ohio DOT (Kennedy et al., 2006). A pin and loop system was used for segment connections. The connection system was somewhat unique, using a double shear connection at the top and bottom and an anti-symmetrical connection in the center (see Figure 7). Crash testing using NCHRP 350 Test 3-11 found all criteria were met, with the barrier deflecting 6.23 feet (Kennedy et al., 2006).

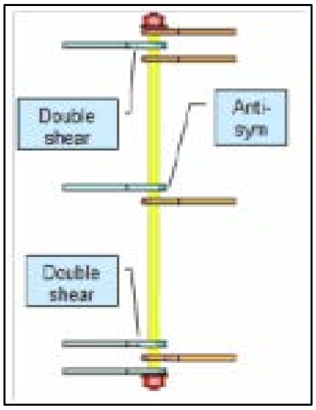


Figure 7: Ohio double shear connection (Kennedy et al., 2006)

2.2.6.4. Bligh et al. (2005a)

Bligh et al. developed and tested a portable barrier system for high-speed roadway applications in Texas (Bligh et al. 2005a). The F-shape barrier was precast concrete in 10 foot sections using cross bolt connectors (Bligh et al. 2005a). Cross bolts were used to limit deflection when the barrier was impacted. During crash tests, a deflection of 27 inches was observed, which was within the constraint of 36 inches set for the barrier. Crash tests showed the barrier met NCHRP

350 criteria and exhibited the lowest deflection of any PCB approved under NCHRP 350 requirements.

2.2.6.5. Bligh et al. (2005b)

Bligh et al. discussed the development of a low deflection precast concrete barrier for areas with restricted work space in Texas (Bligh et al., 2005b). The barrier that was developed was an F-shape with a length of 30 feet and a height of 32 inches. A cross bolt connection system was used which employed two 7/8 diameter A325 bolts. This system was selected as it had a high potential for limiting lateral barrier deflections (Bligh et al., 2005b). NCHRP 350 TL-3 tests were performed on this new design, and it was found to satisfy these criteria. The new barrier deflected 19 inches, well below the Texas Department of Transportation's (TxDOT) three foot constraint for barriers. As this barrier was developmental, an in-depth discussion of its connection system was not made as part of the work.

2.2.6.6. Bligh et al. (2002)

Bligh et al. evaluated a Texas PCB system employing a grid-slot connection (Bligh et al., 2002). The barrier was a Type 2 design with grid-slots and steel straps used for connection of segments (see Figure 8). The grid-slot connection used a prefabricated tie bar grid which was inserted into slots formed in the concrete of adjacent barrier segments. The steel strapping was placed at the base of the segments spanning the joint and anchored into each segment using two bolts on each side. During crash tests using NCHRP 350 guidelines, the barrier deflected four feet, which satisfied the test criteria (Bligh et al., 2002). It should be noted the steel strapping connection was used in conjunction with the grid-slot system after previous crash tests on the grid-slot system alone yielded excessive (although still passing NCHRP 350) barrier deflections.

Figure 8: Texas grid-slot connection (Bligh et al., 2002)

2.2.6.7. Bligh et al. (2001)

Bligh et al. conducted NCHRP 350 Test 3-11 on PCB with an I-beam connection for the New York State DOT (Bligh et al., 2001). The barrier was a New Jersey shape 20 feet long and 34 inches high, connected by an I-shaped connection key fit inside steel tubes cast into each end of the barrier section. Crash tests using a pickup truck indicated the barrier met NCRHP 350 criteria, with a barrier deflection of 50 inches.

2.2.6.8. MacDonald and Kirk (2001)

MacDonald and Kirk performed NCHRP 350 crash tests on F-shaped PCB for the Oregon DOT (MacDonald and Kirk, 2001). Both standard wall (32 inch) and tall wall (42 inch) barriers were tested, each 12.5 feet in length and connected by a steel pin and bar loop assembly (MacDonald and Kirk, 2001). NCHRP TL-3 crash tests using a pickup truck showed both barriers met NCHRP criteria. The standard wall barrier produced a deflection of 30 inches, while the tall wall produced a 32 inch deflection. The potential contribution (if any) of the connection system to these different results was not discussed by the report.

2.2.6.9. Peter and Jewell (2001)

Peter and Jewell discussed the results of Caltrans crash tests on Type 60K barriers for semi-permanent installations (Peter and Jewell, 2010). Type 60 PCB is a single slope design with a connection pin dropping into a sleeve cast into the base of the barrier. For this work, loops were originally employed in the connection system, but initial crash tests found they did not perform satisfactorily. The design that ultimately met NCHRP 350 criteria employed a longer, two pin connection at each joint with steel plates instead of loops. Crash tests using this version of the barrier (Type 60K-v3) resulted in an observed deflection of 29.5 inches, which met the established NCHRP 350 criteria.

2.2.6.10. Albin et al. (Undated)

Albin et al. discussed the results of crash tests performed on a Washington DOT PCB design then in-service for both temporary and permanent applications, as well as an alternative design using additional connection loops (Albin et al., Undated). The in-service design was a New Jersey shape 32 inches high, 12.5 feet in length and 24 inches wide at the base. It was connected by a 2 by 2 wire loop and pin system (Albin et al., Undated). The wire loops nested, meaning the loops from one barrier segment were positioned between the loops of the adjoining segment. The wire loops were 5/8 inch diameter while the pins were 1 inch steel rods with no restraint at the bottom of the pin. Full scale crash tests for NCHRP 350 compliance included tests 3-10 and 3-11, which were conducted using a full size pickup. Tests on the in-service design produced a deflection of 4.6 feet, while an alternative design which incorporated an extra set of wire loops produced a 3.8 foot deflection. The results of all tests were found to meet NCHRP 350 criteria.

2.2.6.11. Guidry and Beason (1991)

Guidry and Benson developed a low-profile PCB for use in low speed (45 mph or less) work zones in Texas (Guidry and Beason, 1991). The barrier was a Single Slope shape 20 inches high and 26 inches wide at the base. A new connection system was developed that aligned each end of a barrier by sliding two ASTM A36 bolts through connection holes which were in a rectangular trough recessed into the end of each segment (Guidry and Beason, 1991). Crash tests were conducted in accordance with NCHRP 230 guidelines, which were then in effect. The crash tests showed a barrier displacement of 5 inches when struck at an angle of 26.1 degrees at a speed of 44.4 mph using a 4500 lb. pickup. The test results were within acceptable NCHRP 230 guidelines, and the barrier was recommended for field use.

2.2.6.12. Beason et al. (1991)

Beason et al. discussed the results of crash tests on a single slope PCB for the Texas DOT (Beason et.al, 1991). The design was 42 inches high (tall wall), 30 feet long and connected by a slot-grid system and steel strapping (Beason et.al, 1991). Crash tests were conducted in accordance with NCHRP 230 criteria, which were then in effect. The test results found that the barriers performed within the acceptable criteria (specific barrier displacement figures were not provided by the authors).

2.2.6.13. Glauz (1990)

Glauz discussed the crash test performance of a movable concrete barrier system in California (Glauz, 1990). The barrier was movable for the purposes of facilitating lane shifts between morning and afternoon peak periods. It was a modified F-shape with a T-shaped top to allow for mechanized movement, with each segment approximately 3.28 feet long, 2 feet wide at the base, and 32 inches high. The connection (or hinge system in the text) was described as being link and pin, although no specifics (materials, dimensions) of it were provided. However, from general schematics provided in the text (presented in Figure 9), the connection system appears similar to those in use today, although it appears a plate was used in place of steel rod or wire rope loops. Crash tests showed the system could fully contain a 4,500 pound vehicle striking at 60 mph at a 25 degree angle with no structural failure or debris. However, testing took place in 1987 and were performed under NCHRP Report 230 criteria, so the results of this work and their transferability after 25 years are limited.

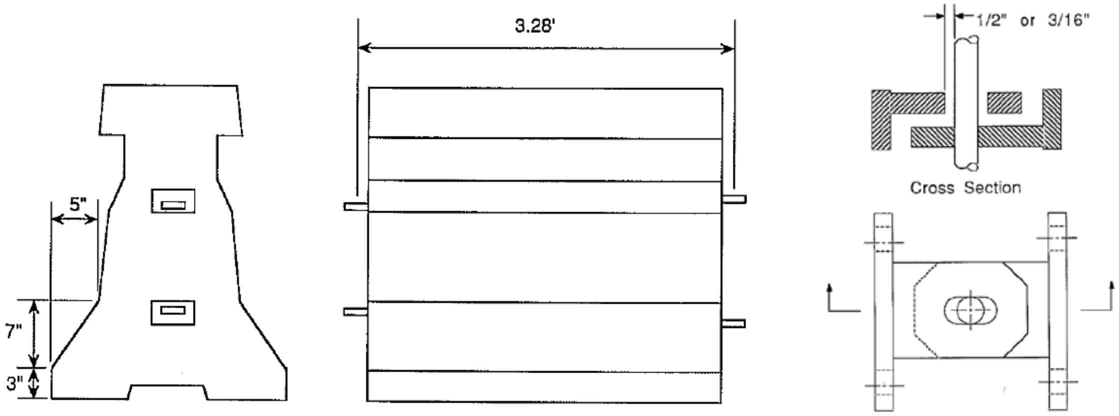


Figure 9: General overview of moveable concrete barrier connection system (Glauz, 1990)

2.2.6.14. Hahn and Bryden (1980)

Hahn and Bryden conducted crash tests of construction zone traffic barriers, including a PCB design, for the New York DOT (Hahn and Bryden, 1980). The PCB design was a New Jersey shape, 20 feet long, 32 inches high and connected by an H pin system (an H-beam inserted into slotted steel tubes cast into each end of the barrier) (Hahn and Bryden, 1980). Crash tests were conducted using a 4,250 pound sedan. The specific crash test criteria followed was not cited, but given the early date of the test (1978), this was not surprising. Crash test results indicated the PCB was an effective barrier for impacts of speeds up to 60 mph and an angle of 25 degrees (Hahn and Bryden, 1980). The barrier deflected between 11 and 16 inches when struck.

2.3. Corrosion

Corrosion is a natural process which compromises a material's integrity and thus impacts assets, environment, and people. Chemically, it is the transformation of a metal to its oxide through a reaction involving oxygen, water, or other agents. Chemicals used in snow and ice control operations may cause corrosion damage to the transportation infrastructure, particularly the exposed metal wire and steel pins that form the connection system of PCB. Advanced corrosion of rusting reinforcing steel can also exert expansive forces within the concrete of PCB, as shown in Figure 10. The associated stresses generated as a result of corrosion cause the concrete cover over the reinforcement to spall, leaving the exposed steel to further deteriorate. Moisture and chlorides then migrate along the deteriorating interfacial bond surface between the reinforcing steel and concrete, further advancing corrosion of the reinforcing steel in PCB (Staton and Knauff, 2007).

Recognition of the severity and the resulting economic impact of the corrosion problem by various industries and government agencies has led to significant effort over the past 50 years to prevent and control corrosion. A congressional study in 2002 estimated the cost of metallic corrosion annually for the United States was approximately $276 billion. The direct annual cost of corrosion to the US infrastructure and transportation system was estimated at $52.3 billion (Thompson et al., 2007). This section provides an overview of the physical phenomena of corrosion, a description of the corrosion process, an overview of the prominent technologies employed to evaluate corrosion, and the prevention and repair of corrosion.

Figure 10: Typical advanced deterioration of horizontal cracks (Staton and Knauff, 2007)

2.3.1. Corrosion Fundamentals

Corrosion is an electrochemical process. It requires metal, an electrolyte, and current flow. Corrosion occurs between metal areas having a higher tendency to corrode (anode) and metal areas having a lower tendency to corrode (cathode). An electrolyte which allows current flow must be in contact with the anode and cathode for corrosion to occur. The basic mechanisms of corrosion are well documented and understood, and Schweitzer has defined corrosion as the destructive attack of a metal by chemical or electrochemical reaction, and identifies nine basic forms of corrosion as follows (Schweitzer, 2003).

1) Uniform corrosion: In these cases, exposure of metal to air results in the formation of a passive film on the surface of the metal. This film (provided it maintains structural integrity) then protects the underlying metal from further corrosion. Clearly, the formation of such a passive film can be beneficial to protect vehicles and equipment including the connection loops and embedded steel in PCB.

2) Intergranular corrosion: This form of corrosion attacks the grain boundaries within a metal preferentially, and can be rapid and progress deeply into the material, reducing both the strength and the ductility of the metal very rapidly. Examples of intergranual corrosion are presented in Figure 11.

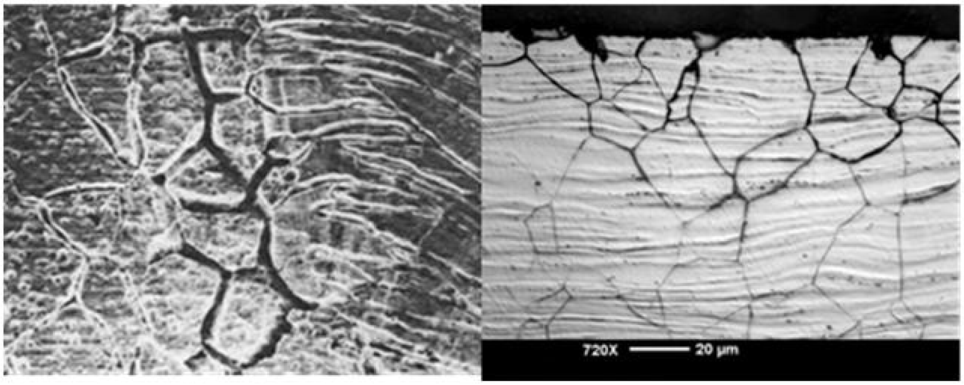


Figure 11: Intergranular corrosion (Kopeliovich, 2009)

3) Galvanic corrosion: This form of corrosion occurs when two different metals are in contact with one another in the presence of an electrolyte, causing an electrochemical reaction to occur. In this reaction, current flows from the metal acting as the anode to the metal acting as the cathode. Examples of galvanic corrosion are presented in Figure 12.

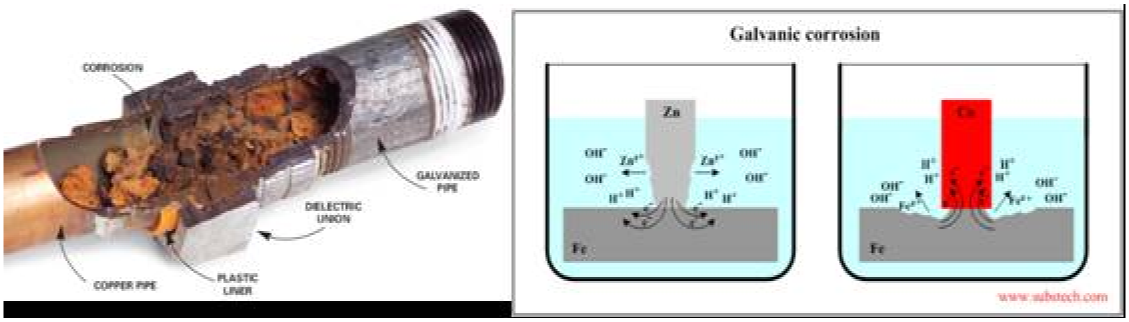


Figure 12: Galvanic corrosion (Kopeliovich, 2009)

4) Crevice corrosion: This form of corrosion occurs at the interface of a metal and another surface, often where a confined or stationary area is formed. Commonly this is observed beneath surface deposits, seals, gaskets, washers, clamps, sleeves, and similar junctions. Examples of crevice corrosion are presented in Figure 13.

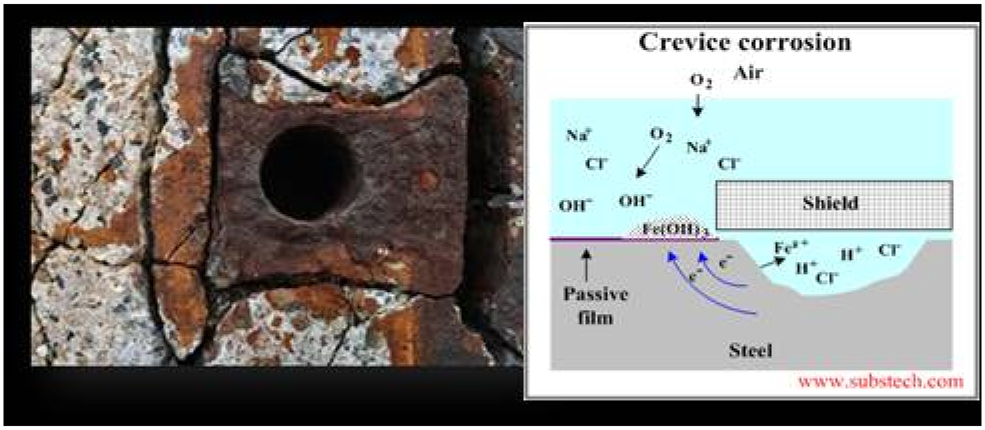


Figure 13: Crevice corrosion inside concrete (Kopeliovich, 2009)

5) Pitting corrosion: Pitting corrosion is often localized on the metals surface and is often difficult to detect due to the relatively small amount of metal loss. Examples of pitting corrosion are presented in Figure 14.

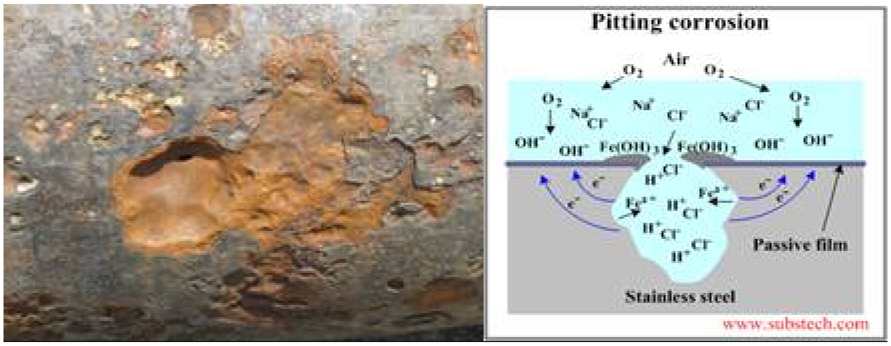


Figure 14: Pitting corrosion (Kopeliovich, 2009)

6) Stress corrosion cracking: This is the result of applied mechanical stress and corrosion. The presence of residual stresses due to manufacturing processes and corrosion fatigue due to cyclic loading are common causes. Examples of stress corrosion cracking are presented in Figure 15.

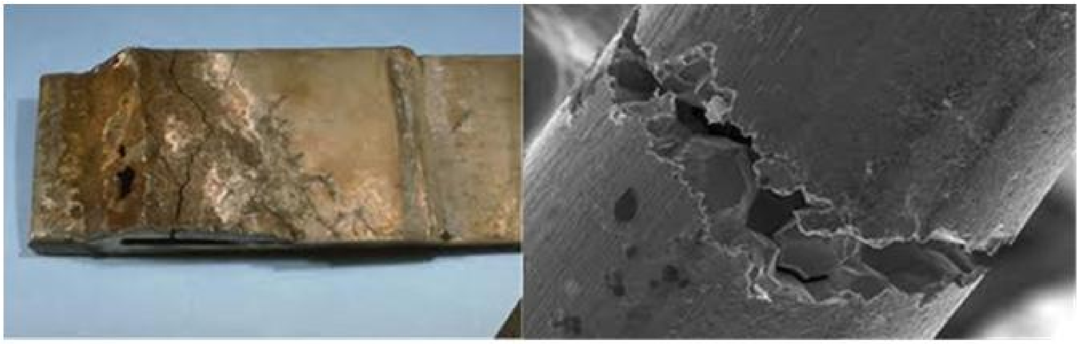


Figure 15: Stress corrosion (Kopeliovich, 2009)

7) Erosion corrosion: This is the combination of erosion and corrosion, resulting in an increased rate at which the metal is lost. Examples of erosion corrosion are presented in Figure 16.

Figure 16: Erosion corrosion (Kopeliovich, 2009)

8) Biological corrosion: Living organisms may under certain circumstances impact the anodic and cathodic reaction processes. This means that their presence may significantly accelerate corrosion, or even enable it to occur under circumstances in which, absent the organisms, corrosion would not have occurred. Biological corrosion often appears very similar to pitting, so if pitting is observed it may be necessary to test for the presence of microorganisms to determine the true cause of the pitting.

9) Selective leaching: The removal or corrosion of a single element in an alloy is known as selective leaching or dealloying (or, if the element being removed is zinc, dezincification). Typical conditions for such corrosion include high temperatures, a stagnant, acidic environment, and the formation of a porous scale on the surface of the alloy or component. This is not likely to occur in a highway environment. Typically, this form of corrosion can be avoided by selecting a different alloy for a given component.

Chloride-based salts, such as sodium chloride, magnesium chloride and calcium chloride, are widely used chemicals in winter road maintenance, but the use of such salts may cause damage to concrete and metal (Staton and Knauff, 2007; Koch et al., 2002; Cook and McCoy, 1977; Jones, 1996; Shi et al., 2008; Shi et al., 2010). The presence of chloride exacerbates corrosive situations because the chloride ions help the formation of a thin electrolyte film which draws water from vapor in the air, in which the metal is the anode and thus corroded (Dubuisson et al., 2007). Moreover, the conductivity of the solution containing chloride ions is better than water, thus the flow of electrons will be increased, or a higher corrosion current appears (Minsk, 1998).

In cyclic, humid conditions where wet-dry-wet periods occur, it was found that magnesium chloride caused more corrosion damage than sodium chloride did. However, when metals were exposed to dry and an immersion condition, sodium chloride was more corrosive. These results were attributed to the greater viscosity of magnesium chloride relative to sodium chloride, allowing it to adhere to the metal better and crystallize on the surface in the cyclic condition (Lazarus, 2009). Another study found magnesium chloride was more corrosive than sodium chloride when tested using the cyclic exposure test SAE J2334. Additionally, when a continuous spray test is done using ASTM B117, it has been found that sodium chloride is more corrosive than magnesium chloride (Xi and Xie, 2002). These studies show how great of an impact the environment/conditions in which deicers are used has on corrosion.

Corrosion of rebar in reinforced concrete is now recognized as a major problem in maintaining structures. The concrete pH, usually in the range 12–13.5, provides chemical protection to the rebar due to steel passivation. However, with time, severe corrosion problems may occur in reinforced structures. The most important causes of corrosion initiating in reinforcing steel are the ingress of chloride ions and carbon dioxide to the steel surface. Chloride ions cause local destruction of the passive film, leading to localized corrosion. Carbon dioxide, on the other hand, reacts with the hydrated cement matrix, leading to a pH decrease and subsequent loss of steel passivity and to corrosion initiation (Montemor et al., 2002).

In summary, corrosion in different systems, including PCB, is a highly complex phenomenon and takes many different forms. The result of all corrosion is the loss of strength of the material and the structure. Understanding the various types and combinations of corrosion is essential to determining the importance of each and to finding the most appropriate technologies for detection and characterization of corrosion. In the case of Montana, pitting is the most likely cause of loop connection corrosion, given that MDT personnel observed salt presence when inspecting corroded loops. Preventing this corrosion will require several different approaches, depending on how the corrosion is occurring, and what parts on the PCB connection system are corroding.

2.3.2. Corrosion Detection Technologies

Two types of inspection techniques, destructive and non-destructive, have been used to detect corrosion (Raeburn et al., 2008). Because the destructive technique is not suitable for assessing the corrosion on-site, non-destructive testing methods are extensively used to obtain instantaneous corrosion rates. The following sections discuss six corrosion detection technologies: 1) visual/optical, 2) electromagnetic eddy current, 3) acoustic ultrasonic, 4) radiographic, 5) thermographic, and 6) electrochemical method.

1) **Visual**: Visual inspection is the oldest and most common form of non-destructive method used to inspect corrosion (Peters, 1972; Matzkanin and Yolken, 2007; BDM Federal, Inc., 1998). The physical principle behind visual inspection is that visible light is reflected from the surface of the part being inspected to the inspector's eyes. By observing the appearance of the part, the inspector can infer its condition. Visual inspection is a quick and economical method of detecting various types of defects before they cause failure. Its reliability depends upon the ability and experience of the inspector. The inspector must know how to search for critical flaws and how to recognize areas where failure could occur. The human eye is a very discerning instrument and, with training, the brain can interpret images much better than any automated device. Optical devices are available to aid the naked eye in visual inspection and flaw detection. This equipment, such as borescopes, can be used to magnify defects which could not be seen by the unaided eye or to permit inspection of areas otherwise hidden from view. Visual inspection is often conducted using a strong flashlight, a mirror mounted on a ball joint, and a magnifying aid. Magnifying aids range in power from 1.5X to 2,000X. Fields of view typically range from 3.5 to 0.006 inches, with resolutions ranging from 0.002 to 0.000008 inches. A 10X magnifying glass is recommended for positive identification of suspected cracks or corrosion. To date, many visual techniques, such as borescopes (Ellicks and Stuhr, 2011), fiberscopes (Williams, 1982), and video imaging systems (Agarwala et al., 2000), have been developed to detect corrosion. Surface corrosion, exfoliation, pitting and intergranular corrosion can all be detected visually when proper access to the inspection area is obtained.

2) Eddy current: When an electrically conductive material is exposed to an alternating magnetic field that is generated by a coil of wire carrying an alternating current, eddy currents are induced on and below the surface of the material. These eddy currents, in turn, generate their own magnetic field which opposes the magnetic field of the test coil. This magnetic field interaction causes a resistance of current flow, or impedance, in the test coil. By measuring this change in impedance, the test coil or a separate sensing coil can be used to detect any condition which would affect the current carrying properties of the test material (Smith and Hugo, 2001). In the past, eddy current non-destructive technique was limited to detecting hidden corrosion at very shallow depths by the lack of penetrating capability of the eddy currents. However, over the last several years there have been several notable advances in eddy current non-destructive techniques stemming from research to detect hidden corrosion and other types of defects. Eddy current testing is used extensively to detect cracks, heat damage and corrosion thinning. High Frequency Eddy Current is used to detect exfoliation corrosion around installed fasteners. Inspection is usually directed at specific small areas rather than large areas (Rempt, 2002; Giguere et al., 2001; Sun et al., 2001; Thome, 1998).

3) Ultrasonic: Ultrasonic inspection utilizes high frequency sound waves as a means of detecting discontinuities in parts. Ultrasonic (above human hearing range) sound waves are sent into the material to be examined. The waves travel through the materials and are reflected from the interfaces, such as internal defects and the back surface of the material. The reflected beam is displayed on an oscilloscope and analyzed to determine the condition of the part (Goedecke and Beller, 1995).

Ultrasonic testing is accomplished by sending an electrical pulse to a transducer. This pulse causes the transducer to send a pulse of high frequency sound into the part. A coupling medium, such as water, between the transducer and the material is required. This pulse travels through the material until it reflects from a discontinuity or from a back surface. The reflected pulse is received by the transducer and converted back into an electrical signal. This signal is displayed on an oscilloscope for analysis. By examining the variations of a given response pattern, discontinuities are identified. Techniques have been developed to employ different kinds of waves, depending on the type of inspection desired, which include longitudinal waves, shear waves, surface waves and lamb waves. Ultrasonic inspection yields immediate results which can be viewed on an oscilloscope or detected audibly, enabling a relatively rapid rate of inspection. Contact type ultrasonic equipment is highly portable, hand held, and lightweight. However, ultrasonic inspection requires a high degree of experience and skill to set up the inspection and interpret the results, and both couplant and reference standards are required (Goedecke and Beller, 1995).

4) Radiography: Radiographic inspection is a nondestructive method of inspecting materials for surface and subsurface discontinuities. This method utilizes radiation in the form of either x-rays or gamma rays, both of which are electromagnetic waves of very short wavelength. The waves penetrate the material and are absorbed, depending on the thickness or the density of the material being examined. By recording the differences in absorption of the transmitted waves, variations in the material can be detected. The variations in transmitted waves may be recorded by either film or electronic devices, providing a two-dimensional image which requires interpretation. The method is sensitive to any discontinuities that affect the absorption characteristics of the material (Peters, 1965).

In principle, radiographic methods are capable of detecting and measuring both generalized and localized corrosion damage. With either type, corrosion is measured by analyzing the radiographic image through comparisons with calibration images of specimens of known thickness. If damage is localized, then calibration is not necessary for flaw detection alone because the presence of pitted areas is evidenced as regions where the image intensity differs from that of surrounding regions. If, on the other hand, damage occurs as uniform thinning, then comparison with a calibration image is necessary to determine the extent, if any, of material loss (Peters, 1965).

5) Thermography: Thermography is based on the principle that a good mechanical bond between two materials is also a good thermal bond. The temperature distribution on a PCB connection or component can be measured optically by the radiation it produces at infrared wavelengths. Several techniques have been developed which use this temperature information to characterize the thermal – and therefore the structural - properties of the sample being tested (Sakagami and Kubo, 2002).

Many defects affect the thermal properties of those materials, such as corrosion, debonds, cracks, impact damage, panel thinning, and water ingress into composite or honeycomb materials. By judicious application of external heat sources, these common defects can be detected by an appropriate infrared survey. Several organizations have demonstrated techniques for infrared structural inspection in the laboratory and field tests at maintenance facilities. Use of thermography techniques currently range from laboratory investigations to fielded equipment. Mcknight and Martin found infrared thermography to be a feasible method to evaluate the performance of coatings on steel in the laboratory (Mcknight and Martin, 1982). The presence of localized corroded areas appeared hotter than the surrounding area. Preliminary tests by Birring et al. showed that thermography could be used to detect 3-mm deep, 50-mm diameter, flat-bottom holes in 6-mm thick aluminum plate. A flame from a propane torch was used to instantaneously heat the surface opposite the side-drilled hole, and the temperature of the heated surface was then measured by an AGA thermovision camera (Birring et al., 1984). Birring et al. also used thermography to successfully detect corrosion under paint. For the experiments, a 1500 Watt lamp was used to heat the plate surface for a short time (~1 second). The surface temperature of the specimen was monitored by a thermovision camera. Photographs clearly showed the hot areas where corrosion was present (Birring et al., 1984).

6) Electrochemical corrosion monitoring techniques: Electrochemical non-destructive testing methods, such as polarization resistance, linear polarization resistance, Alternating Current (AC) impedance, and electrochemical noise, are used to obtain instantaneous in-situ average corrosion rates. Applying the obtained rates will provide an average corrosion rate for the entire reinforcement element in its stressed state. Measurements can be taken at any time in order to monitor performance more closely (Elias, 2000). For example, Oliveira and Ferreira found that electrochemical impedance spectroscopy (EIS) could be used to assess the degradation and ranking of paint coatings. The increase of temperature of tests proved to be useful in ranking candidate paint systems exhibiting high performance against corrosion degradation (Oliveira and Ferreira, 2003).

In summary, corrosion detection is a subset of the larger fields of Non-Destructive Evaluation (NDE) and Non-Destructive Inspection (NDI). There is an entire professional field associated with NDE/NDI and a related field on corrosion engineering. Corrosion itself is an extremely complex subject, and corrosion engineering combines several disciplines, including mechanics, structures, material science, chemistry, physics, and numerous sensor technologies. The many forms of corrosion and the attendant damage that results further complicates the subject. Furthermore, corrosion detection is frequently combined with other inspection requirements, such as crack, fatigue and hardness testing. As more technologies are being explored for application to the corrosion detection problem, different sensing and measurement mechanisms come into play. Eddy current, ultrasonic, and thermal wave imaging (singly or in combination) measure electrical impedance, ultrasonic attenuation, time of travel, and thermal diffusion which are dependent on the material thickness and any flaws. Comparative measurements or calibration of the parameters on known specimens enable detection of flaws or estimation of material thickness. Comparison with reference documentation allows the calculation of material lost due to corrosion. Enhanced visual techniques detect surface deformations caused by internal formation of corrosion products. Correlation with known specimens allows the estimation of material volume, and therefore material thickness, lost due to corrosion. Radiography techniques can provide a measurable image of the part in question and can highlight the presence of the products of corrosion.

2.3.3. Corrosion Inspection

Corrosion inspection is used to identify types of corrosion, record their effects and appraise/characterize corrosion conditions. It is a specialized inspection typically involving inspectors with specialized training and knowledge of corrosion. The level of corrosion inspection is generally determined by the government agency, such as a DOT, needing the information or by a private party with possible guidance from a consulting engineer. The inspection level is based on the intent of the inspection, the amount of information needed to evaluate a specific requirement, and the amount of time and money available. Corrosion evaluation procedures presented in an NCHRP report on the corrosion of steel bridges may be appropriate for PCBs (Kulicki et al., 1990). Following these procedures, corrosion evaluations can be divided into two levels. Level I uses relatively simple analysis methods to determine corrosion properties. Level II is a more exhaustive approach using the sophisticated analysis techniques mentioned above to evaluate corrosion. The information needed for a Level I evaluation is obtained from a cursory or general field inspection. From these findings, either the basic overall requirement can be satisfied or a determination made that a more comprehensive inspection is necessary. A Level II evaluation involves a multidisciplinary team of inspectors, corrosion specialists, and office evaluators. A detailed field inspection is needed to support this level of evaluation.

1) Level I: Cursory Inspection. The cursory inspection provides an overview of corrosion conditions without detailed examination of deficient areas or the use of sophisticated tools and equipment; it relies on visual observation and experience to evaluate the corrosion conditions. In the case of PCB, a cursory inspection will answer such basic questions as: a) is extensive corrosion present (without actually measuring metalwork losses)? b) is corrosion global (found throughout the entire exposed metal bar/wire and steel pins which form the connection system for PCB) or localized? and c) has corrosion caused or contributed to the misalignment of PCB (without actually measuring the amount of displacement or fixity)?

The cursory inspection offers overall observation, but lacks the close scrutiny that would quantify conditions or find remote effects. Visual estimation of physical losses can be made without measurement by using percentages of section loss or equivalent section thickness loss. The primary use of the cursory inspection is to determine in a quick and inexpensive manner the overall PCB connection condition and whether a more extensive Level II evaluation may be needed. A cursory inspection may not provide all the information needed for a Level I office evaluation.

2) Level I: General Inspection. The general corrosion inspection is used for Level I evaluation. In the case of PCB, the inspection would be a manual approach in which connection parts that are accessible without the need for specialized equipment are directly observed by the inspector. Both general and worst case conditions would be checked. A combination of estimating and measuring is used for determining the extent of corrosion damage.

While a general inspection is consistent with the need for an overall condition determination with a sampling of conditions, it lacks the detail of a complete survey as it cannot inspect areas which are not readily accessible.

3) Level II: Detailed Inspection. The detailed inspection is an in-depth inspection covering all corrosion aspects of a system. If necessary, special access-gaining equipment may be used to observe each part and make detailed measurements of all metalwork losses. Steel surface cleaning is performed, as required, to make accurate surface measurements and precise determination of metalwork losses. The detailed inspection provides the full range of information required for a complete evaluation of PCB connection.

At all levels of inspection, because debris and corrosion product can mask defects and prevent accurate evaluation of conditions, it is necessary to clean the steel surface to allow for the level of corrosion inspection required. For general inspection, the inspector should be prepared to use a whisk broom, putty knife, and chipping hammer to clean metalwork as needed to make selective measurements. For detailed inspection, the same cleaning equipment may be sufficient in relatively clean conditions, but compressed air is needed to blow off debris in a heavy debris accumulation and/or if large amounts of corrosion products are present. For both Level I and Level II corrosion inspections, the PCB inspection team leader will have to determine the types of equipment needed to gain access to all areas of the connections.

The measurement of corrosion should be consistent with the level of evaluation of the PCB. For a cursory inspection, estimation of a loss from a trained eye is close enough; for general inspection, loss measurements of an area of metalwork may be estimated based on caliper measurements, equivalent areas, or a series of D-meter (ultrasonic) measurements; for detailed inspection, loss measurements may be accurately obtained from caliper readings, D-meter readings, or the use of more sophisticated instruments or technologies mentioned previously.

For uniformity in the description of corrosion conditions during the field inspection and for proper interpretation by the office evaluator, an objective condition rating system is used. One such system described by Kulicki, et.al (1990) and shown in Table 3 uses a scale of 0 to 9, with 9 being the best condition and 0 being an unsatisfactory rating. Following this rating system, PCB loops and pins with ratings of 0 to 4 would need to be replaced, while for ratings of 5 to 7, coatings or materials should be used to prevent/address future corrosion. Ratings of 8 and 9 would likely incorporate connections which have already been treated.

Table 3: Condition rating scale (Kulicki et al., 1990)

Rating	Description
N	Not applicable
9	Excellent condition
8	Very good condition-no corrosion
7	Good condition-minor corrosion with no significant metalwork loss
6	Satisfactory condition-minor corrosion with minor metalwork loss but element functioning as intended
5	Fair condition-moderate corrosion with element functioning at a reduced level
4	Poor condition-major corrosion with element functioning at a marginal level
3	Serious condition-serious corrosion with element functioning at an inadequate level
2	Critical condition-severe corrosion with element not functioning as intended
1	“Imminent” failure condition-extent of corrosion severe, requires determination If repairable
0	Failed condition-extent of corrosion renders element beyond repair

For MDT’s PCB evaluation purposes, a compressed rating scale consisting of simply four condition categories to describe the range of corrosion listed in Table 3 may be adequate. Referring to Table 3, the rating scales of 0 to 4 can be compressed to condition 1; scale ratings 5 and 6, to condition 2; scale rating 7, to condition 3; and scale ratings 8 and 9, to condition 4. In the new rating scheme, the PCB loops and pins or the entire PCB section should be replaced for condition 1, while a treatment could be applied for conditions 2 and 3. Condition 4 would represent connections which have already been treated.

As a side note, concurrent with any inspection of PCB connection systems, the overall condition of the PCB should be evaluated. In doing so, any cracking should be noted and addressed through the use of sealants. In recent years, some state DOTs (e.g., Wisconsin and Minnesota) have begun using crack sealants as one method to prevent chloride ion intrusion and the subsequent deterioration of the substructure. In doing so, corrosion to the internal rebar structure and to some extent the connection system can be prevented or minimized.

Currently available crack sealant products include High Molecular Weight Methacrylates (HMWM) resins, epoxy resins, and urethane resins among others. Crack sealant products seal fine cracks by creating a barrier that prevents water and water-borne contaminants from entering the concrete (Hagen, 1995; Pincheira and Dorshorst, 2005).

The amount and surface preparation required before a product is applied to a surface or a crack is an important consideration when selecting a sealant. Recommended surface preparation requirements are provided by the manufacturer for each product. Typical surface preparation requirements for crack sealants range from no specific requirements to pressure washing or mechanical abrasion to clean the concrete surface and remove debris from cracks. In addition, the necessary moisture content of the substrate at the time of application can be included in the surface preparation category and can range from completely dry to slightly damp (Pincheira, 2009).

2.3.4. Corrosion Prevention and Repair

The rate and extent of corrosion attack on a PCB connection will vary according to the environmental conditions, structural details, cleanliness, surface coating, and maintenance history. Based on the inspection and evaluation methods mentioned above, the PCB loops and/or pins may be replaced and repaired, and various techniques are available to prevent corrosion of PCB connections, both in new installations and in repair/replacement scenarios. Currently, two methodologies appear appropriate to prevent corrosion of PCB connections. One is the use of coatings and the other is adding inhibitors. Note that a third option, the use of an alternative material, namely stainless steel, is also possible, although such materials carry with them a significant financial cost (Wenzlick, 2007).

1) The use of coatings. Numerous corrosion coatings, such as metallic, epoxy, polymer, and acrylic coatings, have been developed and tested in an attempt to combat the harmful effects of corrosion on metal. Due to the variations in the physical and chemical properties of each of the different types of metals and alloys, the protection provided by each coating is dependent on the type of metal it is applied to and the environment in which it is exposed. The development of these coatings has focused on enhanced functionality comprising corrosion protection and adhesion, environmentally friendly materials, corrosion and mechanical damage detection, improved fatigue resistance, and water resistance (Taylor et al., 2007).

Corrosion protection coatings generally use barrier protection, inhibitive action or anodically active metal to perform their function. Barrier protection coatings cause oxygen deprivation or resistance inhibition. Inhibitive coatings alter the chemistry at the surface of the metal substrate. Anodically active metal coatings are usually made of zinc and, due to their anodic activity level, they are able to prevent electrical current from discharging from the substrate and causing galvanic corrosion. The zinc sacrificially corrodes, forming a corrosion product that provides protection similar to a barrier coating (Tracton, 2006).

Coating systems generally consist of three layers. Most commonly, the first layer consists of a metal oxide which inhibits corrosion. The next layer is a primer containing inhibitors to provide cathodic protection to the metal. The top layer is generally a barrier which separates and protects the underlying coatings from the surroundings (Sitaram et al., 1997).

Due to their advanced mechanical and physical properties, nano-structured materials have been the focus of many researchers attempting to create advanced corrosion resistant coatings. Work has focused on the types, production, and applications of various nano-structured coatings. “A polymer nano-composite coating can effectively combine the benefits of organic polymers, such as elasticity and water resistance to that of advanced inorganic materials, such as hardness and permeability” (Saji and Thomas, 2007). In addition to these advantages, nano-materials also remove the need to use components which may have negative effects on the environment.

When replacing a coating that is no longer environmentally acceptable, special attention should be given to the corrosion behavior differences of the coatings to ensure the new coating is an acceptable alternative. For example, many zinc-nickel alloys have been used to replace cadmium layers but issues arise due to the differences in their corrosion behavior. Zinc-nickel alloys exhibit localized corrosion and cracking, while cadmium layers are susceptible to uniform corrosion (Gavrila et al., 2000). The differences in corrosion behavior will play a crucial role when providing the necessary corrosion protection system.

Hydrophobic treatment, a recent corrosion protection method, applied to steels provides an effective barrier against moisture on the metal surface and electrically insulates the underlying metal. Thus a hydrophobic fluoropolymer film, deposited on carbon steel using inductively coupled radio frequency plasma and the carrier gas octafluorocyclobutane, is proposed as a corrosion protection system. Fluoropolymer films offer low surface energy, good thermal stability, and chemical resistance. The resulting films adhered well to the steel surface and were hydrophobic. The optimal thickness of 90 nm resulted in a cost-effective and successful approach of corrosion protection.

Specific corrosion protection coatings appropriate for PCB connections were not identified at this time, as this process is dependent on a number of factors (such as nature of the corrosion being experienced, conditions under which the coating will be applied, its expected effectiveness, and its cost), not all of which are presently known.

2) The use of inhibitors. A second strategy being pursed to control corrosion is the use of effective, nontoxic inhibitors. Corrosion inhibitors, as defined by the International Organization for Standardization (ISO), are "compounds that when present in a corrosive system at a sufficient concentration, decrease the corrosion rate of metals without significantly changing the concentration of any of the corrosive reagents." Corrosion inhibitors cause changes in the state of the protected metal surface through adsorption or formation of compounds with metal cations. This results in a reduction of the active surface area of the metal and a change in the activation energy of the corrosion process. The adsorption and formation of protective layers on metals is greatly dependent on both the ability of the inhibitor and metal surface to form chemical bonds and the charges of the surface and inhibitor (Kuznetsov 2002).

Currently, chromate inhibitors demonstrate the highest corrosion inhibitor performance but are toxic and harmful to the environment. Recent research focuses on creating non-toxic oxyanions for use as corrosion inhibitors. Some of these compounds include molybdate, organic thioglycolates and phosphonates while some inorganic compounds include phosphates, borates, silicate and surfactants. Other possibilities for inhibitors involve rare earth metal salts (El-Meligi, 2010). Inhibitors are incorporated into coating systems, in which the coatings contain a physical barrier layer and a conversion layer with an inhibitor that chemically impedes the corrosion process, and play a key role in corrosion protection.

Inhibitors can be used on a wide variety of metal substrates. Steel is the most widely used metal today and in the past, chromate inhibitors have proved successful in decreasing the corrosion rate on steels. However, new, nontoxic inhibitors are being developed as potential chromate replacements for use on steel. Successful protection of steel has been reported in the literature with the use of various inhibitors.

In summary, there has been significant advancement in the field of corrosion inhibitors in recent years. As in the case of coatings, identification of what, if any inhibitors are appropriate for use on PCB connections will depend on many factors, from the corrosive mechanisms involved to the cost of the inhibitors, themselves; thus, such identification has been deferred until the PCB corrosion issues are more fully characterized.

2.3.5. Corrosion Repairs by Retrofitting

Based on the rating scale of corrosion inspection results mentioned above, the loop and pin connections in a PCB segment would be replaced if the rating scale was 0 through 4 on the expanded scale (or simply condition 1, on the compressed scale). No literature was identified which discussed such a replacement process in the field, either specific to PCB or for similar situations, such as the replacement of rebar/wire rope anchored in concrete in corrosive environments (e.g., seaside ports/docks).

Conceptually, a traditional replacement process could be followed in which the corroded metal is replaced with new material. This would entail removing the corroded parts, and installing the new (ideally treated) metal. However, the issue with this approach is the common practice in many PCB designs of casting-in-place the loop connection system. Thus, in replacing this system, any internal corrosion associated with the presence of the embedded system would have to be remediated, and then the system itself would have to be replaced with one probably relying on a "post-installed anchor" technology. The extent of this process may explain why such retrofit approaches are not discussed specific to PCB. Note the crashworthiness of such a retrofit would also need to be determined, which may make the complete replacement of a PCB section with corroded connections a more attractive (and less costly) alternative.

2.4. PCB Maintenance Requirements

Only one piece of literature was identified which specifically discussed any aspect of PCB maintenance. This discussion focused on addressing a specific condition experienced, Alkali Silica Reactivity (ASR), that had an impact on the placement of the barrier and also had a secondary impact on the joint between barriers. As expected during the proposal stage of this work, no additional literature specific to PCB maintenance was identified. Consequently, the survey of state practice, discussed in the following chapter, fills this information gap.

2.4.1. Peabody (2011)

Peabody discussed ASR as a mechanism responsible for expansion issues with a section of PCB along I-295 in Portland, Maine (Peabody, 2011). ASR is a chemical reaction between the alkalis present in the cement and silica in the aggregate that forms an expansive gel causing cracking and movement of the concrete (Peabody, 2011). The PCB section in question had an epoxy coated rebar grid and slot connection which was filled in with grout. A grout failure due to ASR had resulted in the movement of barrier at the joints, with road salts used in winter maintenance possibly contributing to the conditions observed. To address the issue, the offending barrier was moved to leave a 6 inch gap between it and the adjacent barrier. The barriers were then joined by a metal guardrail section (see Figure 17). This repair represented the only discussion of any retrofit approach (albeit site-specific) to addressing an issue with PCB joints (not specifically a metal corrosion issue however).

Figure 17: Maine repair of a PCB joint experiencing ASR expansion (Peabody, 2011)

2.5. PCB In-Field Performance

In addition to general and connection system-specific PCB literature, documents which discussed the performance of PCB systems in the field were reviewed. Such literature discussed the performance of PCB in reducing crash severities and observations of overall damage following vehicle strikes.

2.5.1. Igharo et al. (2004)

Igharo et al. discussed the in-service performance of PCB connected by a loop and pin system in Washington (Igharo et al., 2004). This work involved maintenance personnel documenting incidents, including the extent of damage and repair costs, in a database. This information, along with crash reports, was used to summarize the in-service performance of PCB in the state. Results showed pin and loop connections held up well in crashes and barrier displacements were within design specifications. Based on data from forty crashes, the pin and loop connection system remained intact 75 percent of the time, while the pin was bent or broken 20 percent of the time (Igharo et al., 2004). The remaining 5 percent of cases had joints with pin or loop damage (Igharo et al., 2004). Overall, the existing PCB system showed lower crash severities than were experienced in locations where no barrier was present. While the work itself relied on in-field observations and data collection, no discussion of corrosion occurred in the report. Whether no corrosion was observed, or it was intentionally excluded from discussion in the report, is not clear.

2.5.2. Albin et al. (Undated)

Albin et al. discussed the in-service performance of PCB in Washington compared to all types of beam guardrail (Albin et al., undated). The connection system of the PCB then in use was a 2 by 2 wire loop and pin system using nested loops. The data indicated PCB crashes resulted in a higher percentage of injuries, but fewer severe injuries (disabling and fatal) compared to beam guardrail (Albin et al., undated).

2.5.3. Lisle and Hargroves (1980)

Lisle and Hargroves evaluated the in-field performance of PCB being used in a Virginia work zone (Lisle and Hargroves, 1980). The barrier was a New Jersey shape 32 inches high, 12 feet in length, and using a tongue and groove connection (see Figure 18). To evaluate in-field performance, the researchers examined crashes in which a vehicle came into contact with the PCB in the study work zone. Ten crashes were reported during the three month study period (September to December, 1977) where a vehicle contacted the PCB (Lisle and Hargroves, 1980). Three crashes involved injuries, while the remaining seven were property damage only. Typical barrier displacement observed following these crashes was less than one foot, although one crash experienced a displacement of eight feet. In general, there was evidence (tire scrubbing) that there were 49 vehicle contacts with the PCB for every one crash observed. An in-depth discussion of the performance of the tongue and groove connection system was not made; however, the general evidence offered by the observed low barrier displacement values following crashes suggests the connection system was at least somewhat effective.

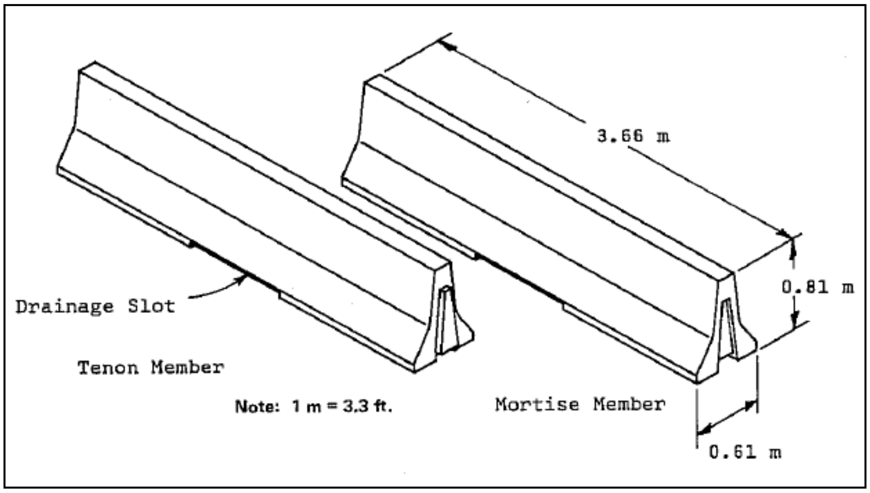


Figure 18: General overview the Virginia tongue and groove end connection (Lisle and Hargroves, 1980)

2.6. PCB Replacement Approaches/Strategies

Ideally, an Asset Management approach would be employed to identify and prioritize the need for replacement or retrofitting of PCB based on available data such as barrier age, connection system materials, etc. Asset Management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively (FHWA, 1999). In such a case, the age and characteristics of PCB would be accounted for through a life cycle approach which identified when replacements should be made. In the case of PCB however, such an approach is not necessarily applicable, given connection system corrosion warrants the replacement of PCB along some roadway segments in the near-term and compliance with NCHRP 350/MASH criteria requires the replacement of additional segments over the longer-term. Much of the existing PCB along Montana roadways requires replacement at some point in time, and the Asset Management approach will not necessarily identify the best scheduling/timing for replacement. Rather, examples from other transportation agencies facing similar replacement needs must be considered.

A search of literature identified different approaches to the replacement (or retrofitting) of PCB that were available. While the body of literature specific to transportation was limited regarding such approaches, they can generally be characterized as a "worst-first" approach, a system wide (single or multi-year) approach, or a prioritized approach. The following sections provide a description of each approach and summarize related literature which has discussed their application.

2.6.1. Worst-First Approach

The "worst-first" approach to replacement is exactly as the name suggests, those items in the worst condition are replaced first, followed by other elements in better condition at a later date. In one respect, this is a prioritized approach, as it places replacement priority on elements that are in the poorest condition. However, it is more simplified as it uses a minimum of information (e.g., a visual inspection) to arrive at a replacement decision. No specific literature discussing the approach as applied during a single year was identified. However, discussion of the need for a multi-year replacement approach was identified.

2.6.1.1. Harris et al. (2007)

New Manual on Uniform Traffic Control Devices (MUTCD) requirements for signs to meet retroreflectivity standards by 2015 represents a similar transition problem to PCB replacement. To this end, Harris et al. discussed approaches to determining existing sign retroreflectivity and prioritizing replacement (Harris et al., 2007). While some of the work completed included modeling of remaining sign life, the conclusions of the work are of interest. It was found that visual inspection of signs was the most cost-effective approach for assessing conditions compared to existing technologies (Harris et al., 2007). Using this approach, signs which did not meet retroreflectivity thresholds would be replaced, while replacement of those which were still in adequate condition was deferred, essentially a "worst-first" replacement strategy. Such an approach could be directly transferred to PCB replacement based on observed corrosion rating results.

2.6.2. Systematic Approach

When faced with the replacement of an entire infrastructure element across the entire roadway system, such as PCB, one available strategy is to simply complete replacement in a straightforward manner, either during the course of one year or multiple years. In the case of replacement being completed over the course of one year, prioritization would not necessarily be employed, as the element would be replaced in its entirety within a short time period. Unfortunately, no literature was identified discussing such a replacement approach being employed in a transportation application. However, an approach specific to bridge rails in Washington State offers an example of a multi-year systematic replacement program.

2.6.2.1. Gripne (1988)

Gripne discussed the development of the Washington state DOT's bridgerail retrofit program (Gripne, 1988). The Washington program came about in 1984 when the need arose to address substandard bridgerails across the highway system. The replacement program sought to systematically replace substandard rails over a multi-year period as part of resurfacing, restoration and rehabilitation (3R) projects. The retrofit considered and applied several alternatives to existing bridgerails to improve their redirectional characteristics (Gripne, 1988). While focused on the replacement of beam guardrail, the general approach taken may have aspects of transferability to the present work. The approach itself, which relied on a systematic, multiyear replacement of all bridgerail, could similarly be carried out in replacing PCB over multiple years across the entire highway system as part of related projects. The drawback to this approach as applied to the PCB connection system replacement is that in the absence of prioritization and/or scheduling, it could stretch out over a long period of time, rather than addressing the issue in a short period of time.

2.6.3. Prioritization Approach

In addition to the systematic approach to replacement, which may rely on the completion of corresponding work at the same site (e.g. repaving), an alternative approach to the replacement of infrastructure is prioritization. In this case, the element which is slated for replacement is still being replaced system wide, but its replacement is based on a prioritization of an aspect specific to it, such as condition, rather than relying on the completion of other, typically unrelated work to at the same location.

2.6.3.1. Frymoyer and Berman (2010)

Frymoyer and Berman assessed the remaining life of in-service luminaire support structures for the Washington State Department of Transportation (WSDOT) (Frymoyer and Berman, 2010). The work sought to prioritize the inspection and replacement of luminaires throughout the state. Modeling was used to estimate the remaining life of support structures based on fatigue and other factors, and the approach to replacement was based on that remaining service life, with the shortest remaining life structures replaced first (Frymoyer and Berman, 2010). Such an approach (minus lifespan modeling) could be transferred to PCB replacement, with the oldest sections (assuming installation dates were available) replaced first. Alternatively, a similar metric such as pin and loop connection condition could be substituted (e.g. segment with worst average corrosion rating replaced first, and so on). Such an approach could be performed either in a one year or multi-year program depending on available resources.

2.6.3.2. Gabler et al. (2010)

A review of repair practices for longitudinal barriers by Gabler et al. found most states employed an approach where repairs were performed at a point when a barrier was determined to be nonfunctional, although quantitative measures of functionality were not often employed in making such a determination (Gabler et al., 2010). In essence, this approach represented a “worst first” strategy toward repair and replacement. However, the researchers developed an alternative strategy which consisted of high, medium and low priority levels for repair and replacement, based on a quantitative approach toward determining condition (Gabler et al., 2010). High priority levels were those where safety was compromised by a defect. Medium priority levels were conditions where multiple crashes striking a barrier would eventually lead to compromised safety. Low priority levels were cases where minor damage or deterioration may be present, but these were not enough to warrant repair or replacement as safety had not been compromised. This overall approach could be applied to PCB replacement based on connection system condition ratings, where the segments which had the most connections with the highest degree of observed corrosion would receive the highest replacement priority (being replaced in the immediate future). Segments where connections were observed to be in good condition would have PCB replaced at a later date.

2.6.4. Recycling, Disposal and Reuse Options

A search of the literature found no published discussions specific to the recycling or reuse of replaced or retired PCB segments. However, as will be discussed in the following chapter, a number of states disposed of (i.e. landfill), recycled (i.e. crushed for aggregate) or reused PCB that had been removed from service. Additionally, a broader body of literature discusses the recycling of concrete as a general product. While focused on the recycled uses of concrete pavement materials, this information is transferable to PCB sections.

2.6.4.1. Recycling and Disposal

Old concrete from PCB sections, similar to other used concrete (e.g., pavements), can be crushed into aggregate for reuse in a variety of applications. A number of researchers have discussed this topic, from a broad overview (American Concrete Paving Association, 2009) to specific applications including the use of recycled concrete as aggregate in new ready-mix concrete (Zega and Di Maio, 2011), as part of the roadway structure (Foth et al., 2011; Taha and Alshamsi, 2008; Depoy, 1999; Wojakowski et al., 1995), in new concrete pavements (Roesler and Huntley, 2009; Sturtevant et al., 2007; Yrjanson, 1989), as a fill soil stabilizer (Burke et al., 1992), and as shoreline protection (Talend, 2005).

In addition to being reused as aggregate, recycled concrete from PCB can also be used in the production of other products, such as acoustic barriers. Krezel and McManus discussed such a use in Australia where recycled concrete was used as aggregate in the production of freeway noise barriers (Krezel and McManus, 2001). While the concrete used in this application came from old pavement, recycled PCB concrete could serve in a similar fashion in creating such noise barriers. It could similarly be used as an aggregate in the construction of new PCB which meets NCHRP350/MASH criteria.

No literature specific to the disposal of PCB or even concrete in general was identified during this work. This is not surprising, given the numerous recycling uses of concrete presently employed, combined with the nature of disposal itself when recycling does not occur. When disposed, concrete is simply taken to a municipal landfill and buried with other waste (i.e. garbage).

2.6.4.2. Reuse

The reuse of PCB would allow for a segment to remain as is (intact) after removal from highway use. That is, it would not be crushed during a recycling operation or disposed of as one piece. Rather, it would be employed in a new use without any changes made to the segment. Although not identified or discussed in the literature, such an option for the reuse of PCB for example is in applications in which crashworthiness is not as significant of a concern as is vehicle separation. The researchers have observed PCB being used, for example, on the ramp of commercial airports to direct ground equipment traffic and separate the area of the ramp where an aircraft is parked from those where ground support vehicles may be parked. In such an application, the intent of PCB is vehicular separation rather than safety, and the crashworthiness of the PCB is of less concern given lower vehicle speeds than its ability to provide a mechanism to protect parked aircraft. Similarly, older PCB could also be used in parking lots to separate different areas and direct traffic flow. As the speeds in such lots are typically low, crashworthiness is once again less of a concern than vehicle separation. In such cases, MDT could potentially provide retired PCB to other agencies at low or no cost.

2.7. Chapter Summary

This chapter has presented the results of a literature review which examined past research and agency reports to provide a synthesis of a variety of topics pertaining to PCB, including general information, connection systems, corrosion, maintenance, in-field performance and replacement approaches/strategies. This review found a number of different designs (dimensions and shape profiles) are currently in use and have been shown to meet existing crashworthiness criteria. These designs have slightly evolved over time to meet increasingly stringent crashworthiness criteria, although the general purpose of PCB (a substantial mass of concrete joined by different connection systems to contain a vehicle impact) has remained unchanged.

As expected, only a limited portion of the available literature on PCB focused on connection systems. These documents tended to focus on discussions of designs, materials and crash testing performance, rather than corrosion or replacement of connections on in-service barriers. In only one instance, the Roadside Design Guide, was the *potential* (not the observation) for metal connection systems to corrode (due to salt exposure) indicated. Even this reference to corrosion was brief, being included as part of a more general overall statement. This absence of discussion of connection corrosion in the body of literature may be indicative of a lack of awareness of the potential for it to occur. It may also simply be the result of a lack of work performed on the subject, even if awareness of the issue does exist. Regardless, it underscores the need for the review and synthesis presented in this report.

Literature specific to the corrosion of PCB connection systems was not found in the literature review. Still, a general discussion of the overall subject of corrosion was compiled to familiarize the reader with the different mechanisms which can impact PCB connections, how it can be detected and characterized, as well as potential prevention and treatment options. These approaches include the use of coatings and inhibitors. Only one specific document addressed any aspect of PCB maintenance, and this was specific to ASR issues, which resulted in the shifting of barrier segments at the joint through expansion. However, this reaction was not corrosion to the connection system but rather expansion of the grout material placed at the joint.

Relative to the in-field performance of PCB, the literature exclusively considered effectiveness in mitigating crash severity, and it was found crash data indicated PCB systems are effective in reducing the severity of crashes. Finally, a search for replacement or retrofit approaches and strategies did not yield any results specific to PCB. However, similar approaches from other areas of transportation that may be considered transferable were identified. These included worst-first, systematic and prioritized replacement. No discussion of retrofitting existing barrier segments with new connections was encountered. In the case of barrier replacement, recycling and reuse options are available for PCB. These include the crushing of barrier into aggregate, use in other applications (such as parking lots) where crashworthiness is not an issue, use as riprap, or disposal in a landfill.

Collectively, the information summarized in this chapter indicates the general state of knowledge on PCB is well established, but its focus is centered on crash testing and crashworthiness. Discussion of PCB connection systems centers on their design and material aspects, with essentially no discussion or recognition of the potential or occurrence of corrosion of their connections. Whether this is the result of a lack of awareness of the potential for corrosion or an absence of its occurrence is unclear. The state DOT survey discussed in the following chapter will seek to answer this question.

3. SURVEY OF STATE PRACTICE

As the information presented in the previous chapter indicated, the overall body of PCB literature did not directly resolve the question of whether corrosion of PCB connection systems is a problem and, if so, how it has been addressed and/or prevented. In order to determine whether such corrosion has been an issue, a survey of state DOTs was completed as part of this work. The survey sought not only to obtain information on experience with connection system corrosion, but also on maintenance practices employed (both to prevent/address corrosion as well as general activities), whether retrofit or transition replacement plans or programs had been used to address any existing connection system corrosion issue, and what agencies did with barrier segments that had been removed from service. A copy of the survey instrument is provided in Appendix A. Note the survey incorporated logic which redirected respondents to different portions of the survey based on responses to specific questions.

The survey was administered online using SurveyMonkey and was sent to all states via their research sections. This was accomplished by distribution via an email list maintained by MDT's Research Program. In the email sent to agencies, it was requested that the survey be forwarded to and completed by personnel from design and maintenance staff who were most familiar with PCB. The initial survey was sent to each state on March 14, 2012, with a follow-up remainder sent on April 4, 2012. Based on these initial contacts, a total of 34 survey responses were obtained (with multiple responses being provided by some states). Consequently, follow-up emails were sent on April 4 and April 25, 2012, resulting in another 10 responses (44 total).

The following sections provide a discussion of the results obtained by the survey of state practice. They also present information on current MDT practices for comparison purposes. Throughout the course of this discussion, please note in some cases, multiple responses were obtained from different staff at an agency (e.g., one response from design and a second from maintenance). Since the survey employed logic which redirected respondents to specific questions based on certain responses, the total responses to specific questions may not be equal to the number of participants in the survey. Conversely, some questions allowed for multiple selections to be made, resulting in a greater number of total responses than the number of participants in the survey. Finally, the comments received from respondents have not been edited so as to reflect the original intent of the information being provided.

3.1. Respondents

A total of 30 states/agencies responded to the survey, providing 44 individual responses. Note that three respondents skipped the initial question regarding their contact information and agency, so it is not possible to know exactly which state/agency they represented. In some cases, multiple responses were obtained from a state (as stated previously, the target audience was design and maintenance staff). Of the responses obtained, 100 percent of agencies indicated PCB was being used in some capacity (work zones, median barrier, etc.) by or for their agency in temporary or permanent applications. A map indicating the geographic distribution of respondents is provided in Figure 19, with the respondent states also listed in Table 4. Note there is a fairly representative distribution of respondents geographically, although one exception could be the Mid Atlantic area. A number of attempts were made to solicit responses from specific states of interest to the MDT project panel, including Minnesota, Maryland, Massachusetts, Vermont and West Virginia, but unfortunately, no responses were provided by these states.

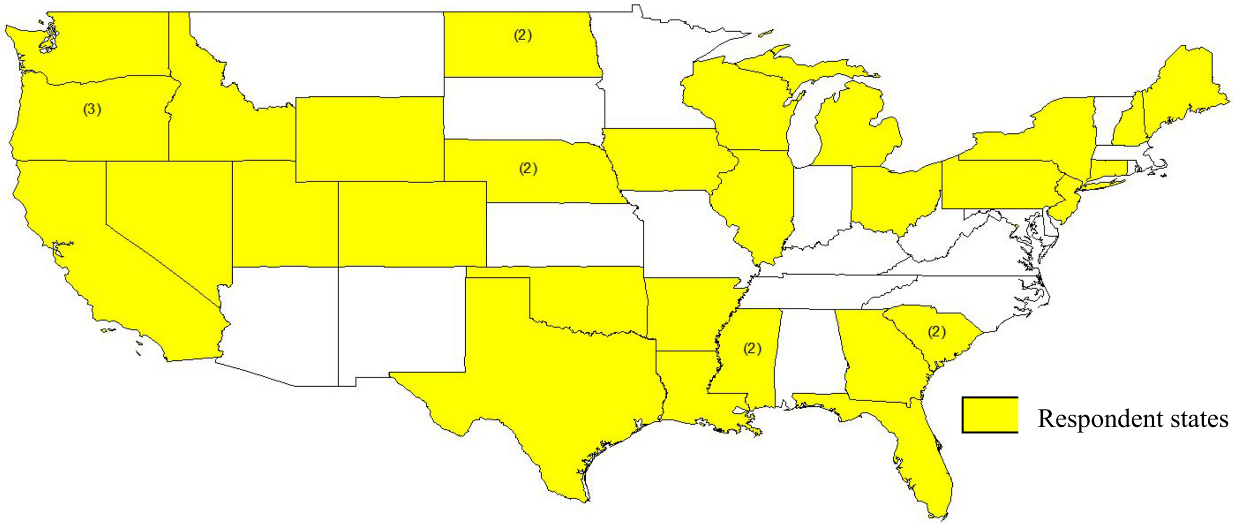


Figure 19: Agency survey responses, respondents not shown: Alaska (3) and Puerto Rico (2) (Note, numbers in parentheses indicate number of responses from that agency)

Table 4: Respondent states (Note, numbers in parentheses indicate number of responses from that agency)

Alaska (3)	Maine	Oregon
California	Michigan	Pennsylvania
Colorado	Mississippi (2)	South Carolina (2)
Connecticut	Nebraska (2)	Texas
Florida	Nevada	Utah
Georgia	New Jersey	Washington
Idaho	New York	Wisconsin
Illinois	North Dakota (2)	Wyoming
Iowa	Ohio	Puerto Rico (2)
Louisiana	Oklahoma	District of Columbia

3.2. PCB Usage: Configuration, Extent, Connection Details

Respondents were asked what shape of PCB was used by their agency, how much PCB they used, and what connection configurations were employed.

Relative to barrier shape, respondents were given the choice of New Jersey, F-shape, Single Slope and "Other", with the "Other" option being exercised by providing a descriptor of their design. A total of 40 respondents answered the question, while 4 did not answer for unknown reasons. The New Jersey shape was found to be most commonly employed by agencies, followed successively by the F-shape and Single Slope (see Figure 20). In Montana, the New Jersey and F shapes are primarily used. Note an agency may employ more than one barrier design. Additional text responses regarding barrier shapes in use were:

- F-shape is preferred, New Jersey is acceptable per FHWA acceptance letter [Alaska]
- F-shape and single slope are used for special circumstances only [California]
- Proprietary shapes such as the ZoneGuard [Pennsylvania]

- WE MOSTLY RENT PCB [Oklahoma]
- Michigan DOT currently allows any PCB design that meets or exceeds NCHRP 350, TL-3 or MASH, TL-3, and meets the following requirements: (1) Tested impact deflection must not exceed 6.5 feet. (2) The bottom width of PCB segments must not exceed 28 inches. (3) The top of PCB segments must be flat and at least 6 inches wide.
- F-shape is current design. Switched from NJ to F-shape in 1997. [Iowa]
- Colorado designates it [New Jersey shape] as Type 7 [Colorado]

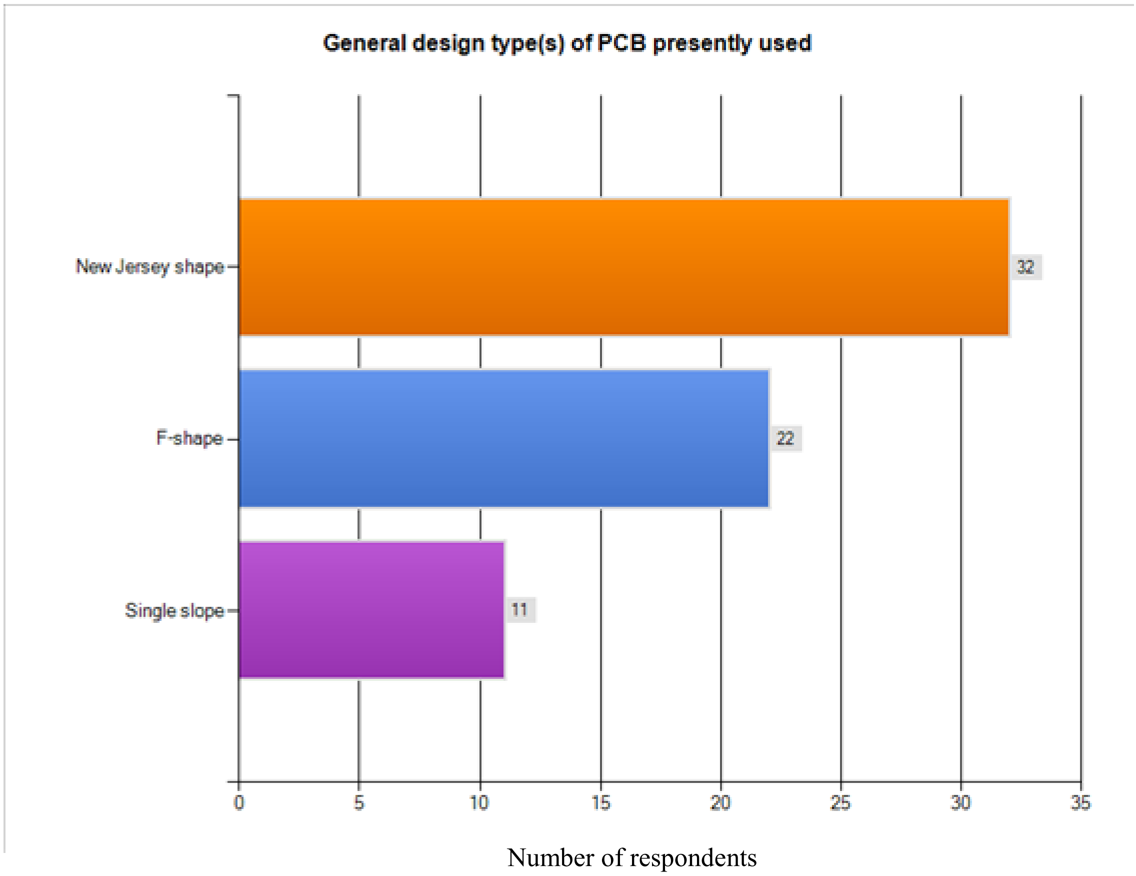


Figure 20: Types of barriers in use

Respondents were asked approximately how many miles of PCB were in use in their state. A total of 38 respondents answered the question, while 6 did not answer for unknown reasons. The results of this question are presented in Figure 21. The results indicate in general, agencies either use PCB to a significant extent (100+ miles) or a limited extent (20 or fewer miles), with fewer agencies using an intermediate quantity of PCB (20 to 100 miles). As noted earlier in this report, Montana has approximately 140 miles of PCB in place.

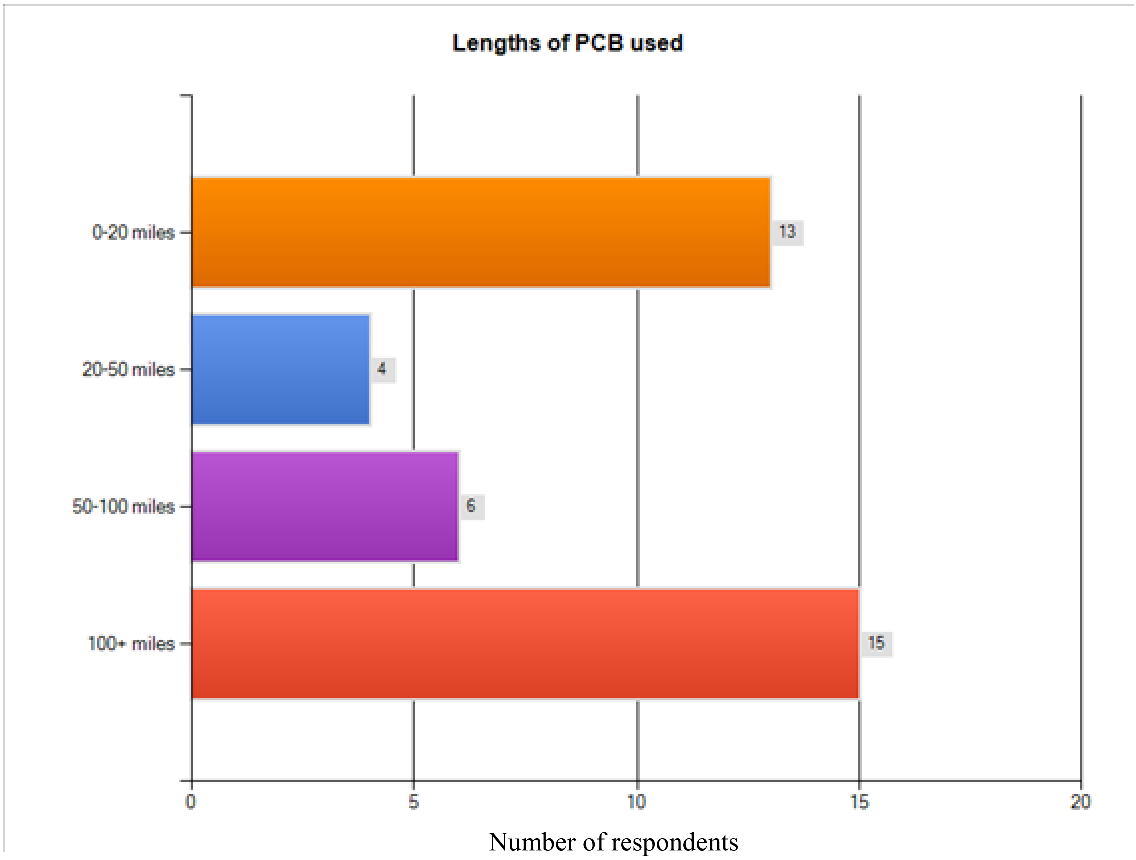


Figure 21: Extent (miles) of PCB use

Respondents were next asked about the types of connection systems used with their PCB. A total of 39 respondents answered the question, while 5 did not answer for unknown reasons. As in the case of barrier shape, respondents were given the choice of specific systems (pin and loop, JJ hooks, H-shape key, T-Loc system, X-bolt, and QuikBolt), as well as the option of specifying another system. The results presented in Figure 22 indicate pin and loop connectors are almost universally used by agencies, and MDT also currently uses this connection type. This corresponds to the body of PCB literature, which frequently mentions the use of pin and loop connections. JJ hooks were used by a moderate number of agencies, while remaining connection systems such as the cross (X) bolt, H-shaped key, T-Loc and QuickBolt were used in limited numbers. Slot and rebar grid/plate systems were also indicated in supplemental text responses by three states. In some cases these are proprietary systems, while in others, they have been developed by a specific state, which may explain their lower usage. Note an agency may employ more than one connection system, based on specific needs. Additional text responses provided the following information regarding connection systems:

- Channel splice, Vertical I beam, Lapped joint [unspecified name/agency]
- Pin and Loop is not the cable variety, solid bar connectors. Our design is substantially the same as Oregon. Our Standard Drawing G-46is on line at: http://www.dot.state.ak.us/stwddes/dcsprecon/stddwgspages/guardrail_eng.shtml [Alaska]

- Generic slot and plate PennDOT Standard Drawing. ftp://ftp.dot.state.pa.us/public/Bureaus/design/PUB72M/RC-57M.pdf ; Proprietary systems (ZoneGuard, Vulcan Barrier, BarrierGuard, others) ftp://ftp.dot.state.pa.us/public/pdf/BOCM_MTD_LAB/PUBLICATIONS/PUB_35/Bulletin15.pdf [Pennsylvania]
- For single slope barriers, we use a slot at each end of each barrier segment. A rebar grid is placed in the slot to bridge the barrier joint. For permanent installations, the slot is filled with grout. Single slope barrier is rarely used for temporary situations. In these instances it is sometimes staged in one location during construction activities, and then set permanently in its final position in the final stages of a project. [Washington]
- See our G-2- series of standard drawings at http://itd.idaho.gov/design/StandardDrawings.htm [Idaho]
- Michigan DOT currently allows any PCB design (including connections) that meets or exceeds NCHRP 350, TL-3 or MASH, TL-3, and meets the following requirements: (1) Tested impact deflection must not exceed 6.5 feet. (2) The bottom width of PCB segments must not exceed 28 inches. (3) The top of PCB segments must be flat and at least 6 inches wide. [Michigan]
- bar loops only, no cable wire permitted [Utah]
- All barrier provided by contractors must meet MASH or NCHRP-350 TL-3 [Wyoming]
- Rebar grid [Texas]

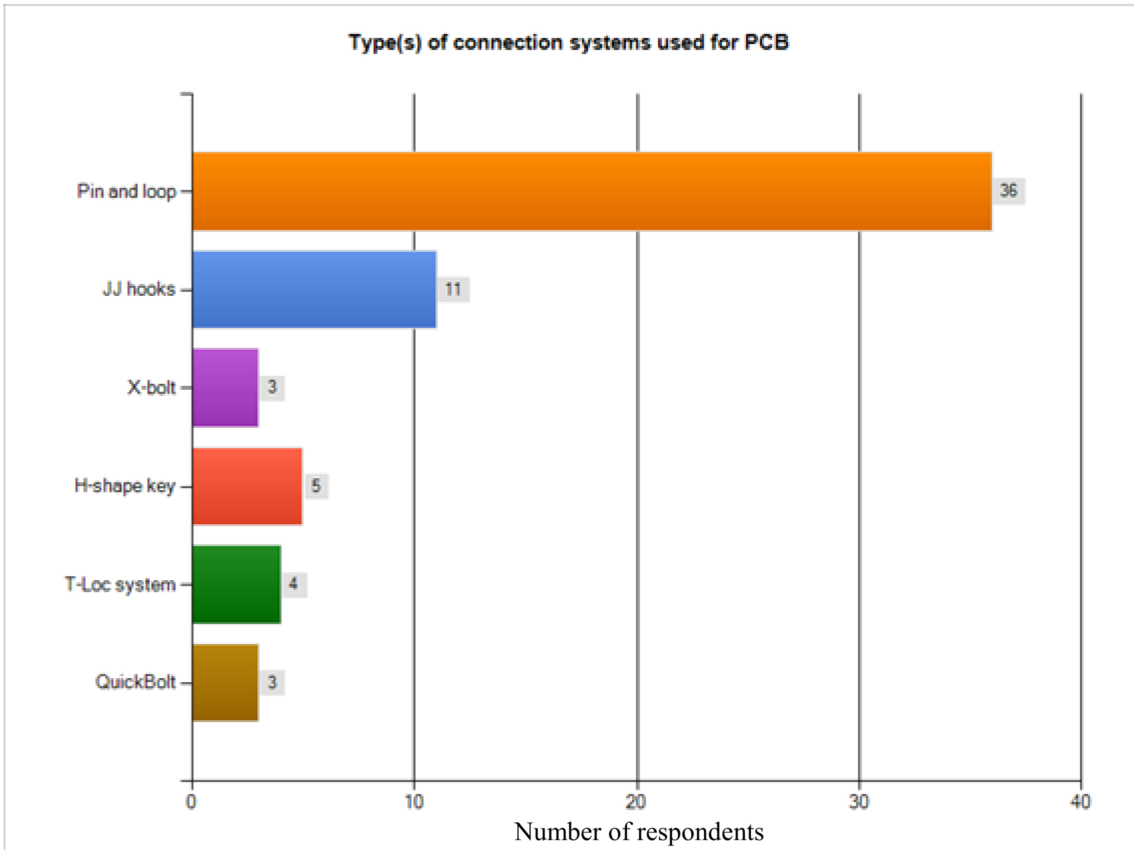


Figure 22: Types of connection systems in use

A follow-up question asked how many loops were used for pin and loop connections. A total of 34 respondents answered the question, while 10 did not answer for unknown reasons. A majority of respondents (20) indicated that 2 by 2 loops were used (i.e. two loops on each barrier end). Other loop configurations included 3 by 3 (6), 3 by 2 (5), and 4 by 4 (2). For reference, Montana presently uses both 2 by 2 and 3 by 2 loop connections.

Responses to the types of materials used to form loop and pin systems are presented in Figure 23. A total of 37 respondents answered the question, while 7 did not answer for unknown reasons. Respondents were provided the material choices of smooth steel, wire rope, rebar, stainless steel, and epoxy coated rebar, as well as the opportunity to specify any other materials they may use. As the figure indicates, smooth steel bar was the most commonly used material, followed by rebar. Materials such as wire rope, stainless steel and epoxy coated bars were less frequently used. Additional comments provided by respondents indicated two agencies use galvanized steel. In the case of stainless steel, galvanized steel and epoxy coated materials, cost may play a factor in their limited use. In Montana, wire rope and rebar are the primary materials used in forming connection systems. Additional text responses provided the following information regarding connection system materials:

- The (4"x4"x1/2") Tube Steel is ASTM A500, Grade B or C on each end of the PCB is connected by a 1/2" thick H shape Key. [New Jersey]
- Rebar is older PCB, Smooth steel is current standards [Oregon]
- MwRSF [Midwest Roadside Safety Facility] is going to crash test a barrier using ASTM A36 next week at the pooled fund meeting [Wisconsin]
- Metal Plate: ftp://ftp.dot.state.pa.us/public/Bureaus/design/PUB72M/RC-57M.pdf Other proprietary systems [Pennsylvania]
- Galvanized 3/4" steel rods [Mississippi]
- 1" diameter 30" long galvanized steel rod with 4" typ. thread both top and bottom [Connecticut]
- Some of our earliest installations may have used rebar - not estimate on the quantity. [Washington]
- A-36 loops with A-36 drop pins no coatings are used. An older 10' system used wire ropes and A-36 drop pins, 2x2 configuration which failed NCHRP 350 but was acceptable under the older NCHRP 230 testing procedure. [Idaho]
- Any connection design on PCB that meets or exceeds NCHRP 350, TL-3 or MASH, TL-3, and meets the following requirements: (1) Tested impact deflection must not exceed 6.5 feet. (2) The bottom width of PCB segments must not exceed 28 inches. (3) The top of PCB segments must be flat and at least 6 inches wide. [Michigan]
- Smooth bars (current), rebar (old), wire rope (long ago) [Iowa]
- We will be considered the use of galvanized steel bar. [Puerto Rico]
- 3/4" rebar for the loops, 1" smooth pin. [Colorado]
- Larg3 Bolt (1.5" diameter) with a nut and washer on the end. [Georgia]

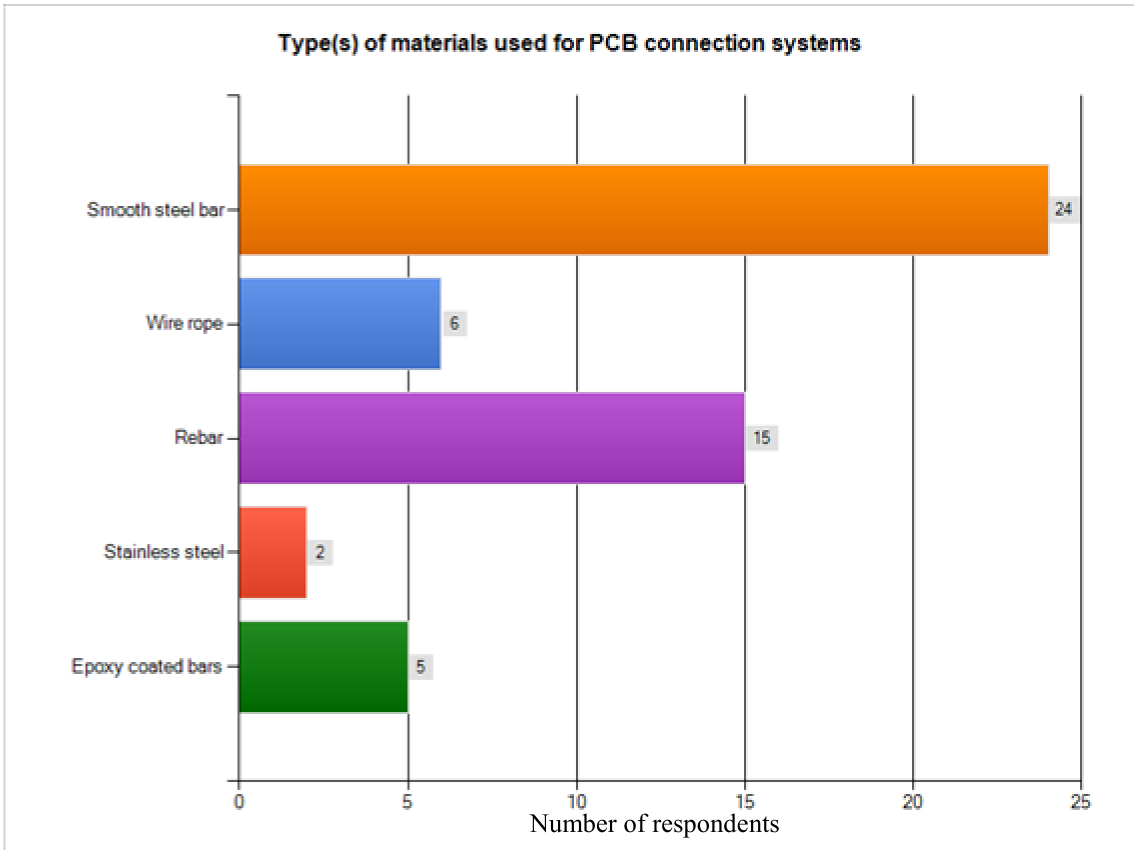


Figure 23: Types of materials used to form connection systems

3.3. NCHRP 350/MASH (TL-3) Compliance

Respondents were asked whether the PCB used by their agency was compliant with NCHRP 350/MASH (TL-3) criteria. A total of 41 respondents answered the question, while 3 did not answer for unknown reasons. As shown in Figure 24, a majority of agencies indicated their PCB was compliant with NCHRP 350/MASH (TL-3) criteria. While a small portion of respondents indicated their agency's PCB was not compliant, a larger portion was unsure. MDT indicated that it is unknown whether existing two loop PCB is NCHRP 350/MASH compliant, but the three loop system used by the state is compliant. These respondents provided the following comments regarding their agency:

- We are still actively working to replace Median T&G PCB. [Oregon]
- We switched to our barrier design completely about three years ago. MwRSF barrier has been crash tested in various configurations [Wisconsin]
- Recent in-house research has prompted an update to our staking configuration details. We used to allow CMB to be staked on the non-traffic side only. Research indicates that this is not as safe as staking on the traffic side only (less lean of the CMB). [California]
- FDOT has some PCB that is being phased out in July 2012 [Florida]
- We did test our NJ barrier with wire rope pin & loop connections 2x2 under NCHRP 350 and passed the testing criteria. Unsure on what percentage if any, is of a different design. Estimate it is not often encountered. [Washington]

- Our old 10' concrete barrier constitutes about 93% of our in use concrete barrier, and about 30% of our guardrail system. [Idaho]
- everything installed after 2000 should be 350 compliant, pre 2000 will be 230 [Utah]
- There may be some very old installations (less than 5%) that are not NCHRP 350 compliant. [Iowa]
- 2% is not compliant. [Puerto Rico]

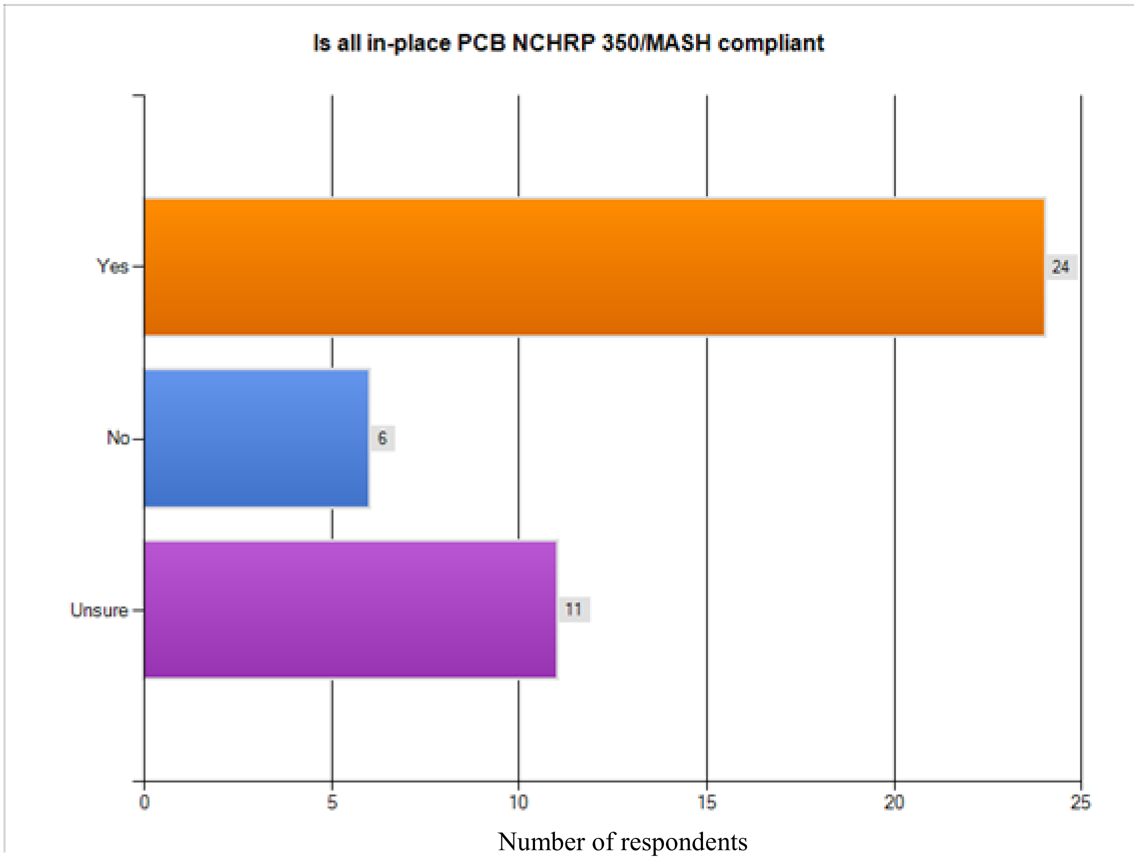


Figure 24: Barrier compliance with NCHRP 350/MASH (TL-3) criteria

3.4. Corrosion Issues

Of specific interest to this work was whether other agencies had experienced any type of corrosion to their PCB connection systems. To this end, respondents were asked whether their agency had ever experienced any corrosion to PCB connection systems. A total of 40 respondents answered the question, while 4 did not answer for unknown reasons. The majority of those responding (28) indicated no corrosion issues had been identified. Twelve respondents (representing 11 agencies) indicated their agency had found corrosion in PCB connection systems. The agencies indicating they had experienced a corrosion issue included New York, Wisconsin, Washington, Utah, Iowa, Puerto Rico (2 responses), Wyoming, Colorado, Louisiana, Texas and one respondent did not indicate their state/agency. MDT has also identified connection system corrosion in the field, which was the motivation for the work discussed in this report. Respondents indicating corrosion had been experienced were directed to a series of questions asking for further details, while those who responded it had not been an issue advanced to a later portion of the survey.

3.5. Transition Plans, Retrofit Methods, Disposal, and Replacement

One of the major objectives of this effort was to determine if other states had developed and executed plans to transition away from or to particular barrier or connection systems in light of performance issues they may have encountered. The motivation for this question stemmed from MDT's need to establish such a plan or program. Activities included in any such transition plans could include retrofit of deficient connections and disposal of retired barrier sections. Further, as part of such a plan, agencies could elect to move away from PCB use altogether, and realize its function using alternative systems (e.g. guardrail). Consequently, questions were posed to the 12 respondents who previously indicated their agency had experienced a corrosion issue with connection systems on these issues.

Relative to a question on any transition plans that may have been used, responses were as follows:

- Problem was anonymous barriers inadequately reinforced. New standard required maker's name be cast into each unit to build responsibility trail. Most barriers are contractor owned. Requirement was announced in 2007 with a compliance date of 2015 to allow current anonymous barriers to be "used up". After 2015, unmarked barrier will not be accepted for use on our projects. Maker's markings began being bought in 2007. [New York]
- Wisconsin only uses precast barrier for temporary construction. However we did have some issues with the quality of the temporary barrier and product construction guidance on this topic. Wisconsin did have some issue with its cast in place permanent concrete barrier as well. However, we recently switched to a single slope design based on Caltrans crash testing. [Wisconsin]
- We have had a project or two that replaced barrier in one area that was found to have deteriorated loops. I don't believe we have tried to retrofit/repair the existing barrier segments. [Washington]
- We are not replacing our older concrete system. I am not aware of any maintenance problems with corrosion on any of our 3 concrete barrier systems. Barrier sections that are in place are when damaged replaced in kind. [Idaho]
- Cable wire loop barriers have to be replaced when moved, if they are not touched they can stay in place and a retro-plate is installed at the joints. [Utah]
- Iowa has VERY few permanent installations of PCB. Contractors own the overwhelming majority of PCB and they use them on a temporary basis on their construction projects. If problems are identified (such as connection system breakage or concrete breakage), the contractor is required to remove that section from the job. There has not been a systematic replacement program put in place. The old PCBs are allowed to be used until they are no longer structurally sound or their connections are no longer compatible with other segments. [Iowa]

- WE REPLACED THE SYSTEM ON MULTIPLE YEARS, PRIORITIZE THE NHS SYSTEM. [Puerto Rico]
- We have not considered a replacement program. We established an expiration date (September 30, 2011) to limit the use of temporary barriers with H-Beam and Re-Bar as connection system in Non-NHS road projects. In NHS road project, the connection systems with H-Beam and Re-Bar with Strands in temporary barriers are not permitted in our projects. [Puerto Rico]
- Replace as needed when the toll of collisions makes the barrier a hazard and ineffective. [Colorado]
- No specific program in place [Wyoming]
- We have switched from a NJ shaper to an F shape and we still use the NJ shape if they are deemed to be in good condition. Any new shapes produced for new projects are all F shape. [Louisiana]

As this information indicates, agencies have taken different approaches to addressing barrier/connection replacement because of corrosion and other damage. One approach is spot replacement when corrosion is identified leaving existing barriers/segments in good condition in place. Another approach is to leave the barrier section with a specific type of connection (e.g, wire rope) in place, but strengthening the joint between barriers with additional connection material (steel plate), representing a type of retrofit strategy. Finally, a prioritized approach was also employed, focusing on National Highway System routes for initial replacement, although the replacement along other routes was not discussed. To date, MDT has also followed the spot replacement approach, addressing individual barrier segments as needed.

On the issue of what retrofit techniques agencies may have used to repair deficient connections, seven respondents provided feedback:

- Not done. [New York]
- If our precast temporary barrier is bad, the contractor has to replace it. [Wisconsin]
- All three of our concrete barrier systems were designed to be interchangeable. [Idaho]
- See above answer [Cable wire loop barriers have to be replaced when moved, if they are not touched they can stay in place and a retro-plate is installed at the joints. You can email me for the drawing.] [Utah]
- N/A [Iowa]
- The temporary barriers with H-Beam and Rebar with Strands in connection systems are not permitted in our projects. We established an expiration date (September 30, 2011) to limit the use of temporary barriers with these connection systems in Non-NHS road projects. [Puerto Rico]
- N/A [Colorado]

As these responses indicate, it appears no agency has performed an operation where corroded connections are removed and replaced with new materials. This conclusion is supported by the lack of such discussion in the body of literature. MDT also lacks such an approach, which was the motivation for the question. The lack of retrofitting operations may be the result of concerns regarding crashworthiness following retrofit, and the integrated nature of connection systems with the rebar grid internal to barrier segments and thus the expense involved in working on such a connection (it may be cheaper to use an entirely new piece of barrier rather than incur the expense in labor and materials to replace corroded metal parts embedded in concrete).

Given the responses to previous questions indicate barrier is replaced rather than retrofit with new connections, a follow-up question sought to determine what was done with barrier after it was removed from highway use. At present, MDT recycles or disposes of barrier that is replaced, as well as turns it over to private contractors for other use. A total of eight responses were obtained from those respondents who had experienced corrosion issues. Of these responses, five agencies simply “disposed” of old barrier, five crushed the barrier for recycled aggregate, and four reused barrier in applications where crash worthiness was not necessary. In addition, further comments included:

- Generally the contractor's problem. [New York]
- Unknown [Washington]
- If our older barrier segments are removed and are in reusable condition, they are stored in out maintenance yards or other designated locations. They may be used to repair our older system. [Idaho]
- Unknown. These are the contractor's property. [Iowa]

In cases where PCB may have experienced corrosion issues, it was also possible/feasible an agency might replace it with another type of barrier, such as guardrail (this is not done in Montana). A question was posed to respondents from agencies which had experienced corrosion whether PCB had been replaced with another type of barrier. A total of eight responses were obtained, which indicated the following:

- We have few permanent installations of PCB. The few we have are not normally replaced with another system. [New York]
- The only instances I'm aware of were circumstances where PCB in the median was replaced with cast-in-place barriers where travel lanes were added to the median side. This was not bases on issues of barrier deterioration. [Washington]
- Do not know of any. [Idaho]
- N/A [Iowa]
- NO [Puerto Rico]
- No. [Puerto Rico]
- We consider PCB as temporary. We use it mainly for work zones. [Colorado]
- N/A [Wyoming]

As these results indicate, most agencies have not replaced PCB with another type of barrier, in part because it is used in a specialized application (work zones), or it has been replaced by a permanent concrete barrier.

3.6. Corrosion Detection and Evaluation

In order to address corrosion, it must first be detected, its nature and extent determined, and the associated causative mechanisms established. To these ends, respondents were first asked how corrosion was first discovered or detected. The ten respondents (note some respondents did not answer all questions in this portion of the survey) that previously indicated their agency had experience with corrosion provided feedback on this question, with responses presented in Figure 25. Interestingly, six respondents indicated corrosion was not an issue, despite previous answers to the survey indicating corrosion had been found which directed them to the corrosion-specific series of questions. For agencies where corrosion was found, this was made by random observation in three cases, as part of another activity such as reconstruction in two cases, as part of PCB inspections in one case and as the result of accidents in one case. This corresponds to MDT experience, where corrosion was identified during reconstruction activities. Further comments provided by respondents included:

- I do not know of any corrosion issues. [Idaho]
- Accidents [Utah]
- I am not aware of any corrosion issues. [Iowa]

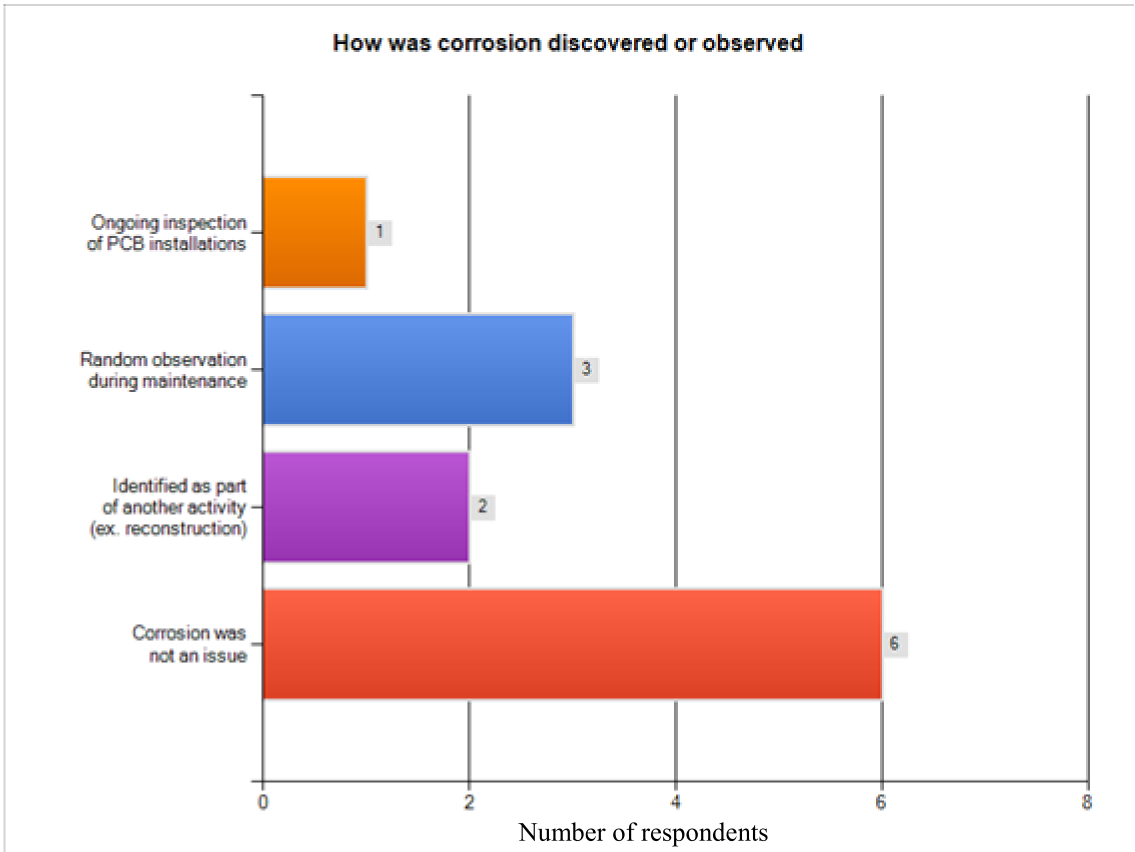


Figure 25: Corrosion discovery and observation approaches

On the subsequent issue of corrosion evaluation, the literature review found no information regarding ranking or rating systems for characterizing or quantifying the extent of corrosion experienced specifically on PCB connection systems. Therefore, the question was posed to respondents that indicated their agency had experienced PCB corrosion asking them to describe any type of ranking or rating system which was employed to characterize corrosion (MDT had no such approach prior to this work). A total of six respondents answered the question, providing the following information:

- See section 1.45.12 of the following link http://roadwaystandards.dot.wi.gov/standards/cmm/145.pdf. For permanent barrier see section 11-45-2.5.3 of the following link http://roadwaystandards.dot.wi.gov/standards/fdm/11-45.pdf [Wisconsin] (Researcher notes: The first document provided guidance on when barrier may be used in temporary applications. The second link provided information on when permanent applications may need to be replaced or upgraded. Included in this discussion was a list of conditions that warrant attention, including "Concrete barrier has exposed or rusted reinforcement", although this does not constitute an approach to ranking (Wisconsin DOT, 2011).

- No. [Washington]
- None [Utah]
- No apply. [Puerto Rico]
- No specific system [Wyoming]
- Not being done at this time. [Louisiana]

As the responses indicate, no agency appears to be employing any type of rating or ranking system related to PCB connection corrosion. It could be surmised the presence of corrosion is something which agencies do not necessarily believe needs to be characterized, but rather, if it is viewed to be severe, it is dealt with (e.g., barrier section replaced) and if it appears minor, it is monitored.

Next, respondents who indicated their agency had experience with PCB connection corrosion were asked whether the cause(s) of that corrosion was identified and what it was. A total of four respondents answered this question, providing the following information:

- No. [Washington]
- environmental issues and use of salt [Utah]
- No apply. [Puerto Rico]
- Winter maintenance materials (salt/sand, chemicals) [Wyoming]

As these limited responses indicate, the source of corrosion was either unknown/unidentified, or was the result of winter maintenance materials, specifically salt. These responses correspond to MDT experience, where winter maintenance materials and weather conditions were believed to be the cause of corrosion. This also corresponds with the mechanisms of corrosion discussed earlier, specifically corrosion caused by selective leaching.

As a follow-up to the previous question, respondents were asked what the level of winter maintenance chemical usage was at locations where PCB connection corrosion was identified. A total of 4 respondents answered this question, providing the following information:

- Deicers were not routinely used in the locations replaced. Another location has materialized where deicers may have been user more frequently. [Washington]
- Unknown [Utah]
- No apply. [Puerto Rico]
- generally a small usage [Wyoming]

With the exception of Puerto Rico, each of the responses was from an agency which performs winter maintenance operations to varying extents. For the two responses that provided background information, it would appear deicing materials (e.g.. salt) were not extensively used. Whether this indicates another corrosion mechanism was at work or even a minimum amount of deicing materials led to the corrosion of metal (likely untreated) is not clear. For reference, MDT has used anti-icers and deicers at the locations which experienced corrosion, although specific quantities were not readily known.

Connection corrosion activity could possibly be biased based on connection type and material. Therefore, respondents that indicated their agency had experience with connection corrosion were asked what type of connections had experienced the corrosion. Four respondents indicated corrosion had occurred on a pin and loop system, while an additional two provided the following feedback:

- wire cable loops [Utah]
- No apply. [Puerto Rico]

The feedback to this question, while limited, was expected based on the previous information provided by respondents indicating pin and loop connections were the most frequently used.

A follow-up question asked what materials were used for the connection systems that had experienced corrosion. As Figure 26 indicates, corrosion occurred to smooth steel bar at one agency, wire rope at two agencies and rebar at one agency. These results are not surprising, as each of these materials when left untreated is susceptible to corrosion. While presented as additional choices, stainless steel and epoxy coated bars were not indicated as experiencing corrosion. Although the small sample size does not preclude the possibility, it is unlikely these materials would have experienced significant corrosion (outside of material defects) given that they are specifically used to mitigate corrosion. In addition to the responses presented in Figure 27, Puerto Rico provided textual information indicating none of the materials applied to its case.

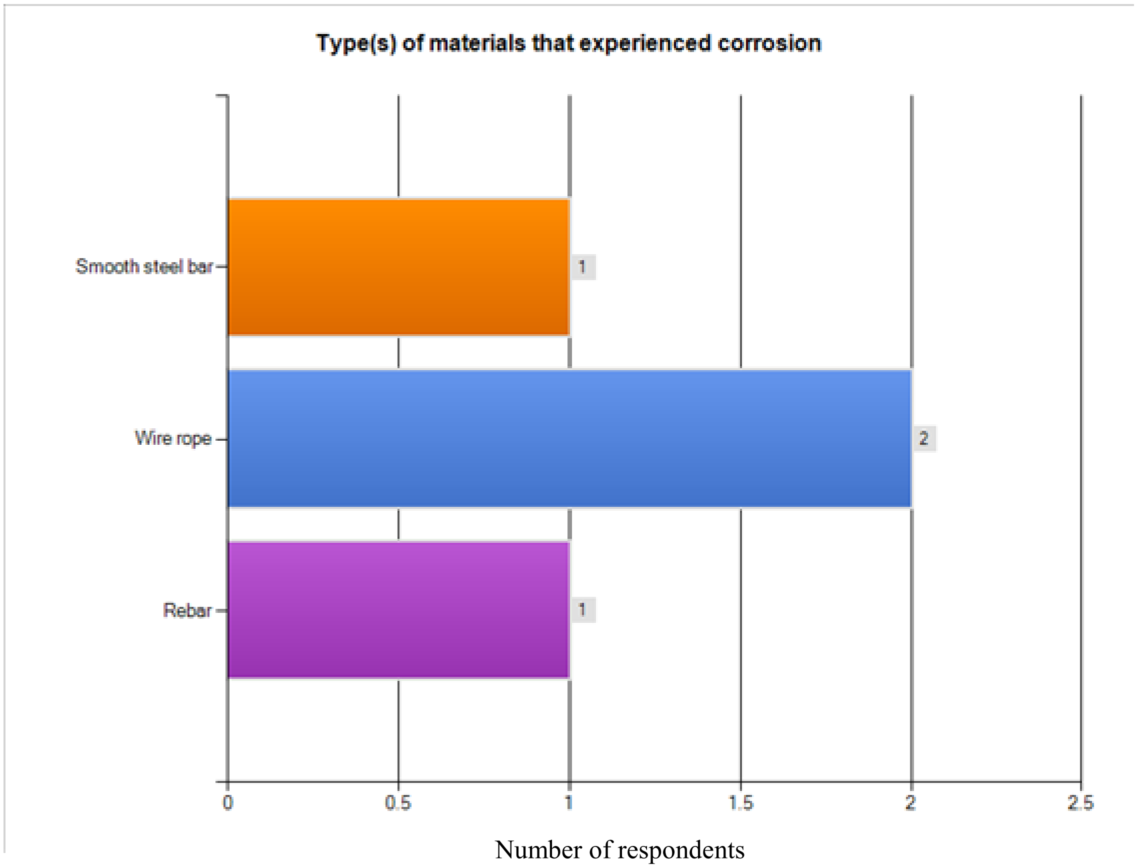


Figure 26: Materials used in corroded connections

3.7. Corrosion Prevention

Following the corrosion-specific section of questions, all survey respondents were presented with a remainder of general questions regarding PCB connection systems. First, respondents were asked whether their agency had applied any treatments (e.g.. coating and inhibitors) to prevent connection system corrosion. For reference, MDT did not indicate the use of any treatments to prevent corrosion. A total of 39 respondents answered this question, with 5 respondents indicating they had used treatments to prevent corrosion, while 30 indicated their agency did not use them (see Figure 27). This is somewhat surprising as one explanation for corrosion generally not being seen as a problem is that the connections have been treated. Obviously, this is not the case.

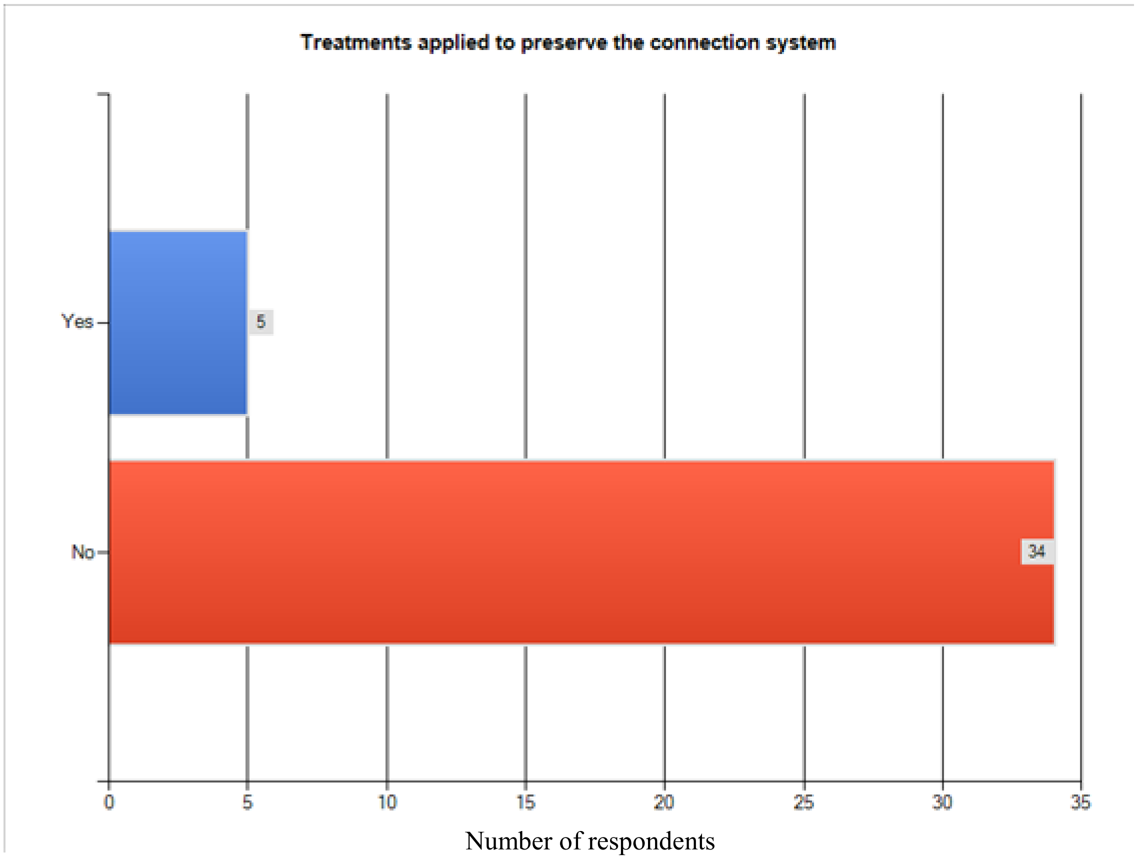


Figure 27: Were treatments used to prevent corrosion

Next, respondents were asked what types of treatments had been used. Choices consisted of epoxy coatings and zinc, as well as an option to specify other treatments. A total of six (note the discrepancy between this figure and the previous question where five agencies used treatments) respondents indicated their agency used zinc. Text responses to this question were:

- None. [New Jersey]
- Our CMB is not used as a long-term barrier. Generally less than 3 years and as long as about 5 years. [California]
- Galvanizing [South Carolina]
- N/A [Iowa]
- No apply. [Puerto Rico]
- Pins and loops are hot dip galvanized [Colorado]

As these responses indicate, galvanizing was another approach used for corrosion prevention treatment.

Respondents were asked whether there were any locations where corrosion to PCB connections has not been an issue. A total of 32 responses were provided to the question, with 26 respondents indicating there were locations where corrosion had not been an issue, while the remaining 8 responses indicated there were no such locations. MDT also has found that there are locations in their system where corrosion is not an issue.

When asked what types of connection systems did not experience corrosion, the majority of responses indicated pin and loop systems (MDT indicated likewise), as shown in Figure 28. This was expected given the majority of agencies previously indicated this system was widely used, and also indicated connection corrosion was not an issue they experienced. In addition to these results, further information provided by respondents consisted of:

- Key is thick enough for a little corrosion not to be a problem within the normal rough and tumble life of a temporary concrete barrier. [New York]
- I need to add a comment here...sorry....relating back to Question 9. To my knowledge we haven't had corrosion failures associate with our metal bar pin and loop design. It could be that the old style wire rope loops which were in use previously could have damage and or corrosion issues. I'm not familiar with those. That type of connection should not be used on our roads now. [Alaska]
- ftp://ftp.dot.state.pa.us/public/Bureaus/design/PUB72M/RC-57M.pdf Proprietary systems just approved and being deployed this construction season. No history yet. Our generic in-house slot and plate design does not appear to have any problems with corrosion. [Pennsylvania]
- I am unsure if corrosion has been an issue [Mississippi]
- with smooth bar [Utah]
- It is my understanding that corrosion has not been an issue with our current design. [Iowa]

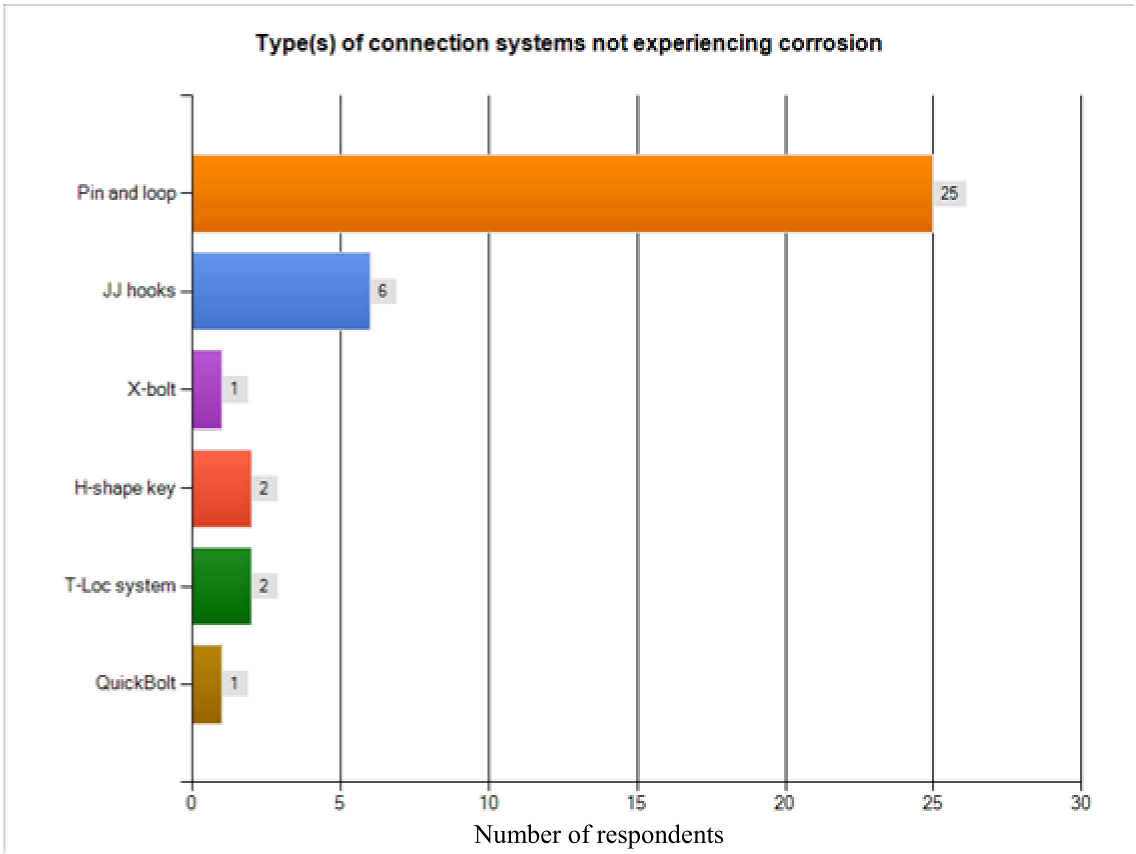
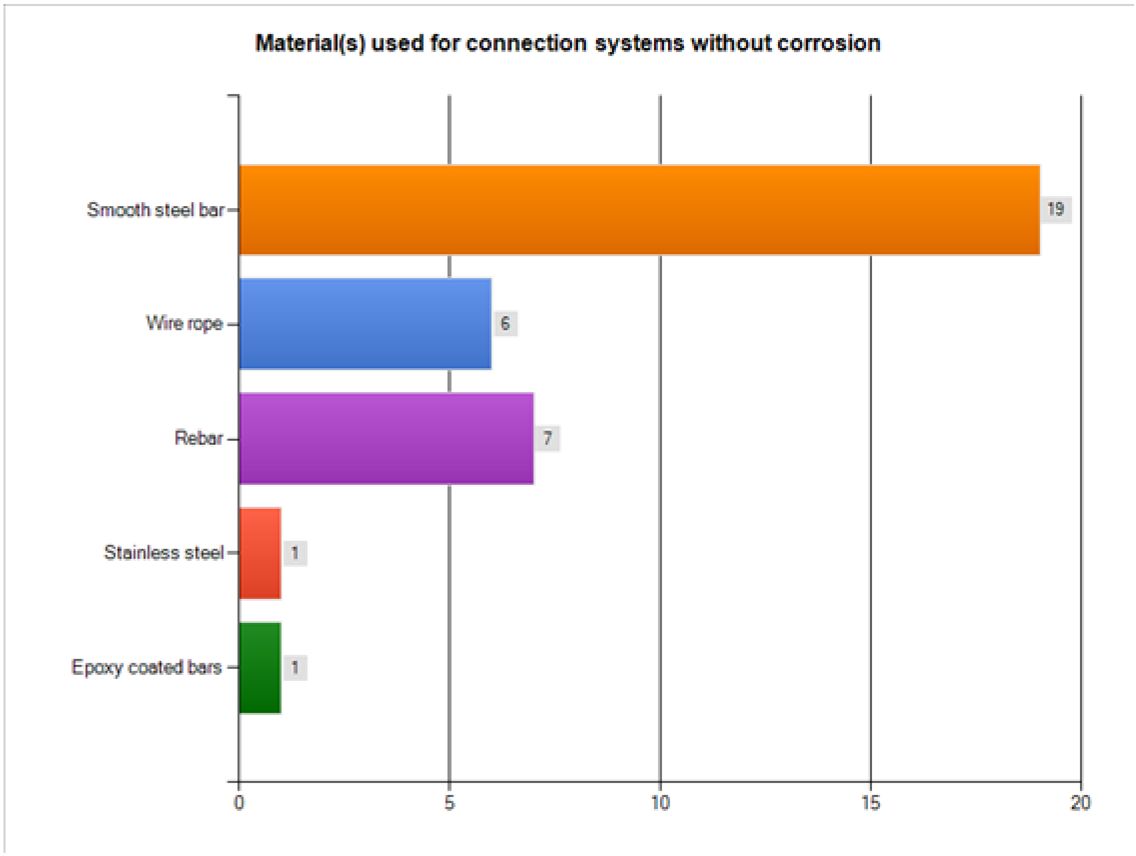


Figure 28: Types of connections that did not experience corrosion

Respondents were next asked what materials were used for the connection systems that had not experienced corrosion. As before, respondents were given the options of smooth steel bar, wire rope, rebar, stainless steel and epoxy coated bars, and the opportunity to identify other materials. A total of 25 respondents answered this question, with the majority indicating their agency used smooth steel bars in their PCB connections, as shown in Figure 29. Just as indicated previously, MDT materials at such locations included wire rope and rebar. Wire rope and rebar were also used to varying extents, while stainless steel and epoxy coated bars saw limited use. In addition, the following comments were provided regarding materials:

- The (4"x4"x1/2") Tube Steel is ASTM A500, Grade B or C on each end of the PCB is connected by a 1/2" thick H shape key. [New Jersey]
- Bent plates for JJ Hook [Florida]
- Threaded rods [Texas]



Number of respondents

Figure 29: Materials for connections that did not experience corrosion

3.8. Environmental Conditions

Respondents were asked to characterize the environmental conditions that PCB and its connections were exposed to while in service. A total of 27 respondents provided feedback to the question. This question required a textual response, and the responses received consisted of the following:

- None [New Jersey]
- All the above. Coastal on Long Island. Rain, snow, ice, and salt everywhere. [New York]
- Oregon is "salt free" state. We still use 1/4-10 aggregate and MgCI de-icer, freeze Gard Plus [Oregon]
- Rain and snow. Some salt for winter maintenance. [Nevada]
- lots of rain with mild temps in winter, mag used as deicing agent when needed [Oregon]
- Rain, snow, ice, dust, sea salt spray, road salt/chemical application. Not saying we don't have corrosion issues just am not aware, and or the duration of installations are short enough to not be a problem. [Alaska]
- Rain and some coastal areas. Snowfall is insignificant in our state and therefore salt usage is not a factor. [South Carolina]
- coastal, mountain, forested (shaded) areas are the most difficult [California]
- Most installations are temporary during construction and are installed by contract. Chemical usage is minimal. PCBs are exposed to the elements. [South Carolina]

- All varieties of precipitation and use of road salt during winter. [Pennsylvania]
- all the above [rain, snow, coastal areas] {Maine]
- Rain, snow, and some coastal areas. We use to use sand and salt application for roads during the winter season. We now use calcium chloride. [Connecticut]
- Rain and coastal areas. [Florida]
- Rain, snow, very little salt used in our area. 4 to 6 ton per year. [Alaska]
- Temporary installations that remain in place over a winter period are exposed to normal Illinois weather (ex. rain, snow, road salt). However, not all of our installations are in place over a winter period. [Illinois]
- Salt and other ambient conditions experienced in interior Alaska. [Alaska]
- Rain and snow (statewide in Michigan). Extensive use of salt on roadways for deicing in winter months. [Michigan]
- Mild [Arkansas]
- The environmental conditions & chemical usage include; rain, snow & salt for winter maintenance. [Nebraska]
- typical environments, rain snow, desert conditions [Utah]
- Coastal areas. [Puerto Rico]
- We get a lot of snow and ice here in the Midwest, so we use various salt/brine treatments. [Ohio]
- NDDOT uses PCB for construction and not too often are they utilized during winter months. Environmental conditions consist of rain and normal summer roadway conditions. [North Dakota]
- Mountains and Plains. Less than 14" moisture per year on average. Colorado is a snow state averaging 50" per year. We have migrated away from Salt/Sand to Mag Chloride Liquid and solid. [Colorado]
- Rain, coastal areas, high humidity, very hot temperatures. [Louisiana]
- PCB are used all over the state, from coastal to desert conditions. [Texas]
- Rain, snow, salt applications [Washington D.C.]

As these responses indicate, PCB is being used in a wide variety of environmental conditions. This is true of use in Montana as well, where PCB is employed on mountain passes, as well as in the plains. Given the low number of responses that indicated a corrosion issue had been detected, it would appear either states have not yet identified/encountered any potential issues (e.g., through reconstruction or inspection), or the materials and treatments being used in PCB connections are proving effective in preventing corrosion.

3.9. Corrosion-Prevention Maintenance Practices

Respondents were asked whether their agency engaged in any maintenance practices (aside from materials and treatments) to prevent PCB connection corrosion. A total of 25 responses to this question were provided:

- None [New Jersey]
- No. [New York]
- Nothing in place from a maintenance standpoint [Oregon]
- No [Nevada]

- At times we wash barrier, and spray for vegetation management. [Oregon]
- None that I am aware of. [Alaska]
- No. [South Carolina]
- CMB is inspected before use. California does not promote long-term installation of CMB due to spalling, cracking, and unseen corrosion potential. [California]
- No. Most are contractor owned. [South Carolina]
- No [Connecticut]
- No. [Florida]
- No. [Alaska]
- Illinois does not have any special maintenance practices [Illinois]
- None [Alaska]
- No. [Michigan]
- No [Arkansas]
- No [Nebraska]
- Unknown [Utah]
- We have not a maintenance practice to prevent corrosion. [Puerto Rico]
- No [Ohio]
- None [North Dakota]
- N/A [Colorado]
- No [Wyoming]
- No. [Louisiana]
- Seasonal Washing of entire barrier and connection system with straight water [Washington D.C.]

As these responses indicate, agencies almost universally do not employ any special maintenance practices to prevent corrosion to PCB connections. Montana practice is consistent with this as well. Interestingly, Washington D.C. and Oregon both wash their barrier as a maintenance practice, although in the case of Oregon, this is done for vegetation management as opposed to corrosion prevention. Still, it would appear most agencies do not undertake periodic activities to prevent corrosion.

3.10. General PCB Maintenance

Finally, respondents were asked whether their agency performed any general maintenance activities on PCB. A total of 23 responses were provided to this question. These responses were textual in nature and consisted of the following:

- Typically the portable barrier is damaged by handling and taken out of service prior to issue with corrosion. [New Hampshire]
- None [New Jersey]
- NYSDOT does not maintain as contractors own all of what is used in work zones. [New York]
- None [Nevada]
- Ideally, PCB are temporary installations, though occasionally they stay in place a long time. I can't recall any sort of scheduled or planned maintenance associated with PCB. [Alaska]

- Corrosion is not an issue in our state therefore we do not employ any special maintenance programs. [South Carolina]
- PCB is maintained by the contracts working for the State. CMB is inspected on a per-job basis. [California]
- No specific maintenance process. [South Carolina]
- We do not have one [Florida]
- Realignment after vehicular impacts. [Washington]
- Only real maintenance is keeping them straight from accidents. [Alaska]
- Most of our barrier is contractor furnished. When barrier becomes unfit for use, we terminate its use. [Illinois]
- None [Alaska]
- Michigan DOT personnel tend to use the ATSSA Quality Guidelines for Temporary Traffic Control Devices and Features as a tool to determine if PCB segments are acceptable for use. However, the Michigan DOT does not have specific maintenance guidelines for PCB. [Michigan]
- Very little maintenance required [Arkansas]
- Project manager review of PCBs to remove any having large hunks of concrete missing that may cause snagging if impacted by errant vehicles [Nebraska]
- Unknown [Utah]
- We clean the temporary barrier surface with water pressure equipment and repaint. [Puerto Rico]
- We have an inventory of barriers and when they become damaged they get taken out of service. About 9 years ago we had a few hundred made with a project and they became State property after the project and we use those for future projects. [North Dakota]
- Straighten when hit, replace when damaged. [Colorado]
- Replace existing barriers with new f-shapes when not structurally adequate. [Louisiana]
- Same as above 4 times per year DOT washes barrier system with high pressure water trucks [Washington D.C.]

As these responses indicate, different agencies undertake different types of general maintenance on their PCB. This includes more specific activities, such as washing and painting, as well as routine activities, such as straightening barrier after a crash has occurred or replacing segments as needed. The limited nature of maintenance activities is the result of PCB itself, which is intended to be nearly maintenance free. For reference, Montana maintenance practices consist of activities such as replacement of damaged sections, as well as straightening barrier sections as needed.

3.11. Summary

This chapter has presented the results of a survey of state DOTs which sought information regarding their use of PCB in general, as well as information related specifically to the connection system(s) they use and whether any corrosion to those connection systems has been experienced. In general, respondents indicated PCB was used to varying extents, with most agencies using either less than 20 miles or greater than 100 miles. The difference in usage is likely the result of the specific needs of each particular agency. The New Jersey and F-shape barrier was most commonly used, with pin and loop connection systems being used almost universally by respondents. Only JJ hooks saw any significant usage compared to pin and loop connections. Most agencies used smooth steel bar or rebar to form connection systems. A majority of respondents indicated their PCB was in compliance with NCHRP 350/MASH criteria.

Only 12 respondents indicated they had experienced corrosion issues with PCB connections, although only a portion of these fully responded to the questions specifically posed regarding corrosion. Where corrosion was identified as an issue, spot replacement, the use of additional strengthening and prioritized replacement were the strategies used to address the problem. In no case did an agency remove corroded connections and replace them with new materials, reusing the existing barrier. Instead, barriers were replaced in their entirety with the barrier recycled for aggregate, used in another application (where crashworthiness is not needed) or simply disposed of. In no instance did an agency replace PCB with another barrier system, such as post tensioned guardrail.

Approaches to identifying corrosion varied and included PCB inspections, and casual observation during other activities such as moving barriers after a crash and reconstruction. No agency used a ranking or rating system to characterize corrosion. When corrosion had occurred, it was primarily thought to be caused by the use of winter maintenance materials, specifically salt. However, the usage of such materials at sites where corrosion had occurred was thought to be normal (i.e. not excessive) by respondents. Only limited responses were provided regarding the materials used in connection systems at sites with corrosion. Smooth steel bar, wire rope and rebar were all identified as having experienced corrosion. Interestingly, only four agencies indicated they had treated connections in any way to prevent corrosion, using zinc or galvanizing to do so.

Most respondents to the survey indicated there were locations that they believed corrosion had *not* been an issue, and, once again, pin and loop connections were most commonly used at these sites. Steel bars, wire rope and rebar were commonly used in the connection systems at locations without corrosion. Most agencies employed no maintenance practices, either specific to connection systems or PCB in general to address corrosion. Those that did employ some type of maintenance mainly employed simple actions such as washing and painting, as well as straightening segments after crashes and replacing those which were damaged.

The primary conclusion which can be drawn from the survey is that most agencies have not experienced corrosion with their PCB connection systems. Whether this is because states have not yet identified/encountered any potential issues (e.g.. through reconstruction or inspection), or the materials and treatments being used in PCB connections are proving effective in preventing corrosion is not entirely clear. Most respondents indicated no special approaches or treatments were being used to prevent corrosion, so it may be more likely corrosion issues have not yet been encountered, but there is some potential for them to occur (or already exist). The findings of this chapter reinforce what was observed in the literature review. Corrosion of connection systems is not something many agencies have encountered to date or given much thought to. Whether this means there will be an increased discovery of such corrosion in the future is not clear, as localized climates, maintenance practices (both general and winter maintenance) as well as other factors all may play a role in leading to PCB connection corrosion. Collectively, all of the information provided by respondents confirmed that practices and observations in Montana were consistent with those nationally.

4. CONCLUSIONS AND RECOMMENDATIONS

Precast (or Portable) Concrete Barrier is a movable barrier system which consists of discrete elements connected together in some manner to form a continuous structure. The section-to-section connections are important to system performance, as they provide strength and rigidity to the overall PCB system. Different systems available for use by agencies include pin and loop connections, JJ Hooks, cross bolts, H-shaped keys, grid and slot, and proprietary systems. Many connection systems (i.e. those that incorporate metal in their designs) are susceptible to corrosion, leading to a weakening of the connection itself and potentially having an impact on the overall functionality of the barrier system in restraining a vehicle during a crash.

During a reconstruction project the Montana Department of Transportation discovered the connection system of PCB at the site had experienced potentially significant corrosion. This corrosion is a concern, as it was not expected, it may be present in other locations, and it could impact barrier performance. In addition, there was a question of whether the specific connection configuration used in the past on PCB systems in Montana meets current NCHRP 350/MASH criteria for crashworthiness. Consequently the decision was made by MDT to remove all two loop PCB barrier segments moved as part of any federal aid project and replace it with a three loop system. It was further decided that additional research was needed on this issue to determine if any past research had been done regarding PCB connection corrosion, on PCB in general, the maintenance of barrier connection systems, and approaches to address corrosion on existing and future installations. As a result, the work presented in this report has synthesized available information regarding precast concrete barriers, the corrosion of their connection systems, approaches to rating/ranking corrosion, current state DOT practices regarding PCB maintenance and replacement, and transition approaches for the replacement of barrier. Additionally, a survey was conducted of state DOTs regarding their experience with PCB specifically focused on connection and corrosion issues to obtain a thorough picture of the state-of-the-practice with these systems. The following sections summarize the results of the work and its conclusions, as well as provide initial recommendations of a potential replacement approach which can be employed in transitioning existing barrier systems to new ones in the future.

4.1. Literature Review Conclusions

A review of the general literature on PCB found that a number of different designs (dimensions and shape profiles) are currently in use and have been shown to meet existing crashworthiness criteria. These designs have slightly evolved over time to meet increasingly stringent crashworthiness criteria, although the general purpose of PCB (a substantial mass of concrete joined by different connection systems to contain a vehicle impact) has remained unchanged.

Only a limited portion of the available literature focused on PCB connection systems. These documents tended to focus on discussions of designs, materials and crash testing performance, rather than corrosion or replacement of connections on in-service barriers. In only one instance, specifically in the Roadside Design Guide, was the *potential* (not the observation) for metal connection systems to corrode (due to salt exposure) indicated. Even this mention was brief in nature, being part of a more general overall statement. This absence of discussion of connection corrosion in the body of literature may be indicative of a lack of awareness of the potential for this problem to occur. It could also simply be the result of a lack of work performed on the topic, even if awareness of the issue does exist.

While literature specific to the corrosion of PCB connection systems was not identified in this work, a general discussion of the overall subject of corrosion was compiled to familiarize the reader with different corrosion mechanisms that can impact PCB connections, as well as potential prevention and treatment options. These approaches included the use of coatings and inhibitors.

Only one specific document was found which discussed any aspect of PCB maintenance, and this was specific to ASR, which resulted in the shifting of barrier segments at the joint through expansion. However, this reaction was not corrosion to the connection system but rather, expansion of the grout material placed at the joint. Consequently, it was unclear from the literature, whether any specific maintenance actions were employed by agencies to address or prevent connection system corrosion.

Published work on the in-field performance of PCB systems indicates these systems are effective in reducing the severity of crashes. Finally, a search for replacement or retrofit approaches and strategies for PCB did not yield any results. However, similar approaches from other areas of transportation that may be considered transferable were identified. These included worst-first, systematic and prioritized replacement. The potential application of such approaches in Montana will be discussed later in this chapter. No information on retrofitting existing barrier segments with new connections was found. The lack of barrier retrofit approaches may be the result of inherent difficulties (and thus costs) in working with what typically are cast-in-place connection systems, as well as subsequent unanswered questions about the crashworthiness of the repaired connection. When barriers are replaced, viable recycling and reuse options are available for the PCB sections.

Collectively, the information summarized by the literature review indicated the general state of knowledge on PCB is well established, but its focus is centered on crash testing and crashworthiness. Discussion of PCB connection systems centers on their design and material aspects and how the barrier design they were used in performed during crash testing. Essentially no discussion or recognition is made in the literature of the potential for, or occurrence of connection corrosion. Whether this situation is the result of a lack of awareness of the potential for corrosion or an absence of its occurrence is unclear, although some clarity to these questions was provided by the survey of state practice, summarized in the next section.

4.2. Survey of State Practice Conclusions

A survey of state Departments of Transportation (DOTs) was completed to obtain information on their use and experience with PCB, with a focus on connection system corrosion, whether specific materials had been employed to address or prevent corrosion, maintenance practices employed (both to prevent/address corrosion as well as general activities), whether retrofit or transition plans or programs had been used to address any existing connection system corrosion issue, and what agencies did with barrier segments that had been removed from service.

In general, survey respondents indicated PCB was used to varying extents, with most agencies using either less than 20 miles or greater than 100 miles. The New Jersey and F-shape of barrier was most commonly used, with pin and loop connection systems being used almost universally by respondents. Most agencies used smooth steel bar or rebar to form connection systems. A majority of respondents indicated their PCB was in compliance with NCHRP 350/MASH criteria.

Only 11 agencies indicated they had experienced corrosion issues with PCB connections. Where corrosion was identified as an issue, spot replacement, the use of additional strengthening and prioritized replacement were the strategies used to address the problem. In no case did an agency remove corroded connections and replace them with new materials, reusing the existing barrier. Instead, barriers were replaced in their entirety, with the barrier recycled for aggregate, used in another application (where crashworthiness is not needed) or simply disposed of. In no instance did an agency replace PCB with another barrier system, such as post tensioned guardrail.

Approaches to identifying corrosion varied and included PCB inspections, random observation during activities such as moving barriers after a crash, and identification during other activities (e.g., reconstruction). No agency used a ranking or rating system to characterize corrosion. When corrosion had occurred, it was primarily thought to be caused by the use of winter maintenance materials, specifically salt. Only limited responses were provided regarding the materials used in connection systems at sites with corrosion. Smooth steel bar, wire rope and rebar were all identified as having experienced corrosion. Interestingly, only four agencies indicated that they had treated connections in any way to prevent corrosion, using zinc or galvanizing to do so.

Most respondents to the survey indicated there were locations they believed corrosion had *not* been an issue, and, once again, pin and loop connections were most commonly used at these sites. Steel bars, wire rope and rebar were commonly used in the connection systems at locations without corrosion. Most agencies employed no maintenance practices, either specific to connection systems or PCB in general, to address corrosion. Those which did employ some type of maintenance mainly employed simple actions such as washing and painting, as well as straightening segments after crashes and replacing those that were damaged.

The primary conclusion which can be drawn from the survey was most agencies have not done a great deal in terms of corrosion with their PCB connection systems. This reinforced what was observed in the literature review. Whether this is because agencies have not yet identified/encountered any potential issues (e.g., through reconstruction or inspection), or the materials and treatments being used in PCB connections are proving effective in preventing corrosion, is not entirely clear. In the case of materials and treatments, it would appear this is not the case, as most respondents indicated treatments were not used, and the basic materials employed are susceptible to corrosion. It may be more likely corrosion issues have not yet been encountered, although one would think agencies would be aware of its potential to occur and be looking for it. Whether this means there will be an increased discovery of such corrosion in the future is not clear, as localized climates, maintenance practices (both general and winter maintenance) as well as other factors all may play a role in leading to PCB connection corrosion.

4.3. Final Remarks: Potential Replacement Approaches

A portion of the literature review was dedicated to identifying potential retrofit or replacement approaches which could be used by MDT in addressing connection system corrosion and transition from two loop to three loop connection systems for PCB throughout the state. As the literature review found, no approaches specific to PCB have been documented to date. Responses to the survey indicated three approaches have been used in addressing PCB replacement: spot replacement, strengthening and prioritized replacement. Spot replacement involved removal of a damaged barrier and replacing it with a newly constructed segment.

Strengthening left the existing barrier and connection system in place, but saw the addition of steel strapping across the PCB joints at the base to provide extra strength and connectivity. Finally, prioritized replacement involved the installation of new PCB along higher classification routes (in the case of the respondent, on the National Highway System), before replacement on lower classification routes.

In addition to these approaches, the literature review identified strategies employed for the replacement of other transportation infrastructure that might be considered, namely worst-first. This approach, while similar to spot replacement, would remove the entire length of barrier based on the extent of corrosion observed. The application of such an approach will be more extensively discussed in a following section.

The following sections provide an overview of different replacement/transition approaches which could be used by MDT to address connection system corrosion and/or NCHRP 350/MASH compliance. Note the order of the discussion does not convey the level of applicability or importance of the approach.

4.3.1. Spot Replacement

This approach may be the least feasible for application, particularly if meeting NCHRP 350/MASH criteria is the primary concern. In this application, MDT would replace barrier segments on the basis of whether they are damaged or if corrosion is present. However, it would not address crashworthiness criteria, as the overall PCB system would remain in place. In addition, if the corrosion of connection systems is extensive throughout the segment of PCB, it would be more feasible to replace the entire segment rather than focusing on individual barriers. Consequently, other approaches are more applicable than spot treatment.

4.3.2. Worst-First Replacement

This approach would entail replacement of barrier segments based on the measured condition and extent of the connection system corrosion. In this case, the average corrosion rating/ranking of connections throughout the entire segment would be used to rank the order in which they are replaced. The segment which is rated to be in the worst condition would be replaced first, with segments ranked following that section replaced in corresponding order. This approach allows for the worst segments to be addressed immediately or in the near future, which has an obvious benefit to safety. However, given that it focuses on the conditions of the connection (or overall barriers) along a segment, it does not necessarily account for the classification of the roadway section (e.g. interstate versus local arterial), traffic volume, or particular safety concerns. These could of course be taken into consideration if a hybrid approach to the worst-first strategy was developed to incorporate such information. If used, the schedule of replacement would be at the discretion of MDT based on budget, replacement barrier availability, etc. and could range from one year to multiple years.

4.3.3. Retrofitting

Although no information was identified by the literature review or survey which indicated any agency had retrofitted existing barrier with additional loops, this approach still remains a feasible option to consider. In such a case, existing barrier with two loops would have a third loop added to the middle of each barrier section, probably using some form of “post-installed” concrete anchor technology. However, since this approach has not been tried by any agency to date, crash testing would ultimately be required to establish whether it is a viable option. Prior to such testing, mathematical modeling could be employed to estimate the performance of such an option. This would limit the expense of testing should the model indicate the barrier would not meet crashworthiness criteria during field testing. Should this approach prove feasible following crash testing, it could be implemented on a multi-year schedule, with selected barrier segments modified each year.

4.3.4. Prioritized Replacement

The prioritization approach addresses the concerns raised by the worst-first approach as it considers the highway classification (or other metric of importance) in deciding which barrier segments to replace. As applied by the survey respondent (Puerto Rico), this approach focused on the replacement of all barrier segments along the National Highway System over an unspecified period of time. If applied by MDT, such an approach could begin with the replacement of all PCB along Interstates over the course of one or multiple years. Once that level of classification was completed, the next highway classification of priority would have barriers replaced, and so on until the entire MDT system had new barriers. Once again, the schedule of replacement would be at the discretion of MDT based on budget, replacement barrier availability, etc. and could range from one year to multiple years.

4.3.5. Systematic Replacement

The systematic approach is straightforward in seeking to replace all applicable barrier in a single or multiple year timeframe. In doing so, potential issues with crashworthiness or corrosion are addressed in a short timeframe, but a significant financial cost may be incurred in that timeframe. While not an issue if replaced during the course of a single year, issues with prioritization can arise when pursuing a multi-year replacement program, as the question arises as to which segments (and districts or areas of the state) are replaced in what order. Again, priority may be given to the highest traffic locations or functional classifications first, or another approach may be incorporated.

4.3.6. Hybrid Replacement Approach

Another potential approach to replacement is to use a hybrid strategy which incorporates aspects of all of the approaches previously discussed. Such an approach would incorporate the worst-first approach in considering the extent of corrosion to the connection system for a particular segment, the prioritization approach by considering the functional classification, traffic and crash rate of a segment, and the systematic approach by considering the entire PCB system throughout the state which may need replacement due to corrosion or type of connection system (i.e. two loop). This approach is attractive as it allows for replacement to be budgeted over multiple years, while also prioritizing replacement in a manner which accounts for corrosion/condition, safety and other aspects.

Such a hybrid approach is envisioned as follows. The average corrosion rating/ranking for a particular segment, which is presently being collected by MDT, would be rank ordered with similar information being collected throughout the state, with the worst cases being ranked 1, 2 3…, etc. At the same time, traffic and crash data for each segment could be queried, and a crash rate for that segment developed, with another rating assigned in a descending order, with the worst rate once again being assigned a rating of 1. Finally, the functional classification could also be accounted for as well, with a rank of 1 assigned to Interstates (indicating they receive the highest priority), 2 to arterials, and so forth. Any other categories of interest to MDT could also be accounted for/incorporated in a similar fashion.

Each of the rankings from these different aspects of interest can be assigned a weighting value based on its priority to MDT. For example, if ranking values for two aspects (condition, crash rate) are of interest and developed, and condition is more important than crash rate, then the ranking assigned to condition would be weighted at 75% and crash rate 25% (these are only examples, MDT would assign weights), with the combined value of these two rankings used to set the final ranking priority. This approach is akin to that used by many states in ranking high crash locations based on different factors (crash rate, type, etc.).

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6. APPENDIX A

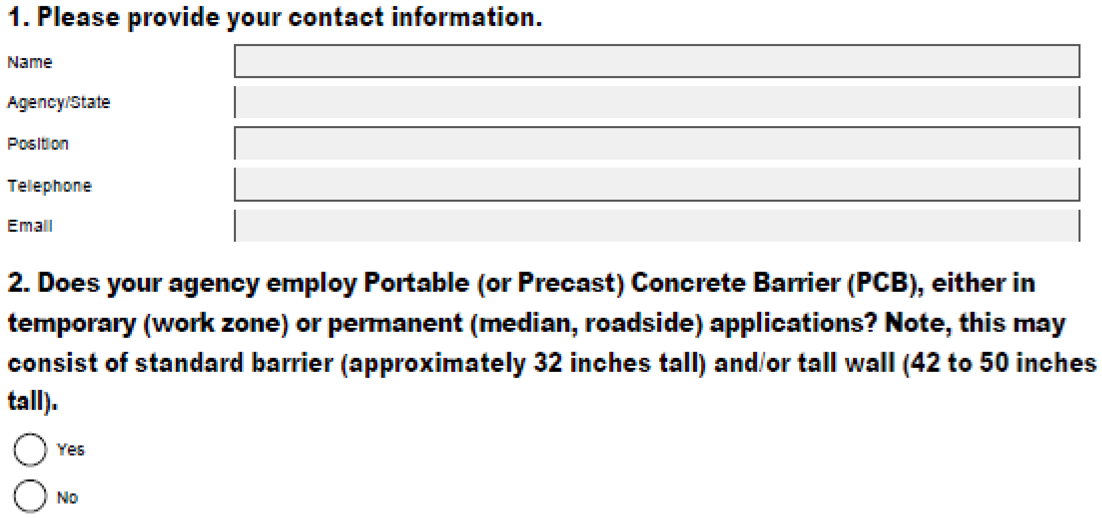
The Montana Department of Transportation (MDT) is undertaking work to better understand the experiences of other states with Portable (or Precast) Concrete Barriers (PCB) and corrosion. The following survey seeks information on your agency's experience regarding a number of different aspects of PCB, including the type(s) used, connection systems and materials, corrosion of connection systems, transition or replacement programs for PCB, and maintenance activities specific to PCB. For respondent reference, general images of PCB and a connection system are provided below. Note that these are only examples; the specific type of barrier and connection system may differ in your state.

This survey is expected to require 15 minutes to complete. When completing the survey, please provide as much detail as you can when applicable. If you have websites or report documentation you wish to share, please email it to David Veneziano at david.veneziano@coe.montana.edu. You may provide this survey to other agencies / organizations that you know of which employ PCB on their roadway system as well. As a participant, you and your agency will be provided a copy of the final results from this survey.

Your contact information will only be used by the researchers for the purposes of this study. The researchers will not contact you for any other reason except for clarification on responses, if needed, and your contact information will not be released or shared for any other reason. For more information about this project, please contact Damian Krings (MDT) at 406-444-6225 or dkrings@mt.gov. For questions about this survey, contact David Veneziano at 406-994-6320 or david.veneziano@coe.montana.edu. For questions regarding your rights as a human subject, contact Mark Quinn, IRB Chair, at 406-994-4707 or mquinn@montana.edu.

Example of PCB

Example of Pin and Loop connection



1. Please provide your contact information.

Name

Agency/State

Position

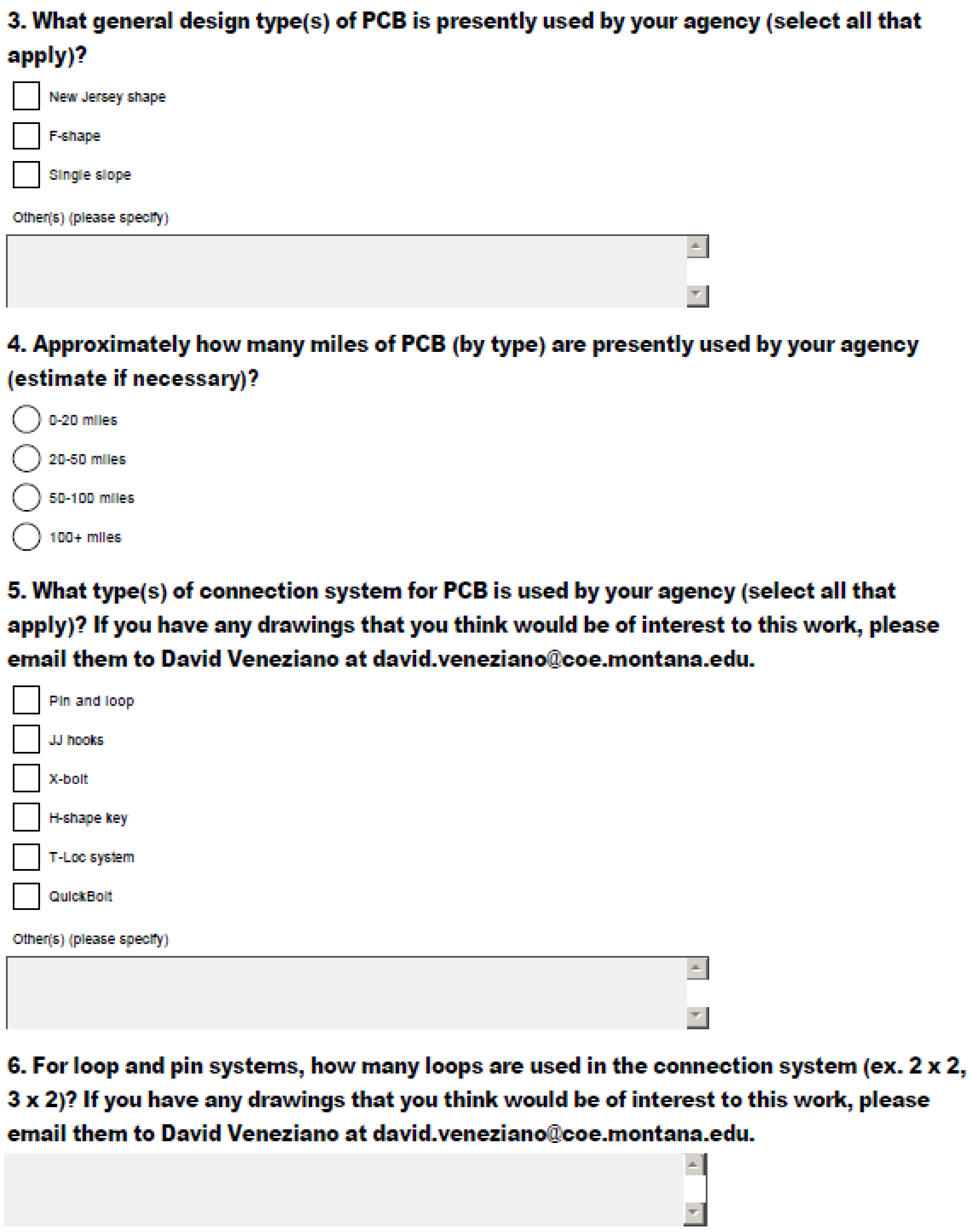
Telephone

Email

2. Does your agency employ Portable (or Precast) Concrete Barrier (PCB), either in temporary (work zone) or permanent (median, roadside) applications? Note, this may consist of standard barrier (approximately 32 inches tall) and/or tall wall (42 to 50 inches tall).

○ Yes

○ No



3. What general design type(s) of PCB is presently used by your agency (select all that apply)?

☐ New Jersey shape
☐ F-shape
☐ Single slope

Other(s) (please specify)

4. Approximately how many miles of PCB (by type) are presently used by your agency (estimate if necessary)?

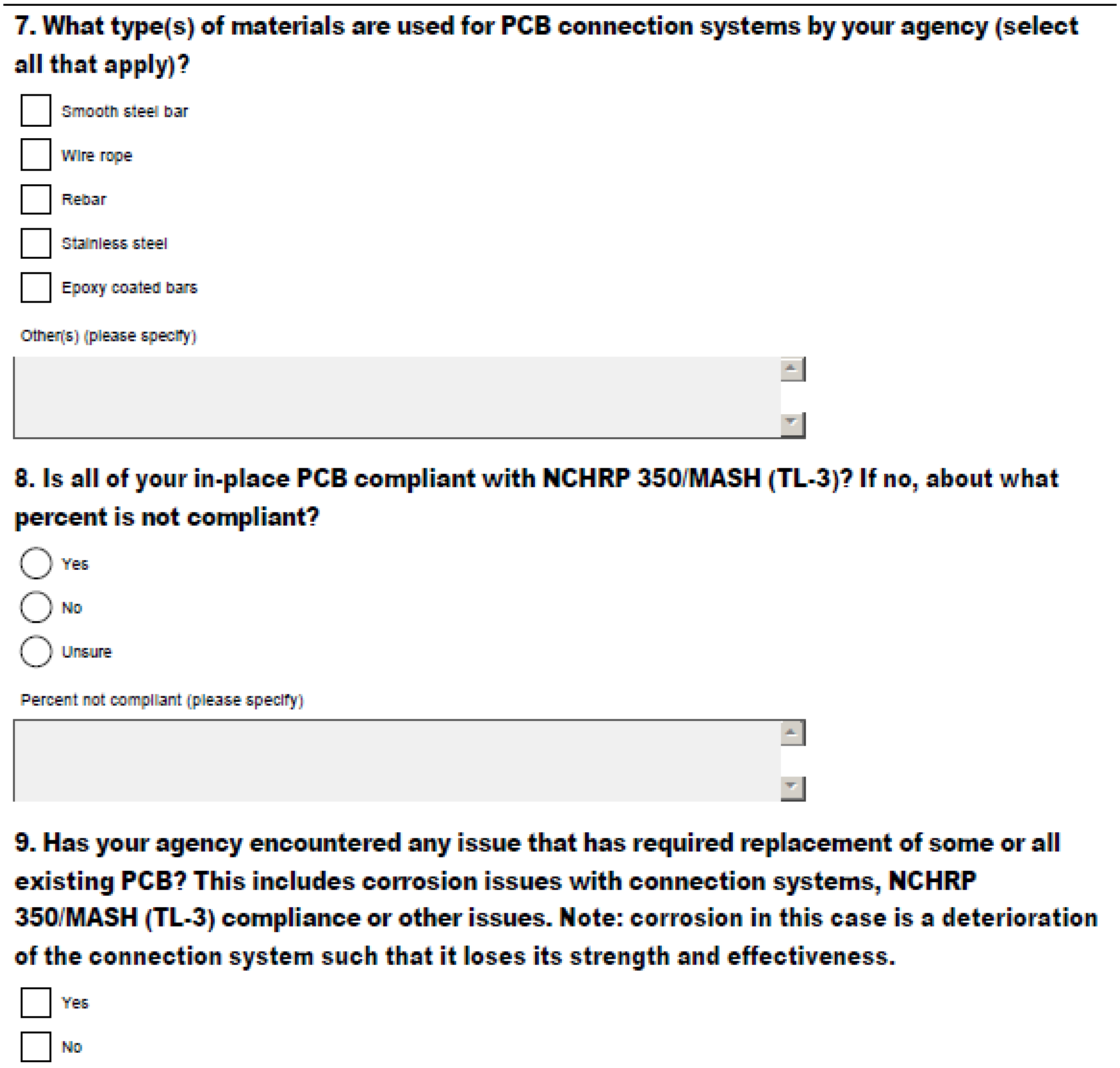
○ 0-20 miles
○ 20-50 miles
○ 50-100 miles
○ 100+ miles

5. What type(s) of connection system for PCB is used by your agency (select all that apply)? If you have any drawings that you think would be of interest to this work, please email them to David Veneziano at david.veneziano@coe.montana.edu.

☐ Pin and loop
☐ JJ hooks
☐ X-bolt
☐ H-shape key
☐ T-Loc system
☐ QuickBolt

Other(s) (please specify)

6. For loop and pin systems, how many loops are used in the connection system (ex. 2 x 2, 3 x 2)? If you have any drawings that you think would be of interest to this work, please email them to David Veneziano at david.veneziano@coe.montana.edu.



7. What type(s) of materials are used for PCB connection systems by your agency (select all that apply)?

☐ Smooth steel bar
☐ Wire rope
☐ Rebar
☐ Stainless steel
☐ Epoxy coated bars

Other(s) (please specify)

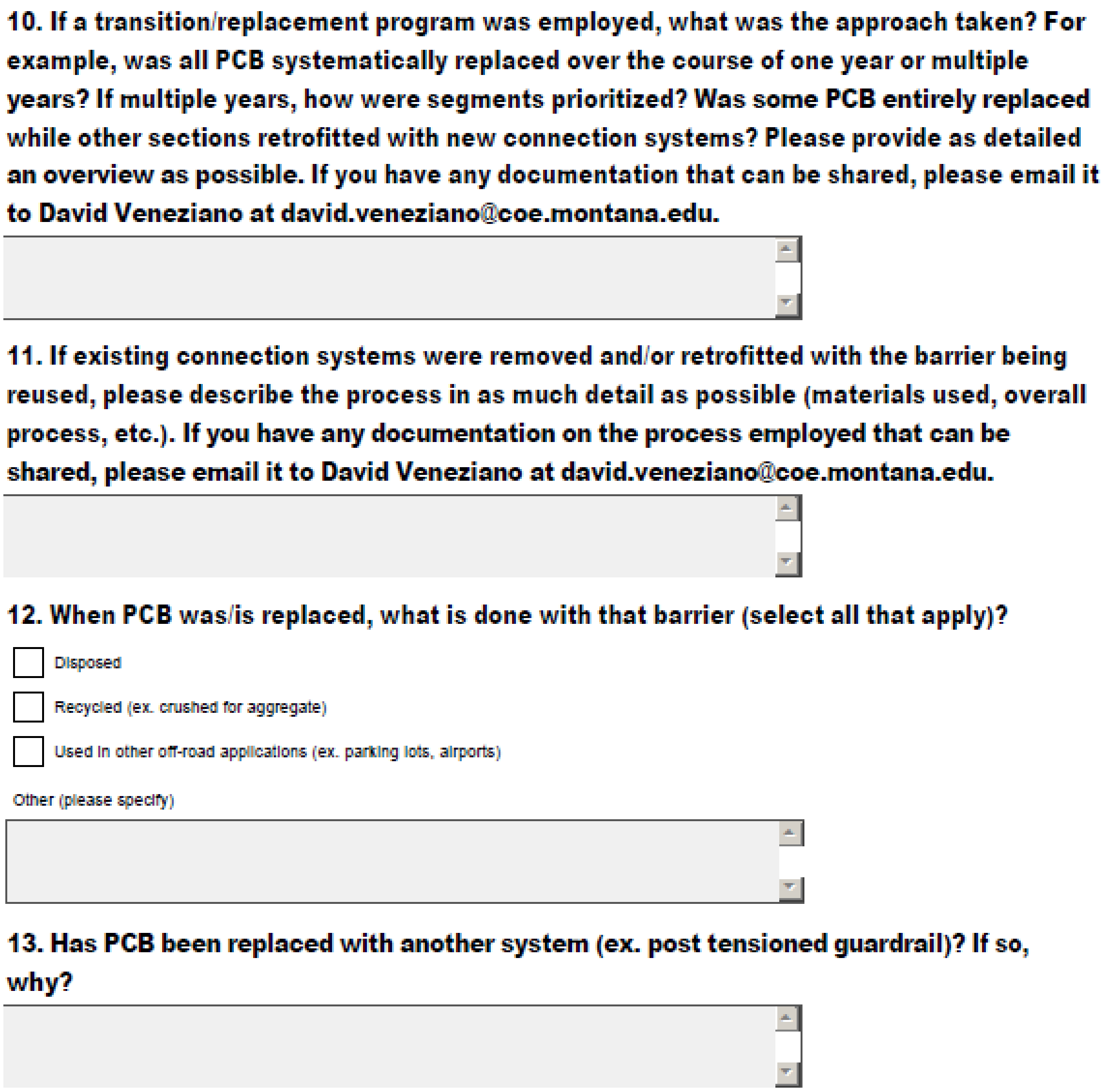
8. Is all of your in-place PCB compliant with NCHRP 350/MASH (TL-3)? If no, about what percent is not compliant?

○ Yes
○ No
○ Unsure

Percent not compliant (please specify)

9. Has your agency encountered any issue that has required replacement of some or all existing PCB? This includes corrosion issues with connection systems, NCHRP 350/MASH (TL-3) compliance or other issues. Note: corrosion in this case is a deterioration of the connection system such that it loses its strength and effectiveness.

☐ Yes
☐ No



10. If a transition/replacement program was employed, what was the approach taken? For example, was all PCB systematically replaced over the course of one year or multiple years? If multiple years, how were segments prioritized? Was some PCB entirely replaced while other sections retrofitted with new connection systems? Please provide as detailed an overview as possible. If you have any documentation that can be shared, please email it to David Veneziano at david.veneziano@coe.montana.edu.

11. If existing connection systems were removed and/or retrofitted with the barrier being reused, please describe the process in as much detail as possible (materials used, overall process, etc.). If you have any documentation on the process employed that can be shared, please email it to David Veneziano at david.veneziano@coe.montana.edu.

12. When PCB was/is replaced, what is done with that barrier (select all that apply)?

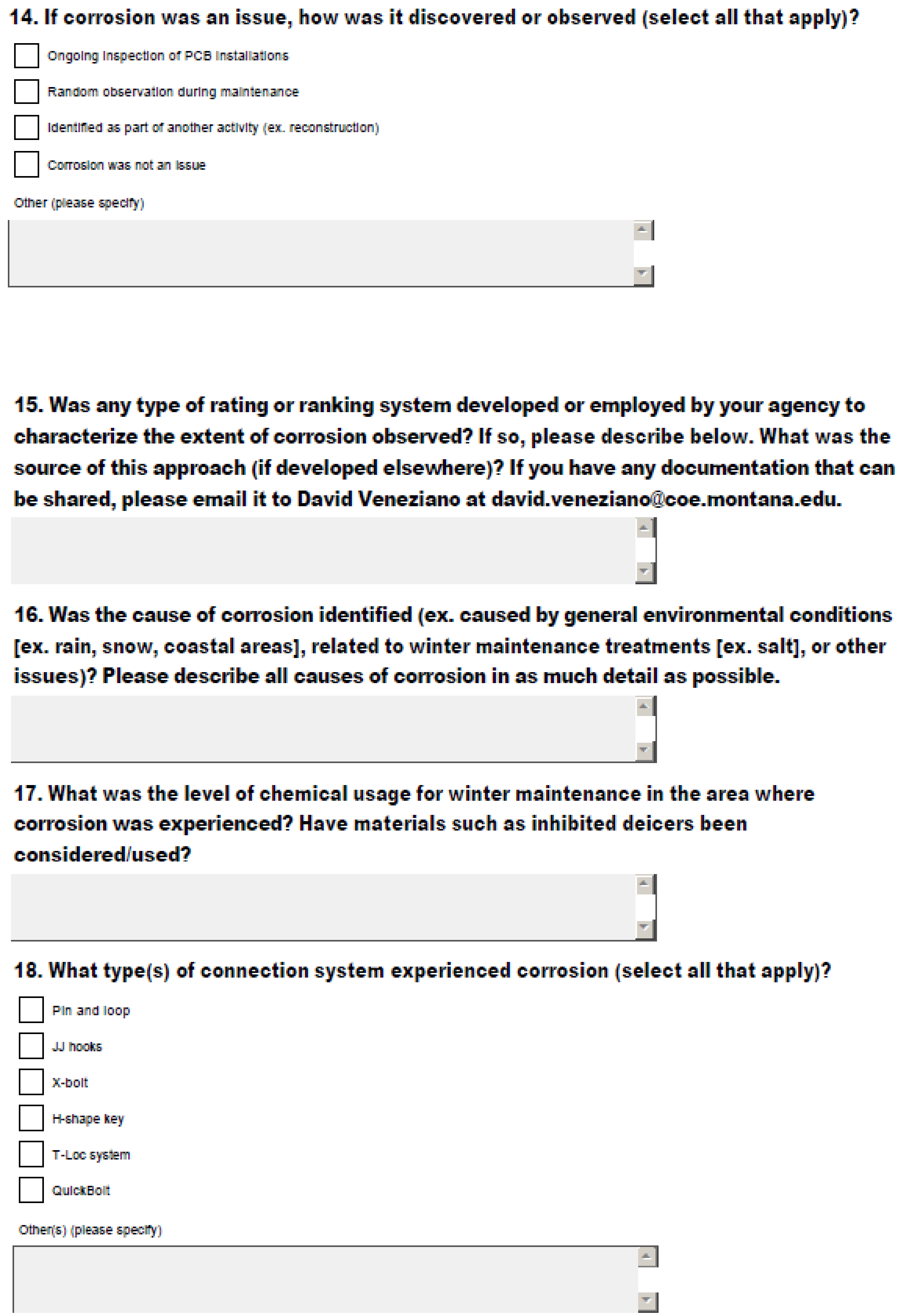
☐ Disposed

☐ Recycled (ex. crushed for aggregate)

☐ Used in other off-road applications (ex. parking lots, airports)

Other (please specify)

13. Has PCB been replaced with another system (ex. post tensioned guardrail)? If so, why?



14. If corrosion was an issue, how was it discovered or observed (select all that apply)?

☐ Ongoing inspection of PCB installations
☐ Random observation during maintenance
☐ Identified as part of another activity (ex. reconstruction)
☐ Corrosion was not an issue

Other (please specify)

15. Was any type of rating or ranking system developed or employed by your agency to characterize the extent of corrosion observed? If so, please describe below. What was the source of this approach (if developed elsewhere)? If you have any documentation that can be shared, please email it to David Veneziano at david.veneziano@coe.montana.edu.

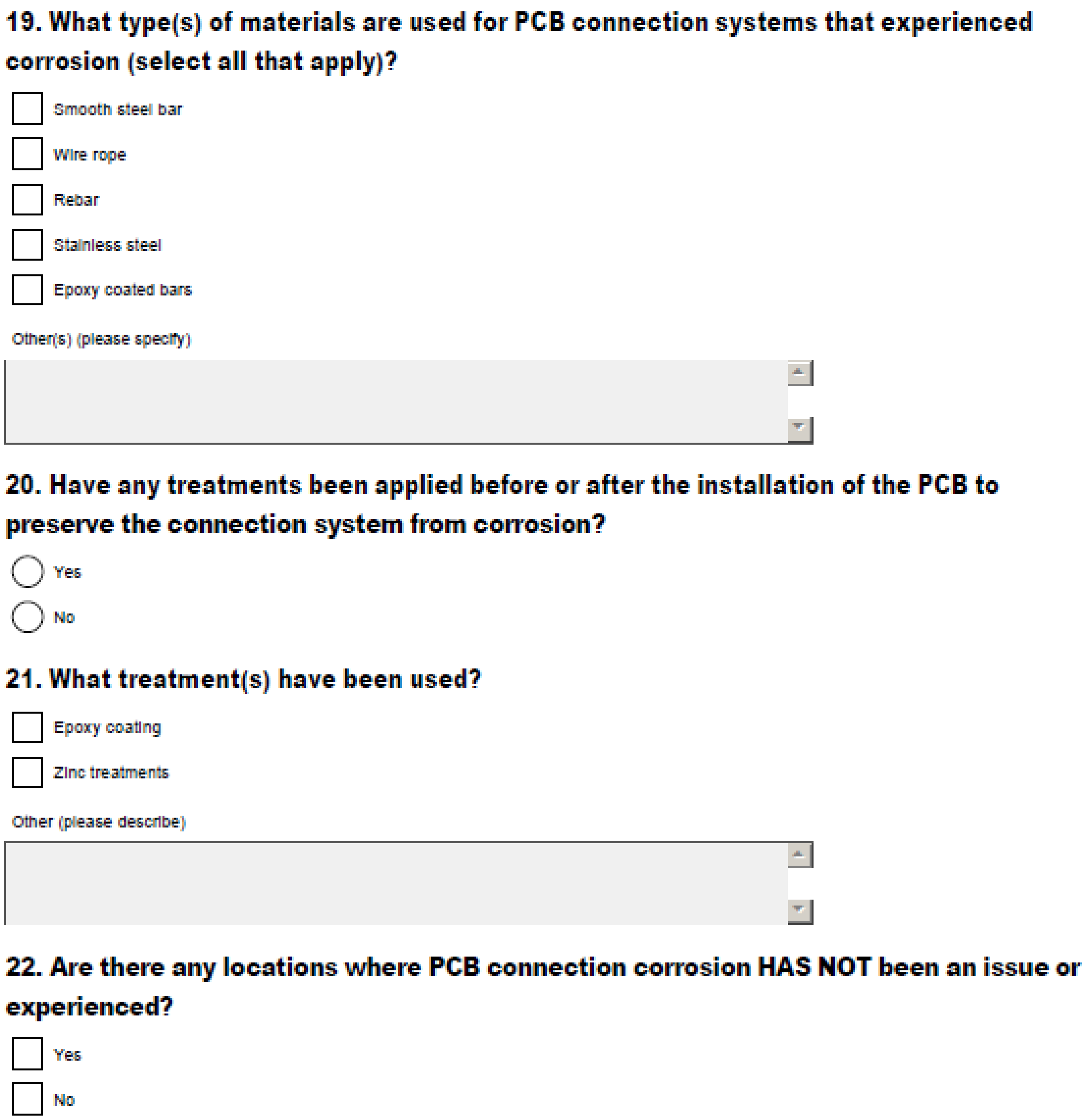
16. Was the cause of corrosion identified (ex. caused by general environmental conditions [ex. rain, snow, coastal areas], related to winter maintenance treatments [ex. salt], or other issues)? Please describe all causes of corrosion in as much detail as possible.

17. What was the level of chemical usage for winter maintenance in the area where corrosion was experienced? Have materials such as inhibited deicers been considered/used?

18. What type(s) of connection system experienced corrosion (select all that apply)?

☐ Pin and loop
☐ JJ hooks
☐ X-bolt
☐ H-shape key
☐ T-Loc system
☐ QuickBolt

Other(s) (please specify)



19. What type(s) of materials are used for PCB connection systems that experienced corrosion (select all that apply)?

☐ Smooth steel bar
☐ Wire rope
☐ Rebar
☐ Stainless steel
☐ Epoxy coated bars

Other(s) (please specify)

20. Have any treatments been applied before or after the installation of the PCB to preserve the connection system from corrosion?

○ Yes
○ No

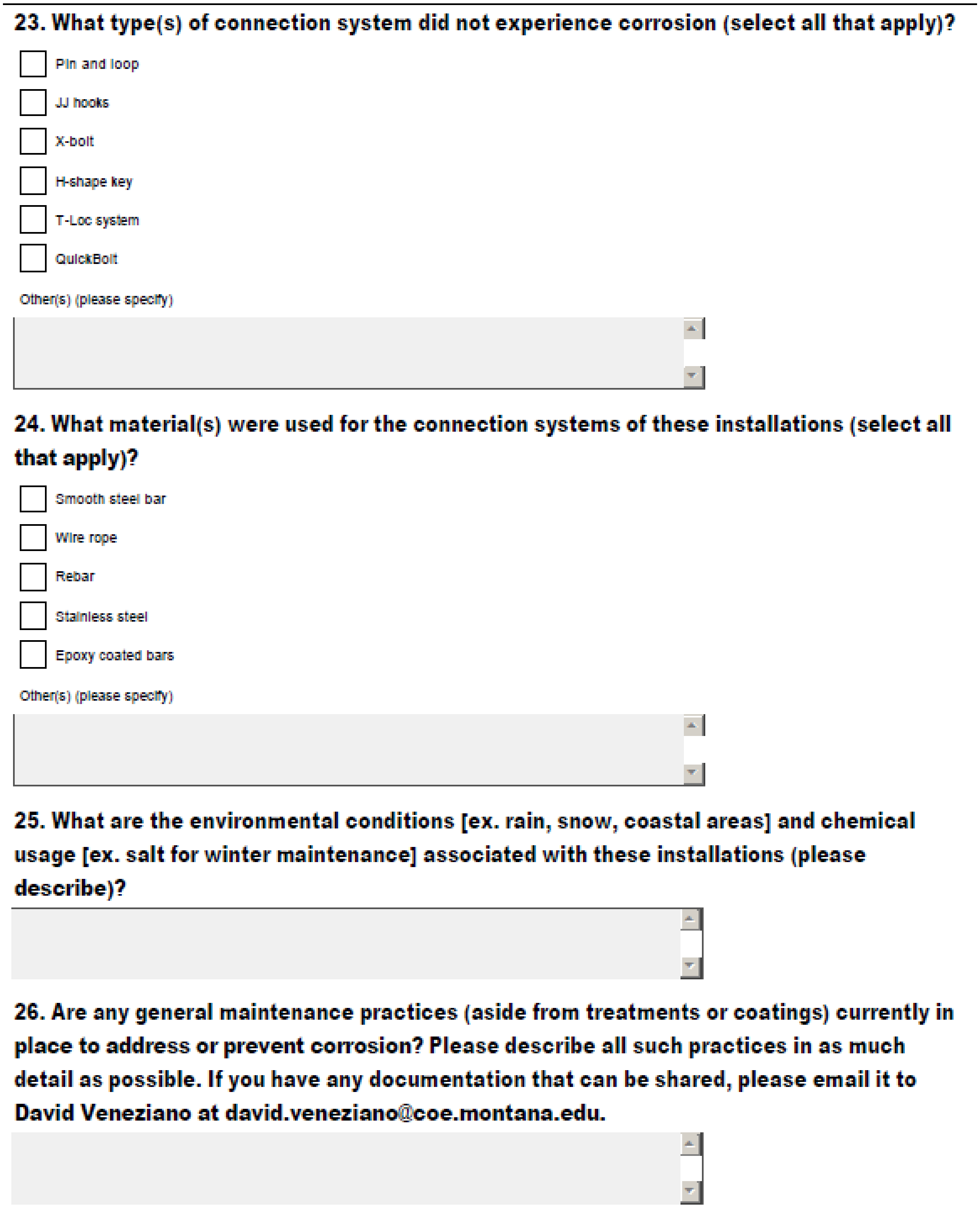
21. What treatment(s) have been used?

☐ Epoxy coating
☐ Zinc treatments

Other (please describe)

22. Are there any locations where PCB connection corrosion HAS NOT been an issue or experienced?

☐ Yes
☐ No



23. What type(s) of connection system did not experience corrosion (select all that apply)?

☐ Pin and loop
☐ JJ hooks
☐ X-bolt
☐ H-shape key
☐ T-Loc system
☐ QuickBolt

Other(s) (please specify)

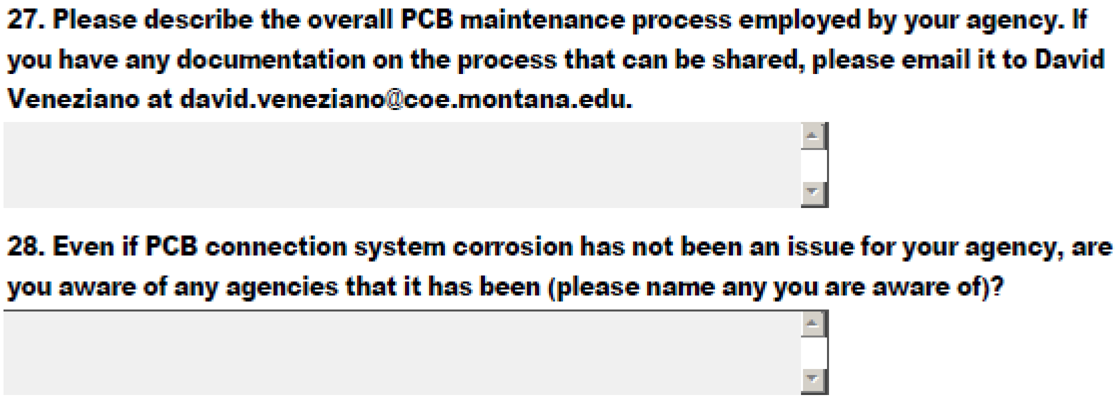
24. What material(s) were used for the connection systems of these installations (select all that apply)?

☐ Smooth steel bar
☐ Wire rope
☐ Rebar
☐ Stainless steel
☐ Epoxy coated bars

Other(s) (please specify)

25. What are the environmental conditions [ex. rain, snow, coastal areas] and chemical usage [ex. salt for winter maintenance] associated with these installations (please describe)?

26. Are any general maintenance practices (aside from treatments or coatings) currently in place to address or prevent corrosion? Please describe all such practices in as much detail as possible. If you have any documentation that can be shared, please email it to David Veneziano at david.veneziano@coe.montana.edu.



27. Please describe the overall PCB maintenance process employed by your agency. If you have any documentation on the process that can be shared, please email it to David Veneziano at david.veneziano@coe.montana.edu.

28. Even if PCB connection system corrosion has not been an issue for your agency, are you aware of any agencies that it has been (please name any you are aware of)?