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Pontis bridge management system for the State of Iowa

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Pontis bridge management system for the State of Iowa

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GENERAL INTRODUCTION

INTRODUCTION

As the condition of the nation's bridge network continues to deteriorate, DOT agencies have struggled to determine an economical solution to improve their bridge inventory. An accurate assessment of a bridge's remaining life is imperative to properly distribute available funding. This has led to the development of the Bridge Management System (BMS) concept, the objective of which was to assist DOT agencies in their allocation of funds to various bridge structures. A BMS utilizes mathematical formulations and economics based principles to assess project alternatives. These project alternatives can range from a do-nothing scenario to replacement of the bridge. The BMS software assists agencies in distributing available resources to protect existing infrastructure investments while simultaneously assessing structural functionality of bridge structures. In addition, it can assist an agency in project development, budgeting, and policy development. A BMS can also simulate different project alternatives, and assess the impact to the bridge network condition. This amount of detail, with regards to structural assessment, is made possible through recently improved computing efficiency. Without efficient storage and access of this data, detailed bridge management would be an arduous task for any agency.

The Iowa DOT has selected the Pontis BMS, which was originally developed by the FHWA, to assist in the management of the nation's bridge network. The Pontis software relies on numerous inputs to function correctly. The first step to an effective BMS requires accurate and regular inspection of bridge elements within a bridge structure. This not only provides the database with the current elements contained within the structure, but also a visual assessment of a bridge's element condition. This visual condition is utilized in the BMS to identify bridges requiring maintenance or repair, and also assesses the degradation of the element condition over the inspection timeframe. Following adequate inspection cycles, deterioration rates of each element can be calculated by the Pontis software. A second input required for an effective BMS is accurate estimates of agency and user costs. The conception of the BMS was driven by financial desperation from agencies when attempting to maintain their bridge network. Without accurate assessment of cost figures, a BMS will not be able to improve current bridge networks.

With the above listed basic parameters, a database can be assembled which includes the current bridge network, the relative condition of bridge elements within the network, and the costs associated with repair or replacement of these bridges. However, this offers little insight to the priority of bridge maintenance on a network level. In addition, with the limited financial sources for bridge rehabilitation and repair, it is imperative that prioritizing of an agency's bridge repair is completed to insure economical use of funds. This priority must account for the factors such as traffic demand, functional characteristics of the bridge, along with costs or impairment to the user if repairs are neglected. These factors were the driving reasons that most of the nation's DOTs started adopting BMS as a management tool. Integrated analysis tools allow the BMS to predict future bridge condition, and future needs due to growth or decline in demand. This allows the BMS to evaluate the least long term cost alternative, which provides more economical use of funds over that of a direct present cost analysis.

Although forecasting of future condition (i.e. deterioration of an element) is left to mathematical algorithms, an accurate assessment of the current condition can be enhanced beyond that of visual inspection. Visual inspection offers little insight to the true load carrying capacity of the bridge, and its current structural sufficiency. Although degradation of structural components may be visible, many mechanisms that bridge structures rely on cannot be accurately verified through visual inspection. For example, the degree of composite action between a bridge deck and bridge girders of a steel girder bridge cannot be assessed through visual inspection. Therefore, the in-service bridge structure may exhibit improved load carrying capacity than that predicted by codified equations. This could affect the bridge load carrying capacity (i.e. the load rating of a bridge) and as a result, the allocation of available funds. Therefore, there is a need to collect field test data that can be incorporated to determine more representative load rating of a bridge structure. If a BMS was capable of incorporating these field test measurements from in-service bridges, more efficient planning and programming of the agency's structures could be conducted through better assessment of future bridge condition.

To accurately assess the load carrying capacity of in-service bridges, many agencies have turned to field testing of their bridges. This can be accomplished by applying instrumentation to the structure to measure values such as strain or deflection, which can then be used to assess the performance of the bridge under a known load configuration. This offers bridge-specific response that can then be compared to the expected performance of the structure from design equations. This approach has traditionally been utilized on bridges of questionable capacity, or to assess the effects of any existing damage. Unfortunately, to the author's knowledge, this approach has not been utilized in conjunction with BMS. In the author's opinion, as bridge networks continue to degrade, systematic field testing of in-service bridges is the next step to accurate evaluation bridge structures.

THESIS ORGANIZATION

This thesis consists of three main divisions. The first part represents a paper that was submitted and accepted for presentation and possible publication by the Transportation Research Board. The first division represents the implementation of a working Pontis database for the Iowa Department of Transportation. This section included input and direction by Omar Smadi and Fouad Fanous, both of which are Professors in the Civil Engineering Department at Iowa State University. The second part of this thesis was prepared and submitted to the Midwest Transportation Consortium. This section represents development of the handheld data acquisition system and initial methodology for the integration of the field measurements into the Pontis database. The third division represents final development of the methodology, along with an expanded description and guide to use of the handheld data acquisition system. Conclusions and discussion on all three divisions of the research, along with recommendations, is included near the end of this thesis.

1. IMPLEMENTATION AND CUSTOMIZATION OF PONTIS FOR THE IOWA DEPARTMENT OF TRANSPORTATION

A paper submitted to the Transportation Research Board

Patrick Stein, Omar Smadi, Fouad Fanous

1.1. ABSTRACT

The IA DOT has selected Pontis, the most widely used Bridge Management System in the nation, to assist in selecting economical projects for their current bridge network. The widespread application throughout the nation allows for data sharing between states and enhances the calibration process of the program; however individual agency customization is often desired to insure accuracy and reliability in the recommendations.

The objective of this research is to develop and implement a working Pontis database for the IA DOT. This will include a description of selected methodology, and implementation of initial Pontis setup, including initial replacement and MR&R costs, initial development of element deterioration rates, along with all Pontis Rules and a Policy Matrix. Following the finalization of initial Pontis values, different verification methods will be completed to insure reliability in the use of the Pontis software by the IA DOT.

A literature review was completed to determine the available implementation methods, and their relevance to the IA DOT. Additional research and communication was completed to develop new methods for initial estimation of pertinent parameters within the Pontis software. Additionally, input from the IA DOT was utilized when possible to instill confidence in the implementation procedure, and the subsequent recommendations from the Pontis software.

The completed research provides a basis for initial implementation of a Pontis database for an agency with limited historical data. It provides comparisons with planned projects from the IA DOT, and the correlation with Pontis generated recommendations.

1.2. INTRODUCTION

As the nation's bridge network continues to grow in complexity to accommodate the increasing demand of travel, the budget of state agencies continues to be limited to maintain the current bridge network. This limitation has lead to the development of Bridge

Management Systems (BMS). The purpose of a BMS is to optimize the use of limited funds, therefore offering the most economical use of resources, and providing the most benefit to the user. Factors that are accounted for in this process include the annual average daily traffic (AADT) of the facility, the condition of individual bridge elements, cost to repair or replace any bridge elements, and additional factors that insure the most cost effective use of limited funds. For the BMS to function properly, intensive data collection and entry must be completed on a regular basis. A majority of the success of the BMS relies on regular and accurate inspection of the bridge system, along with updates to costs and the policy of the agency using the BMS.

The Iowa Department of Transportation (IA DOT) currently owns and maintains over 4,000 bridges and culverts on the state highway system. As the available funds for maintenance work changes over time, it is vital to have a database that contains the condition of each bridge in the network. Updating the current cost of replacement and repair for bridge elements is also essential to the success of the BMS projecting sensible projects for the IA DOT to consider for improvement to their bridge network.

The IA DOT has selected Pontis, the most widely used BMS in the nation, to manage their current bridge network [1]. This program was developed by FHWA, and is continually being updated. Pontis now allows an agency to customize and utilize the program according to the needs of an agency. The widespread application throughout the nation allows for data sharing between states and enhances the calibration process of the program. Recent developments of the Pontis software also allow for improved modeling of an agency's policy. This strengthens the confidence the agency has in the recommended actions and projects that the BMS generates.

To insure accurate maintenance, rehabilitation or replacement (MR&R) alternatives for an element in a bridge structure, condition of a bridge is no longer separated into large divisions such as bridge deck, superstructure and substructure. The Pontis BMS requires a condition evaluation of each separate element each having up to 5 different states. Each record can include a percentage of the element that is in each condition state.

The IA DOT is currently in the beginning stages of setting up a working database in Pontis. Pontis bridge inspections have been collected for various state bridges since 1996.

This data has been loaded into the Pontis database, including inspections through 2003. Although default values are included with the Pontis program, initial customization is desired to assure accurate modeling and project generation by the BMS. These customizations include development of initial:

- Costs : Replacement, Failure, and Maintenance, Repair and Rehabilitation (MR&R)
- Deterioration rates
- Rules : Look-Ahead, Scoping, Major Rehab and Agency Policy

These initial values will provide a foundation for future improvement of the BMS. It is imperative that these initial values are reviewed by the IA DOT to insure that the input is representative of their current actions.

1.3. LITERATURE REVIEW

1.3.1. Pontis Implementation

As outlined in Ref. [1], the Pontis Bridge Management System is being utilized throughout the nation. By allowing various agencies the opportunity to share their individual resources, comparisons of the databases allows for more feasible initial development, along with ongoing updating of the database [1]. Along with the popularity of the Pontis BMS software, the customization of the program for individual agency use is widespread throughout the nation as well [1].

Although the Pontis software is selected at most state agencies for bridge management, certain issues from the program have arisen. For example, although an array of elements is included in the default setup of the Pontis program, individual agencies may desire expanded element lists. These additional elements may assist inspectors in accurate assessment of bridge condition, or include innovative material not included in the default list. For example, the Iowa DOT sought the development of an element representing the bottom of concrete decks, with similar parameters as other deck elements. This allows assessment of the bottom of the deck separate from that of that of the driving surface. Due to traffic wear, the top of a bridge deck often degrades at a faster rate than that of the deck bottom. Overlay of the deck is an optional solution to spalling problems on the top of deck, but obviously is not a solution for spalling of concrete from the bottom of the deck. These continual developments drive addition of bridge elements into the BMS, and corresponding element parameters must be included. These parameters include a cost set representing the replacement, failure, and MR&R costs, along with deterioration rates and repair alternatives. Although this process seems tedious, it is necessary to accurately represent the existing bridge elements in an agencies bridge network.

Following the completion of building the element database, further customization is often desired to eliminate problems of unit measure discrepancies. Each element in Pontis is presented with a given unit of measure so that the costs may be presented generally for the element. The default unit of measure is often unsatisfactory to generally describe the cost of the element, or any action done to the element. For example, the unit of measure associated with concrete box girders is a linear measure. A cost must be associated with the replacement of this element, on a basis of length, when the cross-sectional size is of utmost importance in the estimation of cost. Often in initial development, the unit compatibility problem is not completely addressed [2]. Therefore, following initial implementation of the Pontis program, more customization of the database would be needed by the agency. This customization could include defining new elements in the database, changing the unit measure of different elements, along with changing the layout and creating new forms and additional applications [1]. Changing element unit measure is an especially difficult issue, due to costs and inspection requiring use of identical units. Although changing the units of a concrete box girder to cross-sectional area may benefit the cost estimates, attempting to describe the condition of this element over its length becomes impractical with this unit of measure. Solutions may include expanding the element list, with elements having ranges of element dimensions that are similar in unit cost.

Various methods have been used to implement Pontis into different agencies. Some have chosen to strictly use the default values provided with the program for initial use, and rely on continued inspection and expert opinion to calibrate their database over time. Differences in default database parameters from representative parameters of an agency will result in a BMS that is inaccurate in predicting future project needs due to its lack of resemblance to the agency's environment, element characteristics, and construction practices on bridge maintenance. As outlined in the research by Fanous et al., essential parameters must be accurately estimated for a BMS to be effective early in its use [3]. These parameters include level-of-service goals, agency costs and user costs, along with deterioration rates [3]. These values must remain representative of the agency for Pontis to recommend projects that are common to there ongoing infrastructure management. This will allow for the transition from traditional maintenance planning to further dependency on Pontis to recommend bridge candidates for work.

1.3.2. Implementation Strategies

Various research throughout the nation has summarized the strategies of implementation of certain parameters in Pontis. From the research of Sobanjo and Thompson, the development of agency costs was completed for Florida's Pontis database [2]. Assorted methods were used to determine the final cost values to be used by the Florida DOT (FDOT). A sensitivity study was also carried out to determine the most critical cost elements. It was found that failure unit cost was the most sensitive in the analysis. Also, the discount rate, which represents the loss of value over time, was found to affect the recommendations of the BMS [2]. Historical data from the FDOT was utilized to obtain an estimate of present day agency costs, and proved beneficial for 70% of the elements tested. An expert review process was also used to verify the estimated costs from the historical data, and data was then manipulated according to expert recommendation, or used directly for the final results. Experts also provided cost estimates for elements with little or no historical cost information.

Fanous et. al. conducted similar elicitations to obtain agency costs; however, this study contained no baseline or initial estimate of cost from historical data [3]. Historical data was only later used as a comparison to the estimates made by experts from the state agency. This method created cost estimates that were sometimes quite variable, not only between expert and historical data, but also among the experts [3]. The final values were determined by the judgment of the agency's Bridge Maintenance Engineer.

1.3.3. Deterioration Rates

The study of deterioration on an element level has been an ongoing challenge for those utilizing Pontis. The main requirement for Pontis to calculate this value internally is abundant inspection data with changing condition states. The Iowa DOT currently maintains over 50 structures that were constructed over 50 years ago. With Pontis-style inspections of these bridges beginning less than 10 years prior to implementation, an initial estimate of deterioration rates is essential. Multiple methods for initial deterioration rate estimates have been utilized for various agencies. Certain agencies will use the default values, which stem from a California study [1,2]. Other agencies will conduct a full elicitation study, trying to estimate deterioration from expert opinion [2]. A methodology was developed in Louisiana to utilize there State National Bridge Inventory (NBI) data to determine their initial deterioration rates [4], due to the lack of past Pontis-style inspections. However, NBI inspections include rating of only three bridge components, which then must be extrapolated to cover all possible bridge elements in Pontis. Also, NBI inspections are rated on a scale from 0-9, with 9 being the best condition, while the condition states in the Pontis program are rated on a scale from 1-5, with 1 being the best condition. Therefore, further estimation must be made to merge the condition states together.

1.4. OBJECTIVES

The objective of this research is to develop and implement a working Pontis database for the IA DOT. This will include a description of the selected methodology, and the implementation of initial Pontis values. It will include the development of initial replacement and MR&R costs. Additionally, it will include the initial development of element deterioration rates, along with all Pontis Rules and a Policy Matrix. Due to the significance of failure cost in Pontis, this development was completed in a separate research effort.

Although initial development attempts to model the existing policy of the agency, while still providing the most economical project selection, it is imperative that continual updating be completed in the Pontis database to insure improvement to the current bridge network. It must be understood that software with the complexity of Pontis will require both time, and continual data entry to not only improve the reliability of the management recommendations, but also insure evolution of the BMS with the continual changing standards and policies of the agency.

1.5. PONTIS IMPLEMENTATION AND CUSTOMIZATION

1.5.1. Overview

As outlined in chapters 4 and 5 of the Pontis User's Manual, a preservation policy can be initialized in Pontis for use in program simulation [5]. Although the methodology to collect these values is often left to elicitations over time, the required elements for Pontis simulations are presented. This manual was utilized to update or calibrate the five components in this research; agency replacement costs, agency MR&R costs, deterioration rates, Pontis Rules and a Policy Matrix. After modifying this data, simulations can be completed to verify the performance of the BMS compared to current IA DOT maintenance schedule. It is imperative that the scheduled maintenance of the IA DOT compare well with Pontis simulations to insure confidence in Pontis. As concluded by [1], 50% of the agencies currently using Pontis are only using the program as an inspection database. This represents agency insecurity with the capability of Pontis to effectively manage the bridge network. This also can be attributed to a lack of training on the use of Pontis to recommend projects and maintenance actions for an agency. It is a goal of this research to instill confidence in the IA DOT to utilize Pontis, yet allow the BMS to operate and optimize over time.

1.5.2. Deterioration Model

The Pontis program uses the Markov Chain modeling procedure to predict the future condition of different elements. This model of deterioration correlates a probability of condition change with each condition state. After each cycle, in this case one year, a percentage of the element will transition to the next condition state, and a percentage will remain in the current state. Therefore basic regulations of the model include only transitioning one state during each cycle.

Each element in the Pontis database requires a set of deterioration rates for each possible state. The default rates are based on a California study, which can be used as a baseline, yet are considered to differ from that of Midwest states, due to the different environmental factors. Therefore, the first action was to collect current deterioration rates from surrounding state agencies that are currently utilizing Pontis for their bridge network. These deterioration rates would reflect the environment of the Midwest, and also provide further comparison for any elicitation data from the IA DOT.

State databases that were attained for comparison include Wisconsin and Kansas [6,7]. Illinois also shared their database; however they changed a majority of their element definitions and units of measure [8]. Due to this discrepancy, deterioration rates from Illinois were not used in the analysis.

Transition probabilities can be found using Pontis, utilizing historical data alone. Since Pontis inspections have been done in Iowa since 1996, the BMS was used to calculate deterioration rates strictly from the historical data. However, the inspection data was very limited due to some bridges only occasionally being inspected during each cycle. Some bridges have yet to be inspected using the Pontis format, and many others have only received one Pontis style inspection. These bridges offer no incite to the transition of the element over time, since multiple inspections are required for that relationship to be made. Multiple inspections on particular bridges provide a relationship between the condition state of an element and the time between inspections. This results in a deterioration rate that can be related to a transition probability in Pontis. There are limited bridges with sufficient inspection cycles to provide Pontis with sufficient data to develop accurate transition probabilities, therefore Iowa historical data was included in the analysis, but with known limitations of its use.

In discussion with the IA DOT, it was determined that a simple elicitation would prove the most beneficial in the finalization of transition probabilities. Although more complicated elicitations can be conducted to attempt more accuracy, for the initial implementation it was determined that a straightforward analysis would be favorable. More thorough elicitations could have presented a deterioration matrix for each element to be filled out by the specialist. However, due to the Markov Chain concept, the probability of deterioration to the next state is limited to a one year timeframe. Estimating bridge degradation over a single year for any element is largely speculation, and the input required for multiple elements is intimidating for an agency. By expanding the deterioration over a more significant timeframe, the results of the elicitation will become more intuitive to agency specialists.

Two separate forms were created for elicitation from the IA DOT. They were both based on expansion of the Markov Chain models. Deterioration rates for all elements that exist in more than 100 bridges in the state were utilized in the elicitation. Element deterioration was expanded using the Markov Chain, sufficiently enough to produce significant quantities of the element in its worst condition state. The amount of the element in the worst condition state after the first 50 years were summarized in a chart that included results from Iowa historical data, the default values, and the average of the Wisconsin values, Kansas values, and Iowa historical values. A similar chart system was created that included the time in years required for 50% of the element to reach the worst condition. It was expected, due to the lack inspection cycles, that the Iowa DOT historical values would, for certain elements, be unreliable, and be relatively meaningless. However, for other elements with sufficient inspection cycles containing changes in condition state, the estimates proved more dependable. Therefore, all Iowa DOT historical estimates were included, and were to be judged vigilantly.

Figure 1a shows an example elicitation sheet distributed to the IA DOT with various elements and their corresponding theoretical percent of the element in the worst condition state after the first 50 years of deterioration. Figure 1b shows an example elicitation sheet with various elements and their corresponding theoretical time in years for 50% of the element to be in the worst condition state. Figure 1b also includes the average of the expert opinions, which was included on all charts following the completion of the forms, to assist in the analysis of the findings. As can be seen on both charts, the generated values

The expert elicitations were completed by three personnel from the IA DOT that represented inspection, design and maintenance experience. The results of the elicitations correlated most closely with the average of Wisconsin, Kansas and Iowa historical data. The expert opinion of the IA DOT typically suggested faster deterioration of superstructure elements when compared to that of the average of Wisconsin, Kansas and Iowa historical data. However, expert opinion suggested slower deterioration of substructure elements when compared to that of the average of Wisconsin, Kansas and Iowa historical data.

When the difference in time to reach 50% in the worst condition state exceeded 50 years, additional analysis was done for the finalization of the transition probabilities. If the difference was less than 50 years, the average of Wisconsin, Kansas and Iowa historical data was chosen as an acceptable estimate for initial implementation. It was found that of the 32 elements in the elicitation, only 6 elements qualified for further analysis. Elicitations of these 6 elements were reanalyzed to determine if outlying elicitation estimates was causing the discrepancy. Of the six, four were determined to contain an outlying estimate from one expert with respect to other elicitation values. Once the outlying estimate was removed, the values correlated very closely with the average of Wisconsin, Kansas and Iowa historical data once again. The remaining two elements were adjusted by averaging the elicitation results with the average of Wisconsin, Kansas and Iowa historical data. Interestingly, the remaining two elements had little effect on bridges or bridge performance, concrete culvert and aluminum railing. Therefore adjustment techniques were simplified, due to the lack of bridge network importance.

To adjust element values, the transition probabilities must be changed to reflect the extrapolated Markov Chain value. With up to 5 condition states for each element, any transition probability in any state can be adjusted to correlate to the desired value. It was found through study that the extrapolated values were very sensitive to small changes in the deterioration rates. To adjust these elements it was found to require less than one percent change in any one condition to obtain the desired result.

1.5.3. Replacement Costs

In order to estimate the replacement costs of elements, economic factors for the agency must be considered. The default values in Pontis stem from a study conducted at Clemson University, which represent the regional costs to replace various elements in there specific region. A Midwest state, such as Iowa, has different costs associated with the replacement of elements due to the availability of materials, the cost of labor, along with additional economic factors for the specific region.

The IA DOT Office of Contracts keeps current records for all bridge bid items, and their associated awarded contract prices. Following each fiscal year, a Summary of Awarded Contract Prices is released for each of the bid items that were used during that year [9]. This summary includes the low, high, and average cost per unit that was charged from the winning bidder on each project in the state. This data is a direct representation of what the state would expect to pay for replacement of elements in their current bridge network. However, discrepancies arise when attempting to relate bid items used by the IA DOT, and element definitions from Pontis. Another difficulty is the unit compatibility issue. Many elements are measured differently within Pontis than the measures used by the IA DOT, along with other state agencies. For these particular elements, estimates were made to convert element prices to different units of measure. These estimates stemmed from quantities from bridges that were deemed representative of an average bridge in Iowa containing the needed elements.

For elements without reasonable unit convertibility, or elements not included in the Summary of Awarded Contract Prices, an elicitation to the DOT was made. This elicitation also included cost values from Kansas, Wisconsin, Florida, and the default values stemming from a study in California. With this information, costs were developed by the DOT to represent their experience with bridge element replacement. Elements not used by the IA DOT were left at the default value levels. Table 1 summarizes the results of the replacement cost generation.

1.5.4. Policy Matrix

The Policy Matrix is a summary of various design values including roadway widths, load allowances, and vertical clearances. These values are divided into two categories; legal limits and desired design values. Once a policy set is established, a bridge's configuration and load capacity can be compared to the legal and design limits. Deficiencies of the bridge are easily identified, and improvement projects can be considered. Improvement projects are separated from preservation actions in Pontis. Preservation actions simply maintain or restore the physical condition of the bridge, whereas improvement projects seek to improve the bridges functionality. Improvement projects are analyzed separately, yet are chosen on the same benefit/cost rational as maintenance projects.

It is imperative that the Policy Matrix reflect the current standards of the agency. Therefore, no comparisons were made to other states, or to the default values. A meeting with various engineers from the IA DOT was scheduled to attain the appropriate current design and legal standards for the State of Iowa. Representatives from the Methods Office, which is responsible for developing all of the design standards, details and policies for Iowa's roadways, were present in the meeting. A representative from the Office of Bridges and Structures provided additional experience with specific bridge related issues. Further study was completed by contacting the Statewide Urban Design and Specifications group to ensure all roadway dimensions were collected.

1.5.5. Pontis Rules

Rules were recently introduced to the Pontis software to assist agencies to develop practical projects. Separating a bridge into discrete elements allows for a better assessment of the condition. However, when bridge repair is done, economical factors arise that cannot be interpreted directly by the program, which often resulted in projects that were not feasible. It is imperative to identify elements that are interdependent on each other, and insure that if one element is repaired, the dependant element is also considered for repair. Also, if a bridge is scheduled for replacement or major rehabilitation in the near future, continuing maintenance on the bridge will be considered unwise by the agency. These common issues in planning have been addressed by the Pontis Rules. Rules are separated into four main categories; Scope Rules, Rehab Rules, Look-Ahead Rules, and Agency Policy Rules.

Scope Rules are used to build more complete projects including various elements. If a bridge deck is scheduled to be replaced, the joints will also need to be replaced, and therefore included in the cost estimate and work proposal. The scope rules are designed to assist in considering elements that are interdependent on each other in the project planning process.

Rehab Rules are based on the overall health index of the bridge, which includes an assessment of the condition of all of the elements in the bridge. If the health index is below a certain value, structural actions, such as replacement or rehabilitation, will be recommended.

Look-Ahead Rules are designed to prevent continual maintenance to bridges that are soon scheduled for major rehabilitation or replacement. With limited funds to support major bridge work, it is unfeasible to allow maintenance on bridges that are scheduled for replacement within five years. Therefore if/then statements are utilized in Pontis to discourage the recommendation of smaller maintenance projects, when it is known that more major work is scheduled for the near future.

Agency Policy Rules allow an agency to direct the Pontis software in creating suggested projects that resemble there current practice in maintenance. This may deter optimal economic alternatives from the Pontis software, yet will account for factors that Pontis cannot interpret. Although a percentage of a given element may validate repair, it often is easier to complete maintenance on the entire element, no matter the condition. If a section of concrete deck requires overlaying, it is sensible to overlay the entire deck to ensure a smooth surface and to eliminate further deterioration of other sections of the deck. If a steel element requires partial painting, it is rational to paint the entire element to prevent future painting needs on that element. Often, the mobilization and traffic control of a maintenance project exceeds the cost of the maintenance work itself, therefore it is vital to utilize each project, and prevent repetitive maintenance recommendations to the same bridge structure.

The Pontis software requires no rules to create recommended projects; however default rules are included in the software. It was determined that the default rules would be combined with the current rules being used by surrounding states. This elicitation form would outline possible rules that could be utilized in the IA DOT database to assist in the project planning. Example elicitation forms that were completed by the IA DOT are shown in Figures 2-4. The form allowed the IA DOT to develop a sense of the purpose of the rules, and also allowed for additional recommendations if the listed rules were insufficient in representing the current policy of the IA DOT.

Of the 14 example Scope Rules, 5 were chosen to represent the IA DOT policy. The Rehab and Agency Policy Rules were both accepted as representative of current standards that the agency currently follows. Of the 23 example Look-Ahead Rules, 19 were adopted by the IA DOT. No additional rules were recommended by the IA DOT for the initial implementation; however the current rule set can be easily modified to better serve the agency needs over time.

1.5.6. Maintenance, Repair and Rehabilitation (MR&R) Costs

The MR&R cost evaluation was left as the final task in the implementation of a working database into the IA DOT. The IA DOT has completed minimal element level maintenance and repair on its current infrastructure. Although numerous bridges have received deck replacements, and painting to girders, estimates could not be made on the numerous different actions on each discrete element. Therefore, elicitations were determined to be ineffective in determining the costs of repair on the current infrastructure. A sensitivity study was conducted by Sobanjo and Thompson, outlining the MR&R costs limited sensitivity to changes in recommended actions [2]. Each element maintenance cost was adjusted from the default value by 50, 75, 125, and 150% to determine the effects on the recommended actions. It was found that less that 20% of the elements changed their recommended actions, even after increasing the maintenance cost by 150%. This sensitivity analysis was conducted with all other cost parameters in Pontis being held constant at the default value. For the IA DOT implementation, many parameters within Pontis were already finalized. Therefore, it was determined that a simplified sensitivity analysis would be conducted with the current replacement costs and deterioration rates, to assess the current sensitivity of MR&R costs in the updated database. This was also used to assess the change in similarity with the programmed candidates from the IA DOT.

A ± 25% change in MR&R costs was completed on all elements that are being used in at least 100 bridges in the IA DOT infrastructure. Identical simulations were then run to assess the changes in recommended projects, and the actions of chosen projects.

1.5.7. Simulation Results

To assess the effectiveness of the initial implementation, a list of structures in the five year planning program from the IA DOT was attained. This is generated by BRIDGE CAN, the current software utilized by the agency for project selection. It is clear that projects generated from the Pontis software, which utilizes mathematical methods to ensure economical efficiency, will not coincide directly with that of the current tracking software used by the IA DOT that attains its projects from various engineers throughout the state. However, similarity in bridge selection is imperative for agency confidence in the Pontis software.

Following both simulations, comparisons were made to the IA DOT output. The first simulation was completed after increasing the MR&R costs of the most used elements by 25% from the default values. Pontis recommended 156 bridges for various repair and replacement, 53 of which coincided with bridges selected by the IA DOT in their planning program. The second simulation was completed after decreasing the MR&R costs of the most used elements by 25% from the default values. Pontis recommended 119 bridges for various repair and replacement, 48 of which coincided with bridges selected by the IA DOT in their planning program.

It is intuitive that as MR&R costs decrease, more projects could be recommended by Pontis. However, as MR&R costs decrease, additional actions become more beneficial in Pontis, therefore the projects selected by Pontis grow in complexity, creating a higher cost project, yet theoretically more beneficial to the user.

Although various bridges were chosen for work by both Pontis and the IA DOT, the work recommended by Pontis was most often repair and rehabilitation, when the IA DOT programmed mostly replacement projects. Of the over 135 million dollars allocated for bridge projects by the IA DOT, 74% was issued to bridge replacement projects. This is evidence of the difference in the maintenance policy of Pontis compared to that of the IA DOT. As MR&R costs increase, small repair projects become less feasible for the given benefit to the user. This causes replacement to become somewhat more feasible, which results in a database that would more closely represent the current practice of the IA DOT maintenance strategy.

The percent of projects recommended by Pontis that correlated to a planned project from the IA DOT was calculated. These match rates were found to differ only by 6% between the two simulations, proving the limited sensitivity of the MR&R costs when all other parameters are held constant. Many similarities were found between both simulation results. Pontis consistently recommends projects to be done earlier than the scheduled date by the IA DOT. Also, the bridges that were recommended by Pontis for replacement were the exact same in each simulation. The MR&R costs proved to be insensitive in the updated database, not only to recommended action, but also recommended year for the actions to be completed. It was therefore determined that the default MR&R costs were acceptable for initial implementation of Pontis. If individual actions are determined by the IA DOT to be unreasonable, and causing unreliable recommendations, changes to the maintenance costs can easily be made through an elicitation process described in the Pontis User Manual [5].

1.6. CONCLUSIONS

The completed research provides a basis for initial implementation of a Pontis database for an agency with limited historical data. With a greater number of Pontis inspections, more confidence can be placed on the historical data to produce realistic transition probabilities. The development of the replacement costs for this research was highly dependant on the current price reports collected by the IA DOT. Without such information, a more complete elicitation would be required or additional surrounding state databases for comparison. The Pontis Rules are not essential for the success of the Pontis database to function, therefore could be considered unreasonable for initial implementation. However, it was felt necessary in this research to develop an applicable rule set to ensure a level of confidence in the Pontis software that would spur further use and development of the database. The Policy Matrix was developed directly from current standards that the agency utilizes in current designs. A state agency, such as the IA DOT, is continually updating design methods to ensure safety to the public. As these changes are made in design, the Policy Matrix can be easily modified to accommodate such changes.

It is clear that Pontis will be unable to recommend identical projects and actions matching the current planned projects in the IA DOT, which stem from recommendations of engineers. The results of Pontis are meant as a guide for management of the current bridge network, which relies on economical analysis to distribute the limited funds of an agency. Careful examination of the recommended actions must be completed to insure reasonable projects. It must also be noted that continual updating of the database will not necessarily converge on the typical maintenance strategy of the IA DOT. However, with proper updating of the Pontis database, funds will be utilized more efficiently, and the condition of the bridge network will be improved.

1.7. RECOMMENDATIONS

An agency's current training and experience with Pontis must be considered in the implementation process. With Pontis software continually being updated, corresponding implementation and training strategies have been improved and expanded to assist in the accuracy of the bridge management process. As agencies begin implementation at different stages of historical data collection and Pontis inspections, different implementation strategies may become more beneficial. From the completed research, basic parameters could be identified and implemented with the IA DOT requiring minimal background in the Pontis software. As various agencies across the nation continue in their use of Pontis, sharing of database parameters will become more accurate and beneficial to agencies.

Recommendations for initial implementation of a working Pontis database are as follows:

- **Surrounding agency databases should be collected and assessed to insure correspondence with the given agency.** Surrounding state agency databases were vital in the implementation process for the IA DOT. These databases provided parameters that could be compared to expert opinion, and contained customization examples that assisted in the development of specific modification desired by the IA DOT.
- **Contribution from agency engineers should be utilized when possible to instill confidence with the Pontis software.** By allowing input and opinion from the agency, collection of agency specific parameters could be attained and implemented promptly. Due to the agency providing project planning information, analysis of the practicality of Pontis recommended projects and actions was easily completed.
- **Simplified elicitation forms can be utilized when experience with Markov Chain modeling is limited within the agency.** Bridge elements often have a design life surpassing 50 years. Deterioration of these elements is often difficult to assess in a matrix format, such as required by a Markov Chain. However, by providing experienced engineers with manageable concepts in the deterioration of bridge elements, an estimate can be made on the overall deterioration of that element.
- **Pontis simulation results should be compared to current project planning of the agency to insure an association with current practices.** Although results of this research proved a difference in the maintenance strategy of Pontis when compared to the IA DOT, a relationship was evident in the structures that require attention. This will allow the IA DOT to begin using Pontis as a bridge management tool, and not only as an inspection database.
- **Continual accurate inspection entry and updating to the database is vital to the success of Pontis as a bridge management tool.** As inspections are added, additional bridge elements will experience sufficient condition state transitions to more accurately assess the deterioration of the element. Continual historical data collection will assist in the accuracy of all agency cost values, and updating of Pontis parameters will insure the ability of Pontis to make economical recommendations in bridge management.

1.8. REFERENCES

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6. Kansas Department of Transportation Pontis Database, 2003

7. Wisconsin Department of Transportation Pontis Database, 2003

8. Illinois Department of Transportation Pontis Database, 2003

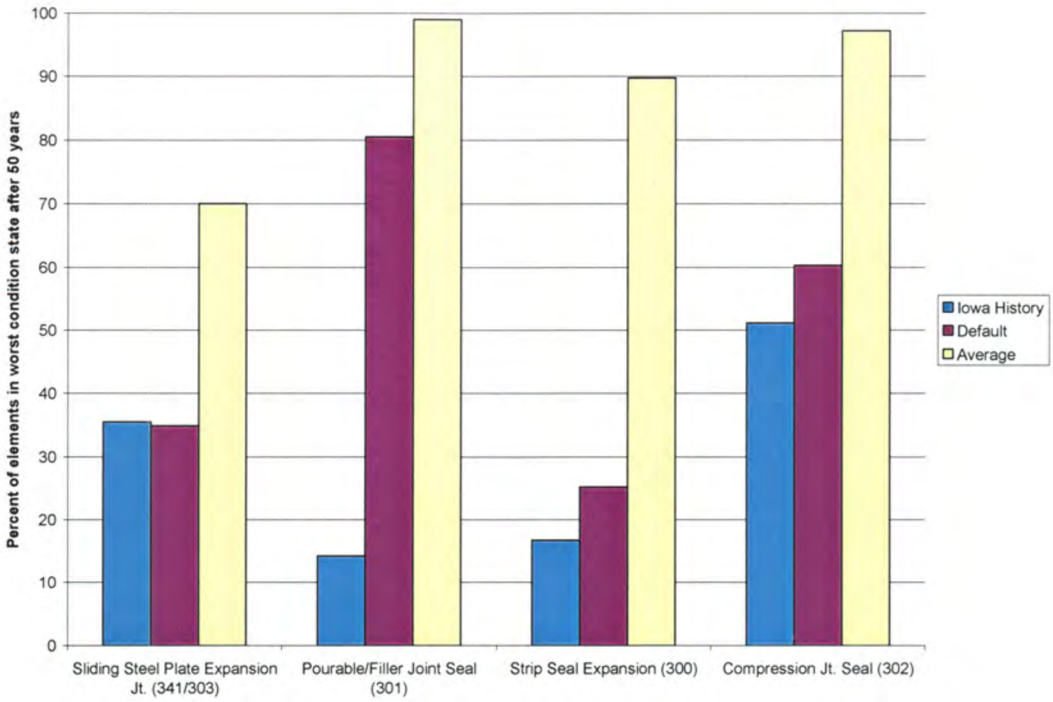
9. Summary of Awarded Contract Prices, Iowa Department of Transportation Office of Contracts, 2001

Table 1. Iowa DOT Replacement Cost Estimates

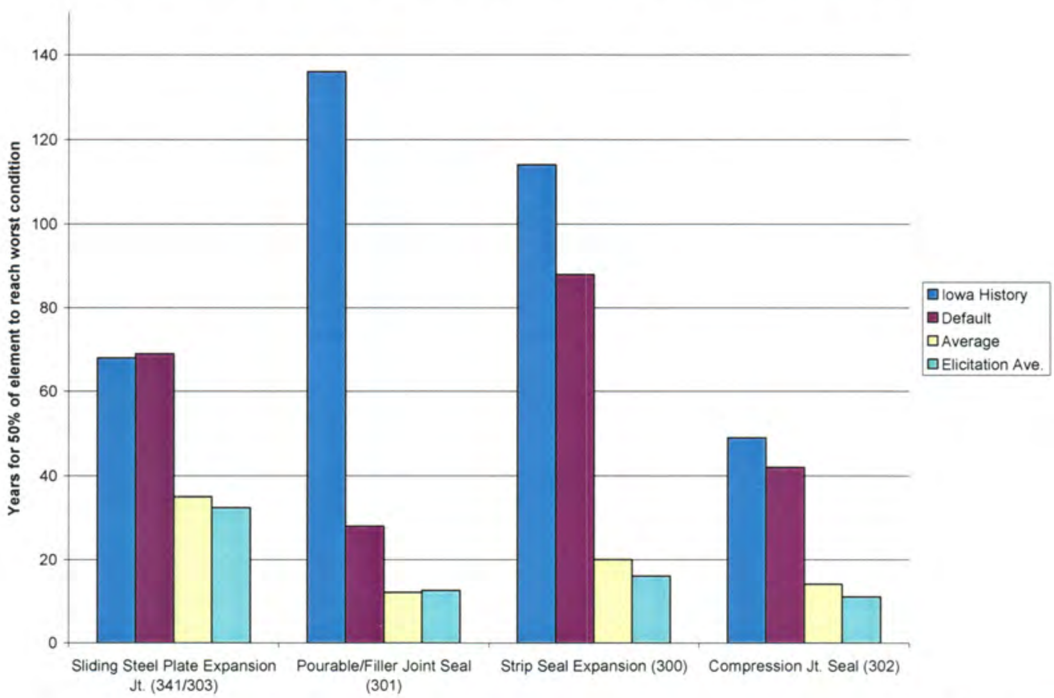
Element #	Elem. Discription	Unit of Measure	2003 Iowa D.O.T. English Unit
12	Bare Concrete Deck	m^2 / S.F.	$11
13	Unprotected Conc Deck w/Asphalt Overlay	m^2 / S.F.	$12
22	Conc Deck w/ Rigid Overlay	m^2 / S.F.	$14
26	Conc Deck w/ Coated Bars	m^2 / S.F.	$11
27	Conc Deck w/ Cathodic Protection	m^2 / S.F.	
28	Steel Deck w/ Open Grid	m^2 / S.F.	$33
31	Timber Deck (bare)	m^2 / S.F.	
38	Concrete Slab (Unprotected)	m^2 / S.F.	$28
39	Unprotected Concrete Slab w/ Asphalt Overlay	m^2 / S.F.	$29
48	Protected Conc. Slab w/ Rigid Overlay	m^2 / S.F.	$31
52	Conc. Slab w/ Coated Bars	m^2 / S.F.	$29
53	Conc. Slab w/ Cathodic Protection	m^2 / S.F.	
54	Timber Slab	m^2 / S.F.	
105	R/C Box Girder	m / L.F.	$3,000
106	Unpainted Steel Open Girder	m / L.F.	$562
107	Painted Steel Open Girder	m / L.F.	$562
109	Pre-Cast Open Girder	m / L.F.	$129
110	R/C Open Girder	m / L.F.	$129
111	Timber Open Girder	m / L.F.	$300
113	Painted Steel Stringer	m / L.F.	$129
117	Timber Stringer	m / L.F.	$60
121	Painted Steel Bottom Chord Through Truss	m / L.F.	
126	Painted Steel Through Truss excluding Bottom Chord	m / L.F.	
131	Painted Steel Deck Truss	m / L.F.	
141	Painted Steel Arch	m / L.F.	
152	Painted Steel Floorbeam	m / L.F.	
156	Timber Floorbeam	m / L.F.	
161	Painted Steel Pin &/or Pin-Hanger Assembly	each	$5,000
202	Painted Steel Column or Pile Extension	each	$1,607
204	P/S Conc. Column or Pile Extension	each	$1,714
205	R/C Column or Pile Extension	each	$2,772
206	Timber Column or Pile Extension	each	$1,157
210	R/C Pier Wall	m / L.F.	$1,168
215	R/C Abutment	m / L.F.	$1,500
216	Timber Abutment	m / L.F.	
231	Painted Steel Abutment Cap	m / L.F.	
234	R/C Pier Cap	m / L.F.	$2,100
235	Timber Pier Cap	m / L.F.	$200
240	Unpainted Steel Culvert	m / L.F.	$139
241	Reinforced Concrete Culvert	m / L.F.	$536
300	Strip Seal Expansion Jt.	m / L.F.	$200

Table 1. (continued)

Element #	Elem. Discription	Unit of Measure	2003 Iowa D.O.T. English Unit
301	Pourable Joint Seal	m / L.F.	$75
302	Compression Joint Seal	m / L.F.	$150
303	Assembly Joint/Seal (modular)	m / L.F.	$1,000
304	Open Expansion Jt.	m / L.F.	$200
310	Elastomeric Bearing	each	$500
311	Movable Bearing	each	$1,500
313	Fixed Bearing	each	$1,500
314	Pot Bearing	each	$2,000
315	Disk Bearing	each	
321	Concrete Approach Slab	each	$5,713
331	R/C Conc. Bridge Railing	m / L.F.	$54
332	Timber Bridge Railing	m / L.F.	$35
333	Other Bridge Railing	m / L.F.	$112
335	Steel Bridge Railing	m / L.F.	$48
357	Pack Rust	each	none
358	Deck Cracking	each	none
359	Bottom of Deck, Slab, or Box Cracking	each	none
361	Scour	each	none
362	Traffic Damage	each	none
365	Steel - Fatigue Cracks	each	none



a. Percent of element in worst condition state elicitation form.



b. Years for 50% of elements to reach worst condition state completed elicitation form.

Figure 1. Example deterioration elicitation sheets.

Scope Rules

Used to build more sensible projects that are cost effective.
Put a **check** next to all additional actions that the IA DOT would do along with the given major action.
If there is an additional action that should be done that is not listed, please write it in.

Major Action	Additional Action that could be done
Rehabilitation of Deck	☐ Replace joints ☐ Rehab. Railings & Barriers
Deck Replacement	☐ Replace Railing ☐ Replace Joints ☐ Replace Approaches ☐ Replace Keyways
Overlay Deck	☐ Replace Joints ☐ Overlay Approaches ☐ Rehab. Railing ☐ Replace Keyway
Repainting Structural Steel	☐ Rehab. Bearings
Rehabilitation of Superstructure	☐ Rehab. Bearings
Replacement of Superstructure	☐ Replace Bearings
Replacement of Keyway	☐ Overlay Decks and Slabs

Rehab Rules
Based on Health Index, which is calculated from Pontis using the condition of each element in a bridge. (100% is bridge in perfect condition)

If the Health Index of a Bridge was less than ______%, we would **Replace** the Structure. (Default =50%)

If the Health Index of a Bridge was less than ______%, we would **Rehabilitate** the Structure. (Default =75%)

Figure 2. Scope and Rehab Rule elicitation form.

Look-Ahead Rules

Look-Ahead is used to prevent Pontis from recommending rehabilitation actions to a bridge that will soon be replaced, or have a major component replaced. Remember that Pontis can project it's projects into the future to recognize needed bridge replacemen

If the **Structure** is programmed to be replaced within 5 years, **don't** do the following actions to the bridge

	Agree	Disagree
Painting of any element		
Maintenance & Repair of Superstructure		
Maintenance & Repair of Substructure		
Maintenance & Repair of Joints		
Maintenance & Repair of Bearings		
Maintenance & Repair of Decks/Slabs		
Rehabilitation of Superstructure		
Rehabilitation of Substructure		
Rehabilitation of Joints		
Rehabilitation of Bearings		
Rehabilitation of Decks/Slabs		

If the **Substructure** is programmed to be replaced within 5 years, **don't** do the following actions to the bridge

	Agree	Disagree
Maintenance & Repair of Substructure		
Painting of Substructure		
Rehabilitation of Substructure		

If the **Superstructure** is programmed to be replaced within 5 years, **don't** do the following actions to the bridge

	Agree	Disagree
Maintenance & Repair of Superstructure		
Painting of Superstructure		
Rehabilitation of Superstructure		

If the **Painting** of the bridge is programmed within 5 years, **don't** do the following actions to the bridge

	Agree	Disagree
Painting of any element		

If **Deck Replacement** is programmed within 5 years, **don't** do the following actions to the bridge

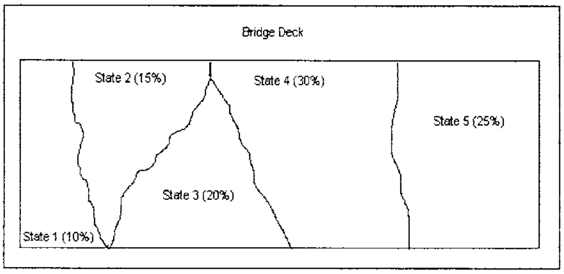
	Agree	Disagree
Rehabilitation of Joints		
Maint. And Repair of Railings		
Rehabilitation of Railings		
Painting of Railing		
Rehabilitation of Deck		

Figure 3. Look-Ahead Rule elicitation form.

Agency Policy Rules

Used to implement a specific department's policies on bridge rehabilitation. These rules will limit the ability of Pontis to recommend projects that result in the least long-term cost, or highest B/C ratio. This is due to the user defining what actions

For each element, different states can exist at the same time. Below is a bridge deck with a different percentage of the area assigned to each state. The agency policy rules determine what action the Iowa DOT would do for each condition state, condition



The chart shown below is entered into Pontis, and a priority number is assigned to each grouping. Below it shows the their are 4 different criteria for Deck/Slabs, and each would be assigned a priority number. This number would tell Pontis to check the

The above bridge deck would have 75% in State 3 or greater, 55% in State 4 or greater and 25% in State 5. Therefore ALL of the Deck/Slab criteria apply, so then it would be decided in order of priority.

Chart Directions: The first entry states: If the Deck or Slab has more than 10% in state 4 or worse, than do the following actions for each given state. It is easiest to start from the worst state, and work your way to the left. For example, if you are

			Actions				
Element	Quantity	State	State 1	State 2	State 3	State 4	State 5
Decks/Slabs	>10%	>=4	Overlay	Overlay	Overlay	Patch & Overlay	Patch & Overlay
Decks/Slabs	>15%	>=5	Replace Elem.	Replace Elem.	Replace Elem.	Replace Elem.	Replace Elem.
Decks/Slabs	>20%	>=4	Replace Elem.	Replace Elem.	Replace Elem.	Replace Elem.	Replace Elem.
Decks/Slabs	>50%	>=3	Overlay	Overlay	Overlay	Patch & Overlay	Patch & Overlay
Keyway	>50%	>=3	Replace Elem.	Replace Elem.	Replace Elem.	Replace Elem.	Replace Elem.
Unpainted Steel Below Joint	>50%	>=2	Replace Paint System	Replace Paint System	Replace Paint System	Replace Paint System	N.A.
Steel Below Joint	>50%	>=3	Replace Paint System	Replace Paint System	Replace Paint System	Replace Paint System	Replace Paint System
Unpainted Steel Bottom	>10%	>=3	Replace Paint System	Replace Paint System	Replace Paint System	Replace Paint System	N.A.
Lower Cord Truss	>10%	>=4	Replace Paint System	Replace Paint System	Replace Paint System	Replace Paint System	Replace Paint System
Moveable Steel Bearing	>25%	>=3	Replace Elem.	Replace Elem.	Replace Elem.	N.A.	N.A.
Moveable Steel Bearing	>50%	>=2	Replace Paint System	Replace Paint System	Replace Paint System	N.A.	N.A.
Girders/Stringers/Beams	>20%	>=4	Replace Super (flex)	Replace Super (flex)	Replace Super (flex)	Replace Super (flex)	N.A.
Joints w/ 3 Condition States	>50%	>=2	Replace Joints (flex)	Replace Joints (flex)	Replace Joints (flex)	N.A.	N.A.
Joints w/ 4 Condition States	>50%	>=3	Replace Joints (flex)	Replace Joints (flex)	Replace Joints (flex)	Replace Joints (flex)	N.A.

Figure 4. Agency Policy Rule elicitation form.

2. UTILIZATION OF HANDHELD FIELD TESTING SYSTEM FOR IMPROVEMENT OF BRIDGE LOAD RATING VALUES IN PONTIS

A paper submitted to the Midwest Transportation Consortium

Patrick Stein

2.1. ABSTRACT

Due to the growing number of structurally deficient bridges in the United States, methods for determining the structural performance of in-service bridges is vital to the preservation of the nation's bridge network. By utilizing field testing, the response of the bridge under a specific traffic load can be assessed and more accurate estimates of structural performance can be determined.

The objective of this part of the research was to develop a field testing system that can be used with the Pontis Bridge Management System (BMS) for selecting suitable bridge candidates for repair or replacement. Currently a handheld computer device has been developed as a tool for gathering bridge inspection data as required by the Pontis BMS. In this part of the research, the same device was utilized, and software was developed to collect strains at different locations on a bridge structure. The developed system was checked for accuracy and usability. In addition, a methodology was developed to assess structural performance from the collected data. A summary of how the developed system can improve the structural assessment of an in-service bridge has been included. In addition, a summary of how this system can be utilized to assist the Pontis BMS in selecting bridge candidates for repair and replacement was also included.

2.2. INTRODUCTION

The Iowa Department of Transportation (IA DOT) currently owns and maintains over 4,000 bridges and culverts on the state highway system. The structural adequacy of these structures has been left to simplified rating equations and continual visual inspection. With heightened concern for the condition of these aging bridges, different solutions have been presented. Methods have been developed to test bridges using applied instrumentation and assess the bridges condition from the collected data. Bridge Management Systems (BMS), however, relies heavily on visual inspection to assess the condition of bridge structures. Field testing of in-service bridges has yet to be linked to the recently accepted Bridge Management System for determining allocation of funds. Although continual visual inspection of bridges is required for a BMS to succeed, these inspections are providing limited reliable information about the performance and the capacity of bridge structures.

The development of an economical data acquisition system that is portable and can be efficiently used on bridge structures could provide a link between visual inspections and actual performance. By pursuing simplicity in the system interface and installation, tests could be completed by persons with limited engineering background. Not only could this concept prevent bridges from being replaced that are thought to be structurally deficient, but could also aid in estimating bridge condition in the database.

2.3. BACKGROUND

2.3.1. Pontis Bridge Management System

Managing the nation's bridges includes tracking the inspection of structures, maintenance needs, along with allocation of funds. Due to the complexity of this, many Bridge Management Systems (BMS) have been developed. A BMS is software designed to aid in the organization of a bridge network and to assist in determining how funds are utilized. Pontis, the most widely used BMS, has been selected by the Iowa DOT to manage their current bridge network. The program is based on mathematical formulations to determine benefit cost ratios, inflation, deterioration of individual elements, as well as additional functions to ensure the highest bridge network condition for a given budget. This program was originally developed by the FHWA, and is continually being updated by AASHTO to allow additional customization for an agency's specific needs.

2.3.2. Utilizing Field Testing

Although many agencies have implemented the Pontis BMS and are currently utilizing its capabilities to determine the maintenance needs of their infrastructure, little structural performance of their bridges is truly known. Although visual inspections are being done on an element level the bridge's response to traffic loads is the primary concern for the safety of the users.

Several of researchers have presented the shortcoming of visual inspection in providing accurate data for a successful BMS [1, 2, 3]. For example, visual inspection does not permit accurate evaluation of bridge serviceability and safety [1]. By incorporating a bridges' existing state and actual response from field testing, parameters such as induced strain can be used to accurately determine the load rating of a bridge system. Current inspection guides offer limited opportunity for the structural adequacy to be estimated, even from a visual aspect [4]. The Manual for Condition Evaluation of Bridges [5], which outlines procedures for visual inspection, agrees that field testing is an effective means of attaining structural performance parameters of a bridge. This load testing is even more essential to those bridges whose response to live load is in question [5].

For the BMS to be optimized, accurate predictions of the remaining life of a bridge must be achieved [3]. Additional research by Chajes et. al. [2] has confirmed that reliable assessments of condition are essential to ensure proper use of limited funds. This project completed by Chajes et. al. [2] has lead to the prevention of unneeded repairs and proven that some low load rated bridges had considerable more capacity than traditional equations would imply. This finding is also established by Wipf et. al. [6], and notes the savings of funds that can result from accurate structural evaluation of bridge parameters.

The current and emerging tools for condition assessment of in-service bridges will assist in the development of optimal maintenance and management of bridges [1]. With the equipment required to field test a bridge becoming more economically viable, the benefits to an agency to accurately assess its infrastructure may outweigh the cost of the testing equipment. This field testing would allow not only insight to the present condition of the bridge network, but also improved maintenance recommendations from the BMS.

Utilization of field measurements allows estimation of various structural properties. An assessment of load distribution, support conditions, along with unintended composite action can all be evaluated through non-destructive testing using strain transducers [6]. This global evaluation can be utilized on bridges made of steel and concrete, along with bridges that contain innovative materials. In addition, structural benefits of various maintenance techniques can be assessed by regularly testing in-service bridges. A histogram of strains may be created for these bridges that will not only prove as a model of changing bridge condition, but will also provide information on the effectiveness of current maintenance techniques [1, 2].

2.3.3. Structural Response of In-Service Bridges

Although the need for accurate structural capacity and condition assessment has proven beneficial to numerous agencies, the method of testing and evaluation is quite diverse. Due to a bridges behavior, interaction between various elements is difficult to assess. Although the load configuration during a field test is known, the contribution of various bridge elements to bridge performance is often qualitative. Due to this uncertainty in the evaluation, two main methods are being used to quantify structural parameters. The first is outlined in research completed by both Wipf et. al. [6] and Farhey et. al. [7], and involves finite element analysis of a bridge structure. This approach adjusts various defined analysis parameters and a repetitive solution is carried out until the analytical results agree with field test data. Parameters that can be adjusted within the model include the modulus of elasticity of various materials, the end conditions of the bridge, along with the stiffness of major elements. Gauge location, along with sensor quantity, must be sufficient to accurately estimate the response of the superstructure. Once these parameters are extracted, the mathematical model can then be utilized to analyze the bridge structure under different truck load configurations.

Drawbacks of such a system include cost of the FE software, along with having personnel with FE background to operate the software. A significant amount of instrumentation may be required in more complex bridges for the program to calibrate itself accurately. Further measures must also be taken to ensure that the vehicle location on the structure is correlated with the measured strain value. These concerns often prove impractical to an agency that is unfamiliar with FE, and also have limited field testing experience.

The second method of utilizing field test data is summarized in by Bakht et. al. [8]. This method involves instrumentation of only critical load carrying mechanisms, such as girders or stringers of bridges. Although less instrumentation may be required to assess these limited members' response to loading, gauge location is critical to accurately assess bridge parameters of concern. This method allows properties of members which will be most effected by live load will be assessed. These parameters can include neutral axis location of a cross-section, lateral distribution of loads, along with maximum live load strain and an estimate of support restraint. By eliminating a computer model of the bridge, significant assumptions may be required to estimate properties of the bridge elements. However, calculations are more practical for an agency to complete without consultation of specialists.

2.3.4. Pontis Load Rating

The Pontis software currently utilizes a transition probability model to estimate deterioration in different bridge elements [9]. Combined with biannual visual inspections, Pontis uses mathematical methods to assess the performance of bridges, and allocates available funds accordingly. A goal of this research is to improve the performance assessment of bridges, therefore preventing rehabilitation and replacement of bridges that have sufficient strength.

The inclusion of field test data into the Pontis software is inherently difficult due to the fact that a bridge structure consists of several elements. Separation of these elements insures more complete visual assessment of the bridge. However, structural interaction of these elements is unavoidable during a field test, making individual element assessment unfeasible. Secondly, the level of this element interaction is vital in the performance of the bridge, therefore separation is undesirable for structural performance assessment. Interaction parameters can include composite action between the deck and girders, end restraint at the abutment, along with distribution of the load between girders. These parameters have significant influence on the load rating of a bridge structure [10]. Therefore, one needs to incorporate such effects to obtain accurate assessment of the structural adequacy of the structure.

Pontis currently separates projects into two categories; functional improvements and preservation actions [11]. Preservation actions are associated with maintaining the physical condition of the bridge, therefore depend on inspection results and deterioration probabilities. Functional improvement projects seek to improve the functionality of the bridge due to deficiencies that can include vertical clearance, bridge width, or bridge strength. Field testing provides an improved assessment of the bridge strength, therefore can deter bridge strengthening projects on structurally sufficient bridges. Pontis associates the strength of each bridge structure with the structural rating. This rating is entered in the appraisal tab of the bridge inspection form, and includes the ability rate the bridge using field testing. Figure 1a shows and example bridge rating page in the Pontis program, with the load testing pull-down selected for the Inventory Rating.

Bridge ratings are separated into two separate categories; Operating rating level and Inventory rating level. Inventory rating level corresponds to the live load which can safely utilize the existing structure indefinite period of time [5]. The Operating rating level corresponds to the maximum permissible live load, which may cause damage to the bridge over time [5]. Field testing conducted for this thesis will concentrate on load levels corresponding closer to the Inventory rating level. Tests conducted near Operating rating level and are often termed "proof load tests", and involve much higher load levels which may be inaccessible by agencies.

Numerous research projects have been completed to assess the utilization of field test results in rating of in-service bridges. Research by Cai et. al. [12] outlines basic concepts behind field testing to rate in-service bridges. Many methods have been presented to use field test information to develop an improved rating. These methods often include further analysis, sometimes in search of improving mathematical models. This expanded method for bridge rating is outlined in research by Barker [13]. The rigorous analysis included in Ref. [13] includes assessment of actual field dimensions, impact factor, both longitudinal and lateral load distribution factor, along with additional considerations. Although this level of input allows for possibly greater increases in the load capacity, few agencies are willing to generate such effort on a statewide plan. From this research, however, it was shown that the dominant factor in increasing load capacity was lateral distribution. Through study of the rating equation, this improvement can be directly applied to the bridge rating, as discussed later in the work presented herein. This concept of direct improvement to the rating factor is verified through research completed by Cai et. al.[10], however includes field measured strains instead of distribution factor.

2.4. OBJECTIVES

The objective of this part of the research was to develop a system that can be utilized in the field to collect bridge test data. Ease and mobility were among the factors that were considered in selecting available systems. With recent advancements in computer technology, handheld devices were deemed capable of attaining the goals listed above. Such a device has also been utilized in collecting visual inspection data on agency bridges.

Testing and verification of the developed system's accuracy and usability, along with the methodology used to assess structural performance was completed. A summary of how this system can improve the structural assessment of an in-service bridge was included, along with how this system can be utilized to assist the Pontis Bridge Management System software in selecting bridge candidates for repair and replacement.

2.5. SYSTEM CONFIGURATION AND PROGRAMMING

The first step in developing the handheld data acquisition system involved determining capabilities of handheld devices and their compatibility with available data acquisition hardware. Handhelds have many different names including Personal Digital Assistant (PDA), Palm Pilot, or Pocket PC. PDA is a general term that includes handhelds that operate on either the Palm OS operating system or the Pocket PC operating system. Palm Pilot and Pocket PC refer to the operating system that is used in the device, but can also be used as a general term to describe a handheld computer.

Due to the limited application of PDA's as data collection devices, it was found to be easier to select companies that could provide signal conditioning of the data, and then determine the needed operating system to ensure compatibility. Signal conditioning refers to the manipulation of a signal or voltage, into a more accurate and recordable value. This is accomplished by providing consistent excitation to the gauge, along with gaining of the signal to a more distinct value. Strain gauge signals are typically gained by 100 to 1000 times the original signal to provide the storage device an opportunity to decipher changes in voltage.

Due to the infancy of the concept, few companies could supply hardware capable of recording numerous channels of data simultaneously. National Instruments, however, had experience with such a system and advertised 16 channels of acquisition. The system could also be utilized with either operating system, so the selection of available PDA's increased. It was determined that the HP iPAQ h5150 was proven capable by National Instruments, and had adequate memory and processing to accomplish field testing. The transfer of data between the signal conditioning unit and the PDA was through a PCMCIA card, typically used in Laptop computers. This card could be used in various PDA's with expansion pack capabilities. The iPAQ had expansion pack capability which included an extended battery, which was deemed necessary for field testing. Although National Instruments advertised 16 channels of acquisition, the initial hardware purchase included only 8 channel capability, with the capability to expand to 16 channels. This was done to insure the hardware was capable for our particular bridge testing application.

The gauges used in the field testing were Bridge Diagnostics Incorporated (BDI) full-bridge strain transducers. These gauges are simple to install and reusable, therefore applicable for economical field testing by a state agency. Figure 1b shows a typical transducer being installed in the field. Following grinding the surface clean, the gauge is glued to the member using a quick setting epoxy.

National Instruments utilizes Labview programming software and various drivers to communicate between the PDA and the signal conditioning unit. Due to the limited computing power of the PDA, some functions of Labview cannot be used; therefore programming was simplified to attain efficient storage of the data. This programming, which is completed on a PC, is then "built" for the PDA by drivers included with the Labview PDA module. Advanced functions such as real time plotting were investigated, yet proved incapable by the limited computing power and development of the Labview PDA software.

2.6. SYSTEM TESTS

The data collection system was configured for a full-bridge gauge configuration, and was initially tested utilizing a load cell for the single channel data acquisition program. Following success of the single channel program, transducers were then used to test the data collection system. Although these initial tests provided no basis for accuracy, due to the loading being arbitrary, it did verify the collection of data, the recording rate, along with the sensitivity of the system. Initial tests of the system were completed relying completely on the battery power from the PDA expansion pack. This battery, although capable of providing adequate power for a single channel, was underpowered for multiple channel acquisition. Secondary tests were then completed with a series of 9 volt batteries powering the signal conditioning unit and providing excitation to the transducers. This was deemed adequate for a short-term solution to the battery problem.

2.7. LABORATORY TESTS

The first test to verify the accuracy of the system was conducted in the laboratory using a small section of aluminum beam, simply supported and loaded with steel weights. The PDA system was tested against the venerable Bridge Diagnostic Inc. collection software. Four BDI transducers were applied, two on each flange. Each system was run separately, yet collected strain data at the same rate. The results are shown in Fig. 2a, with the BDI system shown in heavier line weight. Offset of the data in the abscissa axis is due to unequal loading rates of the beam. As shown in the figure, the BDI system has a much higher sensitivity to input signal than the PDA system. The BDI system fluctuates approximately 0.3 microstrain, when the PDA system fluctuated 3 microstrain in the verification tests. Due to this large variation, it was difficult to assess the accuracy of the data acquisition system, however proved reliable enough for expansion to 16 channel capabilities due to the relatively similar magnitudes and strain profiles. This test also did not verify the applicability of the nine volt batteries, due to the limited duration of the test, and only exciting four gauges. It was determined that these issues would be verified during various field tests of in-service bridges.

Following this lab test, the system was expanded to 16 channels, and the signal conditioning unit was modified to include connectors for gauge cables and a power switch. The system is shown in Figure 1b. Each connection on the signal conditioning unit transfers data for 4 gauges. The Labview program was also expanded to accept data from 16 channels, as advertised by National Instruments. However, initial tests recorded only 15 channels correctly. National Instruments was contacted, and it was verified that a bug existed in the software preventing 16 channels of acquisition from being recorded. Therefore the system was now limited to 15 channels of acquisition. The PDA system screen layout is shown in Fig. 2b, detailing the various controls of the system.

2.8. FIELD TESTS

An objective of this project is to configure a system that is applicable for various bridge types. Therefore tests were scheduled for both steel girder bridges as well as prestressed concrete girder bridges, which incorporated some innovative materials. These field tests were conducted in conjunction with a test where the BDI hardware was being utilized, therefore provided a direct comparison of test results. Gauge locations were the same, as well as truck paths over the bridge.

2.8.1. IA 92 Steel Girder Bridge

The first bridge that was tested was a 3-span steel girder bridge originally built in 1938, then retrofitted with additional exterior girders in 1967. This bridge is located in Pottawattamie County on Iowa Highway 92 near the town of Griswold. The original bridge was constructed with integral abutments; however the girders were constructed noncomposite. Due to this strength deficiency, additional exterior girders were added, and constructed composite with a custom barrier detail. Further strengthening was completed by adding Fiber Reinforced Polymer (FRP) plates to the bottom flanges of all of the girders in 2003.

The current performance of this bridge configuration is difficult to assess without the assistance of a field test. By field testing, properties of the bridge can be estimated to assist in the evaluation of its current strength. Estimation can then be made on the effectiveness of the strengthening system. This bridge is especially unique, due to the exterior girder stiffness being much greater than interior girders due to composite action, along with the spacing of girders being irregular, and the properties of the interior girders being different. A typical section of the bridge is shown in Figure 3a.

Gauges were installed on the top and bottom flange of the steel girders, both at midspan locations and near the abutment. Readings were first taken by the BDI system with the truck at crawl speed. The BDI software is run on a laptop computer, and has a powered signal conditioning unit that receives electricity from a generator on the sight. The PDA system is self powered, and is relies on an excitation of 5 volts, when the BDI system uses 10 volts.

Following the completion of data collection by the BDI system from all truck paths, gauges were disconnected from the BDI system and connected to the PDA data acquisition system. Similar truck paths were then completed using the PDA system to collect strain data. Fifteen channels of acquisition were completed, with 9 channels reading midspan strains, and 6 reading abutment strains. The BDI strain profiles were then compared to the strains collected using the PDA data acquisition strain profiles to assess the accuracy of data collection. Figure 3b shows a direct comparison of selected gauges with significant strain magnitudes. Like colors represent equivalent gauge numbers, therefore should have not only similar magnitudes, but also strain profile shapes. The BDI system is shown in heavier line weight. Although the profiles were of the same basic shape, the PDA system consistently recorded strain magnitudes lower on certain gauges, and somewhat higher on others. Some small differences in magnitude were expected, due to slight changes in transverse truck position for each run. However, two runs were completed for the BDI software and the magnitudes were nearly identical between similar truck paths. The higher excitation voltage provided by the BDI system provides cleaner readings, due to a higher signal to noise ratio. However, excessive noise was not recorded on either systems strain profiles, so this was initially disregarded as the problem.

It was determined that the data collection system operated correctly, and stored readings at the specified rate, and the programmed sensitivity. However, an additional field test was to be conducted to retest the systems accuracy prior to deeming the system complete.

2.8.2. 53rd Street Bridge, Prestressed Concrete Girder Bridge

The second test was conducted on a three span prestressed concrete girder bridge, with various deck configurations on each span. This bridge is located on 53rd Street in Bettendorf, Iowa, in Scott County. The PDA system was utilized only on the east span, which had a Fiber Reinforced Polymer (FRP) deck with a thin wearing surface. This was the first FRP deck in the United States to utilize composite bending action with pre-stressed concrete girders. The connection detail of this design is shown in Fig. 4a. Structural properties of the bridge were originally determined using conventional specified equations, however true behavior of this design type was somewhat uncertain. The bridge test was therefore being conducted to assess the performance of this design. The girders were integral with the abutment for both end spans, and the bridge width was constant across the bridge. Similar truck paths were run for both systems.

Gauges were installed in the center of the bottom flange of the girders, and the side of the top flange. Identical truck paths were completed using both the BDI software and the PDA system to collect strain data. Fifteen channels of acquisition were completed, all reading at midspan of the girders. The BDI strain profiles were again compared to the PDA data acquisition strain profiles to assess the accuracy of data collection. Figure 4b shows a direct comparison of a selection of gauges which had significant strain magnitudes. Like colors represent equivalent gauge numbers, therefore should have not only similar magnitudes, but also strain profile shapes. The BDI system is shown in heavier line weight. This test proved that all gauges reading greater than 20 microstrain had significant loss in magnitude compared to the BDI values. However, strain profile shapes remained consistent with the BDI system, so it was determined that the system was underpowered. Although the nine volt batteries provided sufficient voltage to excite the gauges, the current provided by the small batteries was not capable of returning the signal without losses. This was not apparent in lab tests, due to the connection being significantly shorter between gauge and signal conditioning unit. Field tests were conducted with gauges being up to 75 feet away from the signal conditioning unit, compared to 20 feet during laboratory testing. Also, full 15 channel acquisition was never tested in the lab; therefore additional strain on the batteries was expected during field testing. Research of battery options was completed, and a rechargeable 12 volt battery was purchased, capable of extended acquisition with 2.2 Amp hours of power. Figure 1b details the completed system components, including the rechargeable battery.

2.8.3. East 12th Street Bridge, Steel Girder Bridge

The East 12th Street Bridge is a 2-span high performance steel girder bridge with integral abutments and a conventional cast-in-place deck. This bridge was constructed in early 2004, and spans over Interstate 235 in Des Moines, IA. This test was conducted to insure the performance and reliability of the new battery. At any transverse section of the bridge, the girders have identical section properties and spacing. The PDA system was used to test strains near the north abutment of the bridge. During this test, the BDI software as well as wireless monitoring was utilized in conjunction with the PDA system.

Three separate load paths were conducted at crawl speed, and each truck path was conducted twice to insure consistency. The data collected was then directly compared to the BDI software for accuracy. PDA system test magnitudes and strain profiles matched the BDI software, within the range of the PDA's collection sensitivity. Although numerous digits of reading were being stored, it was still felt that the sensitivity of the system was a concern for calculation accuracy. As shown in Fig. 2a, determination of strain magnitude can become difficult with the lower sensitivity PDA data acquisition system. National Instruments was contacted, and upon further programming the sensitivity was effectively doubled for the system. This translates to a sensitivity of 1.5 microstrain, versus the previously tested 3 microstrain.

2.9. METHODOLOGY

Bridge rating is based on the simplified expression shown below in Equation (1).

$$RF = \frac{C - A_1 D}{A_2 L(1+I)} = \frac{1}{L}\left(\frac{C - A_1 D}{A_2(1+I)}\right) \tag{1}$$

RF = rating factor for the live-load carrying capacity
C = capacity of the member related to current in-service condition
D = dead load effect on the member
L = live load effect on the member
I = impact factor to be used with the live load effect
A_1 = factor for dead loads used in load factor method
A_2 = factor for live loads used in load factor method

The Iowa DOT rates its bridges using this equation, and then enters each rating into the Pontis database. Therefore it is desirable to improve the accuracy of these rating factors with a simple approach, utilizing the additional information the field test data has provided to improve the already rated bridge network. Parameters such as end restraint and neutral axis of the girders can be qualitatively assessed, but offer no direct relationship to the rating equation. However, distribution of the live load to individual members is directly assessed in section 6.7.3 of AASHTO's Manual for Condition Evaluation of Bridges [5]. The option exists to attain this distribution factor from field tests, therefore improving the rating of the tested bridge. Current ratings within the IA DOT database were found using empirical equations within bridge design specifications. As shown in Equation (1), the rating equation is inversely proportional to the live load effect. This allows the distribution factor to be directly changed in the equation without further calculation. If the distribution factor originally used in the rating calculation is known, multiplying the current bridge rating by the ratio shown in Equation (5) satisfies the improvement of the load rating.

$$L = (D.F.)_{CODE}\, L_{TOT} \tag{2}$$

$$RT = (RF)W \tag{3}$$

Combining Equations (1), (2), (3)

$$RT = \frac{W}{(D.F.)_{CODE}\, L_{TOT}} \left(\frac{C - A_1 D}{A_2 (1 + I)} \right) \tag{4}$$

Rating Equation Improvement Using Field Test Distribution Factor

$$RT = \frac{W}{(D.F.)_{CODE}\, L_{TOT}} \left(\frac{C - A_1 D}{A_2 (1 + I)} \right) \left\{ \frac{(D.F.)_{CODE}}{(D.F.)_{FIELD}} \right\} \tag{5}$$

$(D.F.)_{CODE}$ = Distribution Factor determined from empirical equations
$(D.F.)_{FIELD}$ = Distribution Factor determined from field test data
L_{TOT} = Total live load effect on the bridge structure
RT = bridge member rating in tons
W = weight of nominal truck in tons used in determining the live load effect

The distribution factor used in the original rating is needed, as well as a field test distribution factor estimate. This ratio can then directly improve the rating value, preventing unneeded replacement and rehabilitation. Care must be taken, however, to insure that the bridge is capable of additional load. A highly deteriorated bridge may distribute loads effectively, yet have insufficient strength properties to justify an increase in the bridge load rating. Additional research within the subsequent chapter assesses this issue.

An additional assumption made through field testing of bridges is that the bridge responds in a linear manner up until the point of specified rated load allowance. However, nonlinearities can be present as the load nears the bridges ultimate load capacity. Release of locked supports, cracking of concrete, along with other mechanisms can occur during larger displacements due to extreme live load conditions. This will affect the Operating rating level, and are often not triggered by Inventory load levels. Therefore careful consideration must be made when using the below methodology to improve the Operating rating of in-service bridges.

The distribution factor (D.F.) is the fraction of live load transferred to the most heavily loaded girder under maximum live load effects. Therefore, during field tests attempts were made to position the truck to produce maximum effects on the girders. This was typically done by lining a set of wheel-lines directly over a girder centerline for one path, along with straddling a girder with the truck on another path. Estimation can also be made to estimate multiple presence of trucks; therefore a path can be aligned to represent a second truck on the bridge at the same time as one of the first paths. These three paths are the best estimate of maximum live load effects on the bridge. Strain readings from these paths must then be analyzed to estimate the distribution of loads. During the field test, the strains were assumed to be directly related to the bending moment in the section. This assumption neglects the effects of any longitudinal force that could be present due to end restraint. The D.F. is the fraction of moment carried by the most heavily loaded girder, as shown in Equation (6). Determining the D.F. can be done by expanding basic beam theory equations for the girders, which was originally developed by Stallings et. al. [14]. As shown in Equation (7), inertias and neutral axis locations of each girder must be estimated for the tested bridge. Symmetry of the bridge can be used to estimate girder properties that are not instrumented, however strain magnitudes for these distanced girders are typically very small, therefore be can be ignored, and optionally instrumented due to there insignificant effect on the load distribution.

$$D.F. = \frac{M_G}{\sum M_G} \tag{6}$$

$$\varepsilon = \frac{Mc}{EI} \tag{7}$$

Solving for "M";

$$M_G = \frac{\varepsilon_G E_G I_G}{c_G} \tag{8}$$

Combining Equations (6), (8);

$$D.F._j = \frac{\dfrac{\varepsilon_{G_j} I_{G_j}}{c_{G_j}}}{\sum_{i=1}^{n} \dfrac{\varepsilon_{Gi} I_{Gi}}{c_{Gi}}} \tag{9}$$

Methods were developed to determine the inertias and neutral axis locations of girders directly from test strains, and are included in subsequent chapters. Neutral axis location was initially estimated from segments of the strain profiles that recorded significant strain magnitudes. Figure 5 shows the neutral axis plot for the IA 92 Bridge. Clearly interpretation of neutral axis location is necessary, due to variations as the truck changes position. Therefore a statistical program ensuring accurate estimation of the neutral axis is desired. Once this location can be confidently estimated, the composite girder properties of the in-service bridge can be estimated. Figure 6 shows an example D.F. calculation for the IA 92 steel girder bridge. Neutral axis locations were estimated from strain profiles, and inertias of the composite girders were then determined using the steel girder design properties. Properties of the exterior girders were determined using the assumption of fully composite with the deck and barrier. This was verified by comparing test strain magnitudes and estimated neutral axis location with that of conventional design methods. Comparisons were made between the AASHTO [15] calculated value for distribution factor, and that derived from field test results. However, test strains in the farthest girder were neglected due to insignificant magnitude, and as an illustration for distanced girders that may not be instrumented.

2.10. CONCLUSIONS

The completed research provides a basis for the improvement of bridge load rating using field test data. This improved load rating can be directly entered into the Pontis database, which can then assist in the assessment of repair and rehabilitation projects. Further development could allow for field test data to be stored in the Pontis database, and be utilized not only in the improvement of bridge load rating, but also serve as a record of bridge performance.

The components and software provide agencies with an economical method to better assess performance of their bridge network. Through collection of these field measurements, this evaluation will allow an agency to prevent premature replacement or rehabilitation of structures, allowing funds to be utilized on truly deficient structures. Utilizing this handheld data acquisition system is not limited to bridge testing to improve load rating, however this was determined, through evaluation of current options, to be an effective method to improve the Pontis BMS selection of bridges with deficient strength. With proper engineering judgment, various bridge types can be instrumented and tested with any loading, and assessments of bridge performance can be estimated.

The PDA was primarily used as a storage device, with little data manipulation capability due to the limited driver functions. However, recent development of additional drivers for handheld programming insures that further programming of the test equipment could provide additional information to an agency following a field test. In addition to strains, the PDA could collect additional information beneficial to bridge performance. With the proper components added, the data acquisition system could collect accelerometer data, readings from deflection gauges, as well as load cell data. This expandability insures a testing system that can be used for the assessment of various bridge parameters.

2.11. RECOMMENDATIONS

Recommendations for utilizing field test data to improve Pontis Bridge Load Ratings are as follows:

- **Field testing of in-service bridges should include only the test truck at crawl speed.** Distribution factor cannot be accurately determined with the above methodology when dynamic effects or additional ambient traffic is included. The truck should have adequate load to produce significant strain magnitudes ($\geq 15\ \mu\varepsilon$) to assess D.F. and neutral axis location. Trucks used in discussed field tests weighed a minimum of 55 kips, and produced adequate strain magnitudes. The system is fully capable of recording dynamic strain readings, as well as strains due to ambient traffic. However these effects prohibit accurate D.F. assessment.
- **Instrument bridge girders near midspan.** The most critical region for effective distribution of loads is at or near midspan. Gauges should therefore be placed at the

same transverse location of the bridge near midspan. Gauges should be instrumented on the bottom and topmost section of the girder to insure significant strain magnitudes and accurate neutral axis estimation. Field tests were conducted prior to development of D.F. methodology; therefore gauges were utilized at various locations for verification of the handheld data acquisition system performance.

- **Load Rating Improvement methodology is only valid for girder bridge types.** The handheld data acquisition system is capable of collecting strains on any bridge type or element surface; however presented methodology for load rating improvement is only valid for girder bridges. The system could still be utilized to assess live load strain in bridge members to insure safety of older structure types through assessment of stress magnitudes in critical members. Periodic bridge testing could also provide a histogram of strains, modeling the changing bridge condition, and will provide information on the effectiveness of changing maintenance techniques.
- **Bridges with significant skew should be more thoroughly instrumented to assess distribution of loads.** No bridges that were field tested under this research included a skew on the bridge. Instrumentation location is vital on skewed bridges to assess load path issues related to distribution. AASHTO Standard Specifications for Highway Bridges [13] presents no effect to the distribution of loads due to skew angle. Further research on field testing methods to assess skewed bridge distribution factors would further benefit agencies assessment of in-service bridge performance.
- **Further research on field test data integration with BMS databases should be conducted.** This research provides only one method of assisting the Pontis database with project evaluation through improvement of the bridge load rating. Further developments should be completed to assess the lack of structural evaluation in the preservation projects which Pontis recommends.

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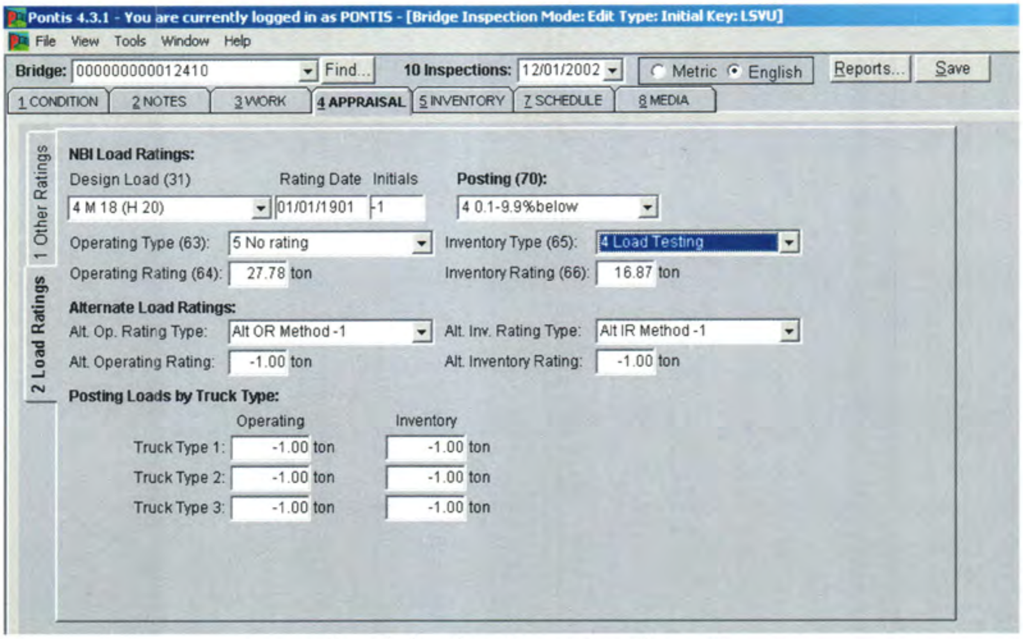
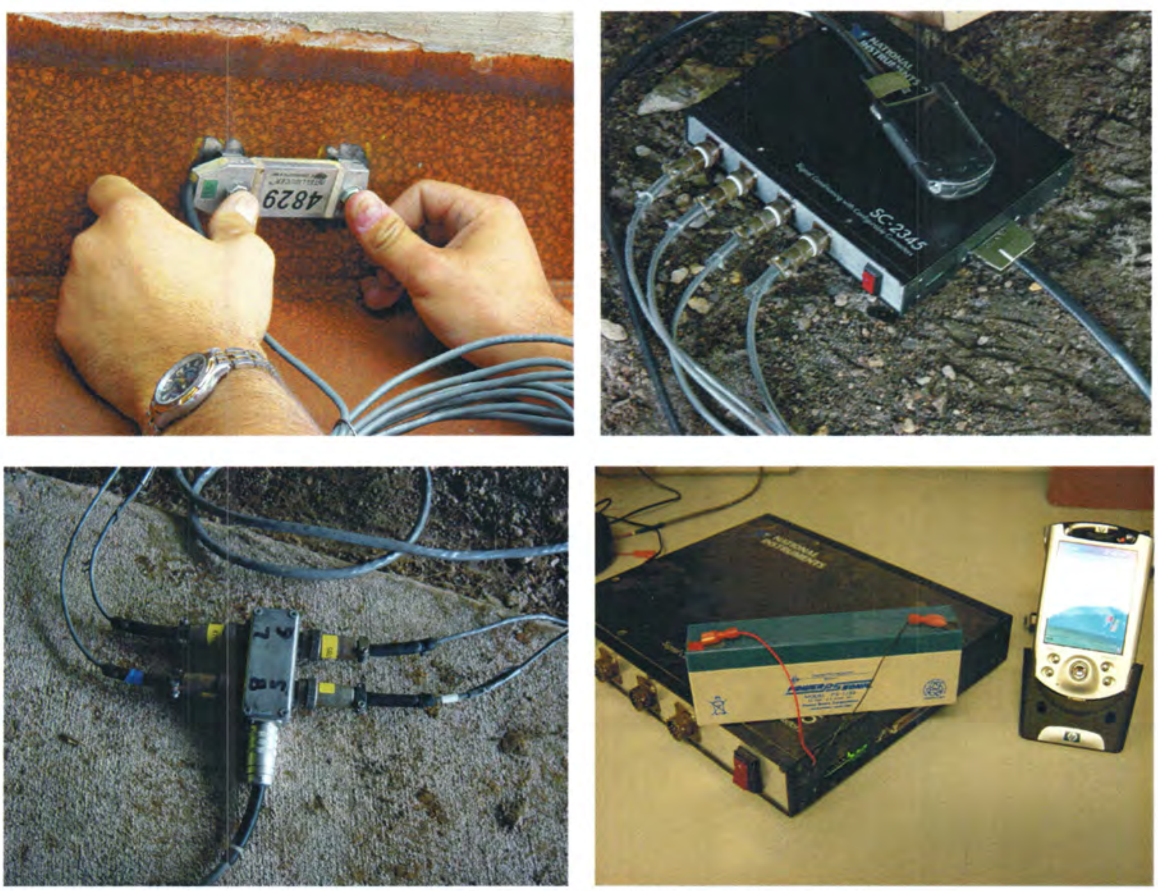
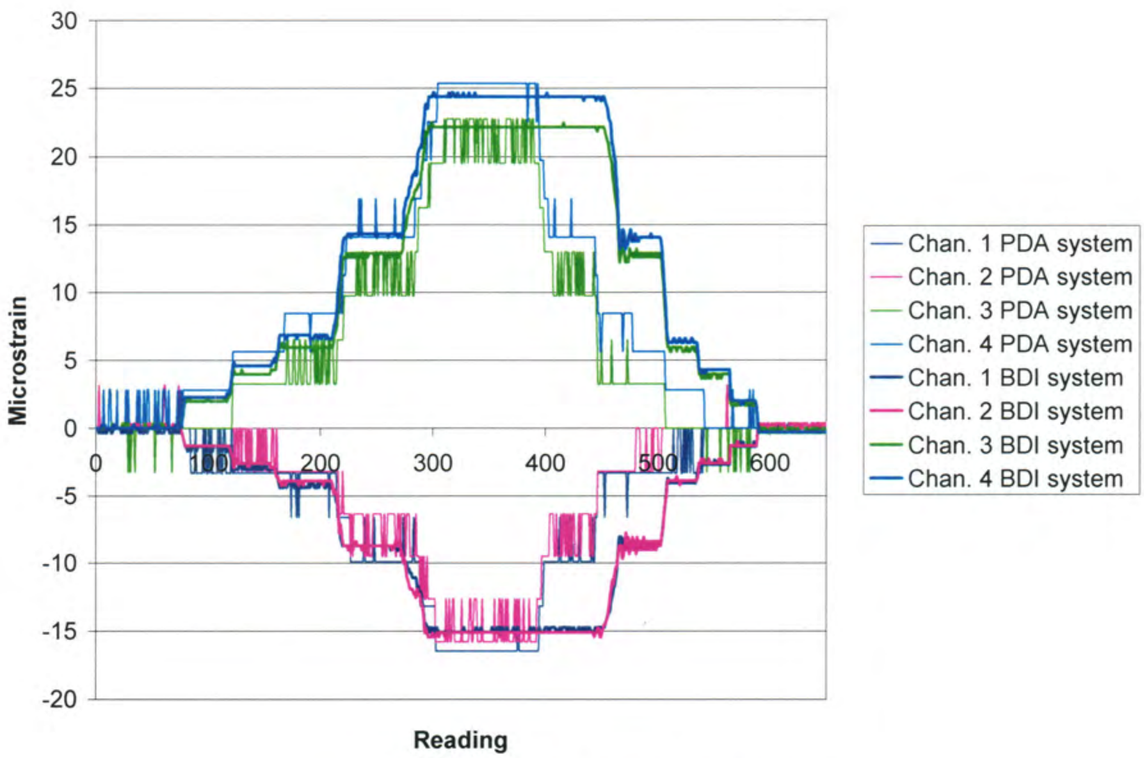


a. Pontis load rating screen layout.

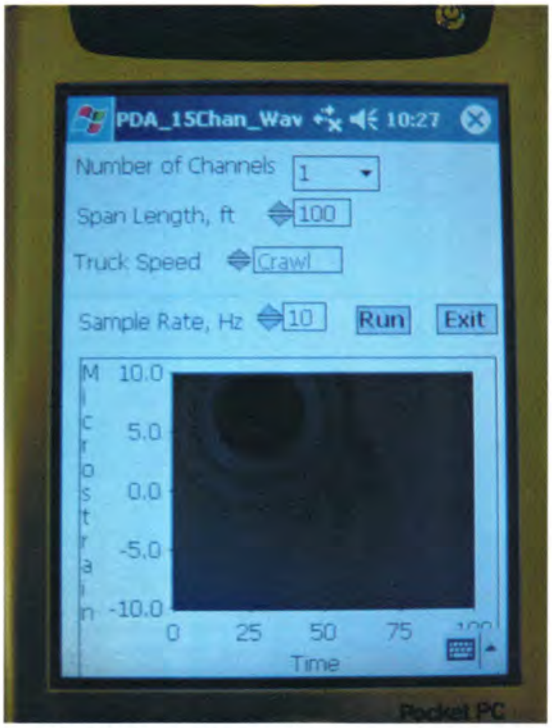


b. Handheld data acquisition system details.

Figure 1. Pontis load rating screen and system layout pictures.

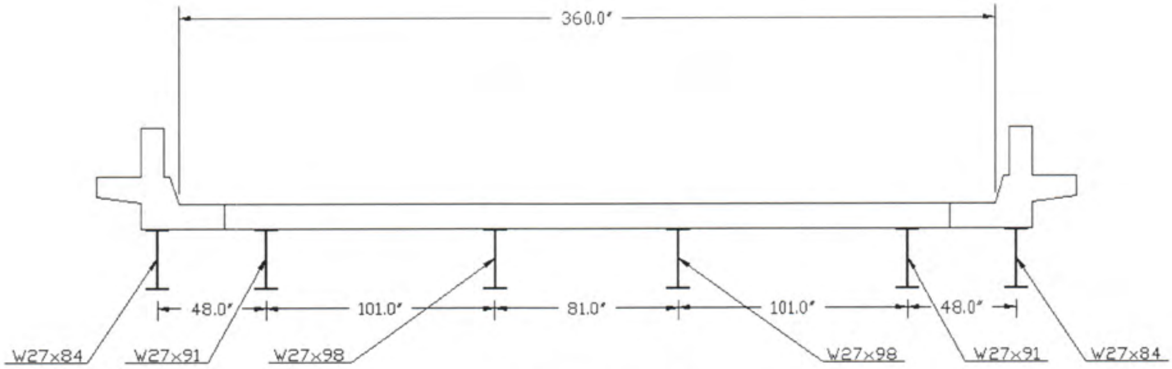


a. PDA system verification results.

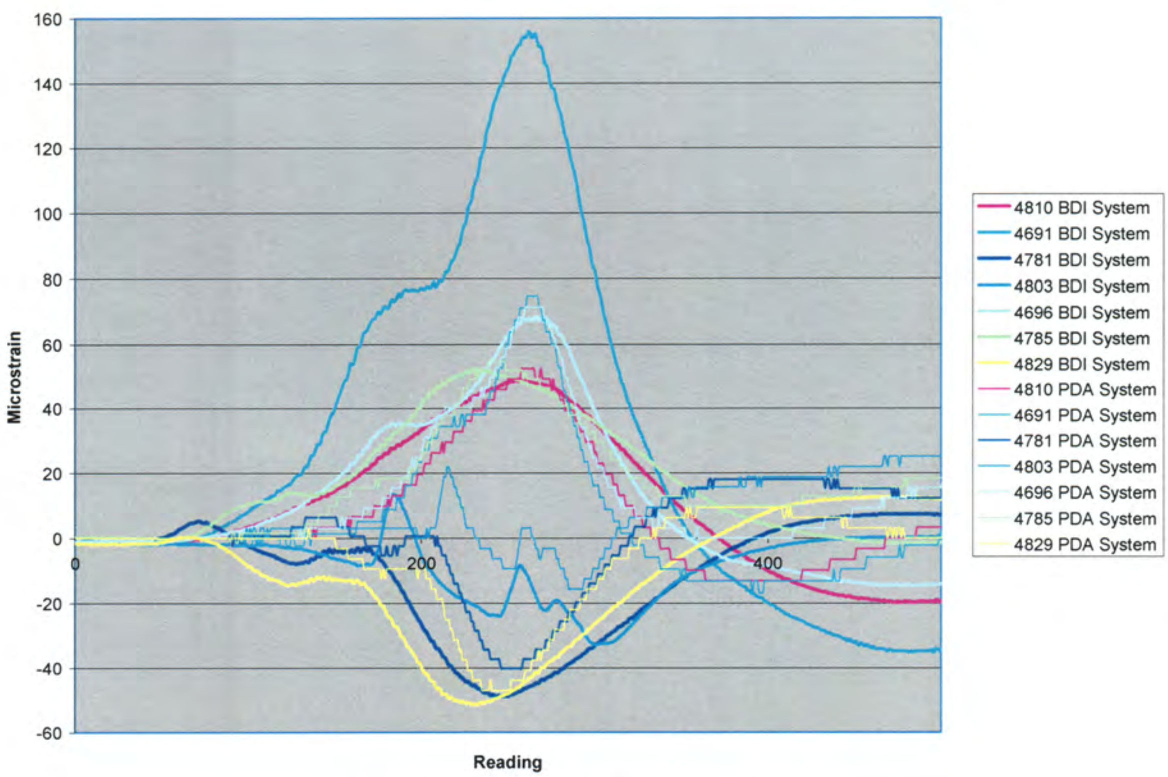


b. PDA data acquisition screen layout.

Figure 2. Data acquisition system verification results and PDA screen layout.

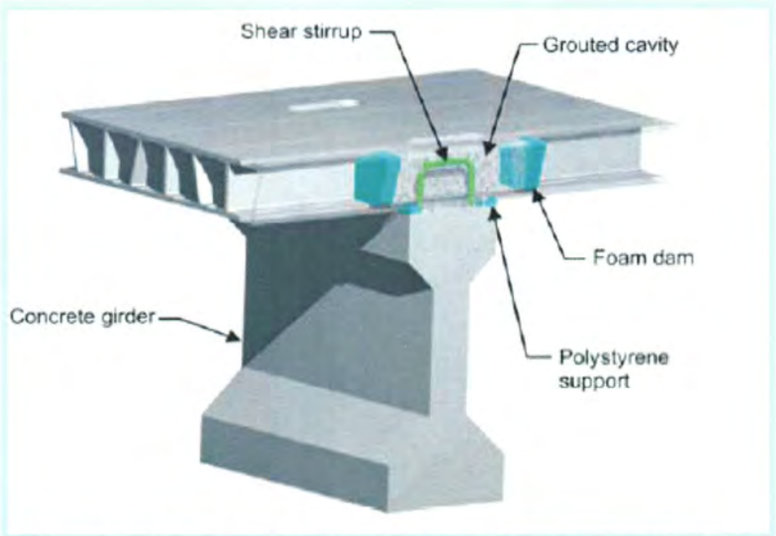


a. IA 92 typical bridge section.

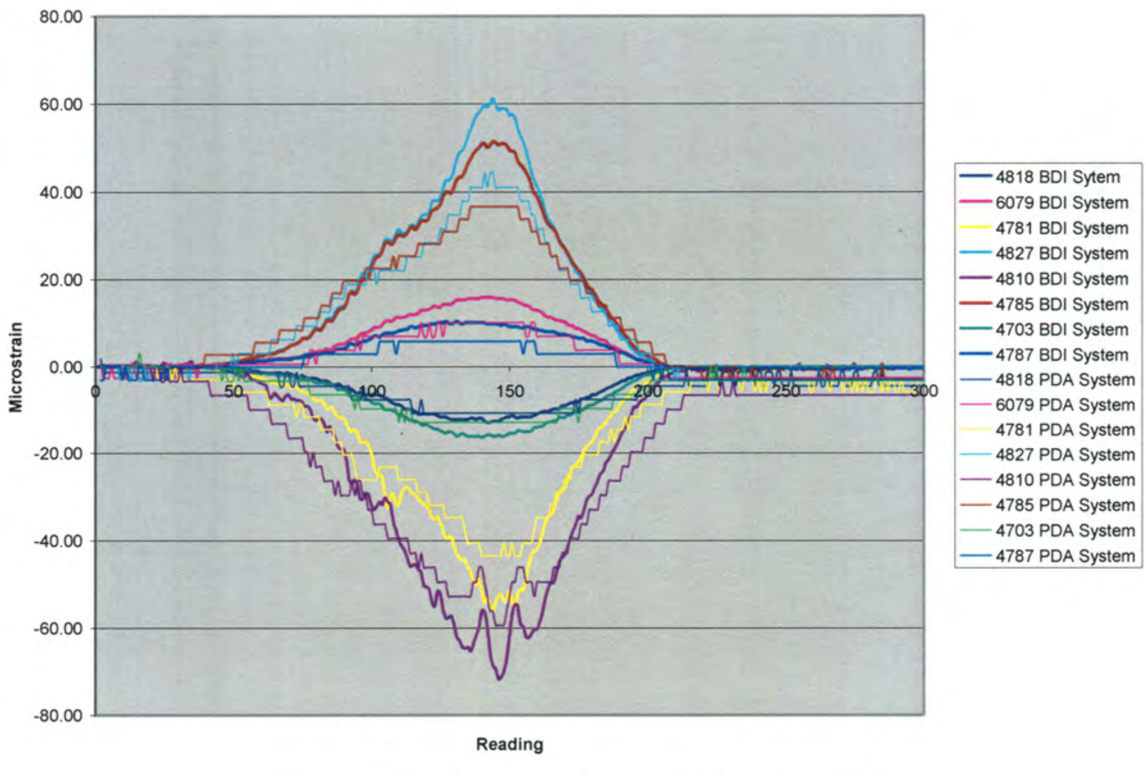


b. IA 92 bridge strain profile comparison.

Figure 3. IA 92 Steel Girder Bridge details.



a. 53rd Street Bridge typical FRP deck to girder connection detail. [16]



b. 53rd Street Bridge strain profile comparison.

Figure 4. 53rd Street Prestressed Concrete Girder Bridge details.

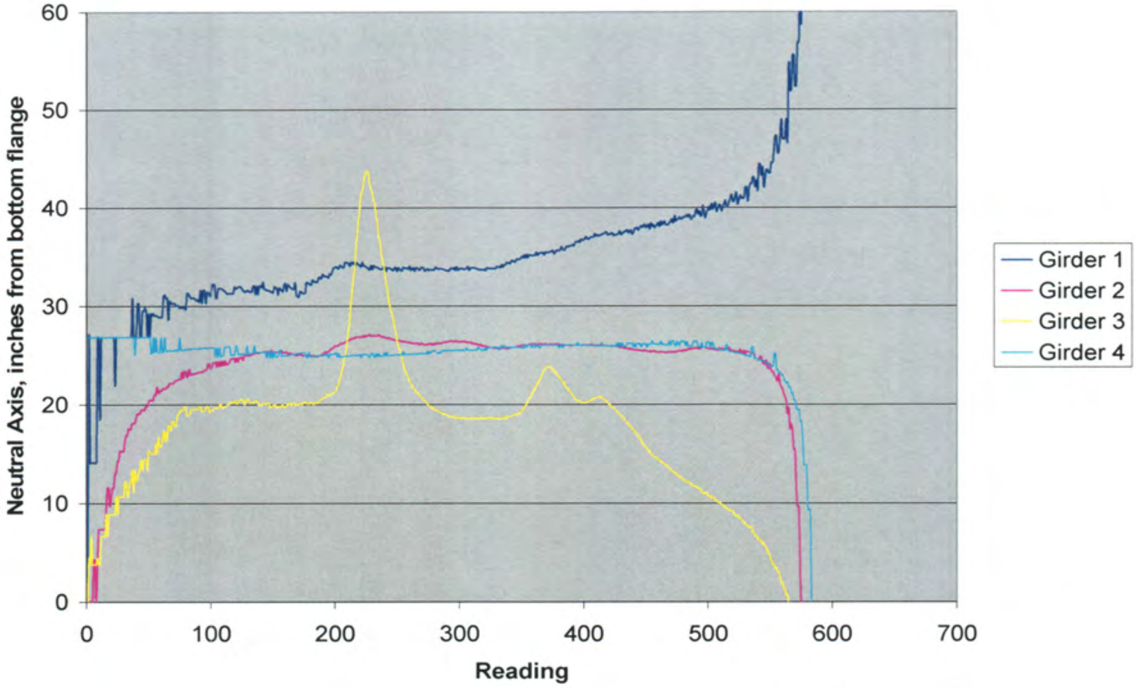
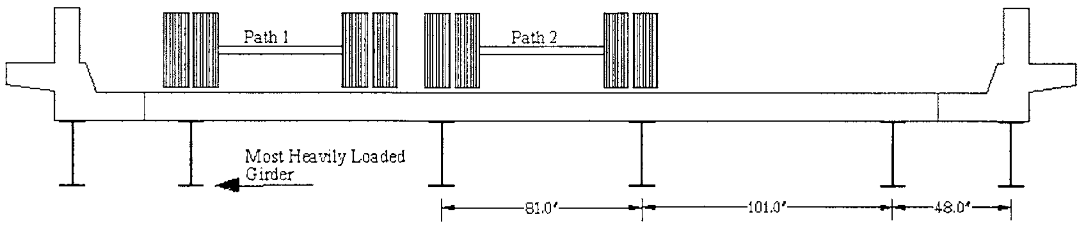


Figure 5. Example neutral axis plot for IA 92 Bridge girders.



Girder #	1	2	3	4	5	6
I_G (in^4)	35313	9890	7618	10385	9890	35313
C_G (in)	37.4	25.8	20.8	25.3	25.8	37.4
ε_G	66.32	230.84	165.77	118.85	39.27	N/A
$\varepsilon_G I_G/c_G$	62619	88489	60713	48785	15054	
$\Sigma\varepsilon_G I_G/c_G$	275660					

$$D.F._j = \frac{\frac{\varepsilon_{G_j} I_{G_j}}{c_{G_j}}}{\sum_{i=1}^{n} \frac{\varepsilon_{Gi} I_{Gi}}{c_{Gi}}} = \frac{88489}{275660} = 0.320$$

$$(D.F.)_{FIELD} = 0.320 \quad \text{(Two Trucks)}$$

$$(D.F.)_{FIELD} = 0.640 \quad \text{(One Truck)}$$

$$(D.F.)_{CODE} = \frac{s}{5.5} = \frac{(101+81)/2}{5.5(12)} = 1.37 \quad \text{(Per Wheel Line)}$$

$$(D.F.)_{CODE} = 0.689 \quad \text{(Per Truck)}$$

$$\left\{\frac{(D.F.)_{CODE}}{(D.F.)_{FIELD}}\right\} = \frac{0.689}{0.640} = 1.08 \quad \text{(8\% Increase)}$$

Figure 6. Example distribution factor analysis for IA 92 Bridge.

3. ADDITIONAL METHODOLOGY DEVELOPMENT AND VERIFICATION

3.1. OBJECTIVES

A methodology has been presented in the previous section which integrates field test measurements with the Pontis software. However, additional programming of these methods was removed from the previous section to allow concise justification of the procedures and findings. This section will include an explanation of the required software, along with conclusions on the applicability of the system. Results from three field tests are included, as well as an evaluation of the system's potential effects on the current IA DOT bridge network.

3.2. PROGRAMMING

Due to the infancy of the handheld data acquisition system concept, a majority of the programming was developed through this research effort. This programming began with utilizing the Labview PDA module [1] to develop a program capable of collecting and storing strain data at a consistent rate. Once data acquisition rate and storage of voltages from strain gauges were verified, additional functionality was added to assess bridge testing parameters, such as span length and the speed of the test truck. The PDA program utilizes this information to estimate the length of data acquisition needed for the field test. Information collected by the PDA program is stored in a condensed ".dat" format, and is unrecognizable by software such as Microsoft Excel. The Labview PDA drivers store data in this format due to the limited memory and processing power of the PDA, however it was felt necessary to convert this data to a more suitable format to allow for use by various personnel.

Further programming was therefore completed in Labview [2] to transform the data to Microsoft Excel format. This secondary program is independent of the PDA programming, and includes additional functions which are not capable with the PDA module. These functions perform reduction of offset in the data, along with application of individual gauge factors to the field test data. These gauge factors transform voltage readings stored by the PDA into an equivalent strain. Gauge factors are specific to each transducer, and are supplied by the manufacturer of the transducer. The final function of this secondary program is to write the manipulated data into Microsoft Excel format, and save the file in a specified location. The user interface of the secondary program, named "DatalogRead", is shown in Fig. 1.

Upon creation of the Microsoft Excel file, analysis of the data can be completed in the Distribution Factor Program (DFP), which was developed utilizing Macros within Excel. This was developed in Excel due to its widespread use throughout agencies. Agency familiarity with Excel allows the program to be more intuitive, and further developments to the program will be more accessible to the users. Although field test data reformatting may be limited to computers with Labview software for this specific data acquisition system, once data is reformatted, the DFP can be utilized by anyone with access to the field test information.

The DFP user interface is shown in Fig. 2. This program was developed to assess field measured load distribution factor, which can then be utilized to improve the bridge load rating. Parameters including number of tested girders, their individual structural properties, along with deck thickness must be entered prior to execution of the program. These entered values must relate to the in-service condition, and should include estimates of deterioration in the section. The current rating by codified equations can then be improved, no matter the condition of the bridge, given that codified ratings relate to the bridge's current condition. Although inclusion of deteriorated properties within rating calculations will likely decrease the load capacity, a more accurate estimate of distribution from load testing can increase this rating, and prove structural adequacy. This can prevent posting of bridges which have sufficient carrying capacity, as well as prevent bridge replacement recommendations on structures with sufficient strength.

Assessment of the distribution factor from field test measurements is summarized in equation (9) of chapter 2. This equation requires an estimate of three values; inertia of the beam, its neutral axis, along with strain in the beam. This information must stem from a strain profile, which may contain spikes due to vibration, localized effects, or noise in the signal. When spikes are recognized by the DFP, the calculation of inertia, neutral axis, and distribution factor is prevented. Spike recognition is accomplished by assessing relative changes in magnitude with respect to surrounding readings. A spike is recognized when strain readings both prior to and following a single strain reading are found to have a large magnitude difference from that of the single strain reading. When only readings prior to a given strain readings are found to have large differences in magnitude, a spike is not recognized. This would represent a release of a stiffening mechanism, which may also register large changes in strain magnitude. Figure 3 outlines example strain profiles for both possible cases.

Additional programming was completed to assess only regions of the strain profile which have significant strain magnitudes. This is completed to insure the measurements used to estimate properties are not negatively affected by the sensitivity of the acquisition system. For the completed field tests, estimation of girder neutral axis was limited to ten times the sensitivity, i.e. 15 microstrain. This provided consistent results for each test, even with maximum magnitudes differing significantly between tests. Changes in the minimum magnitude can be made in the user interface if data collection sensitivity increases, or confidence in data accuracy changes.

Following initial bridge parameter entry, the DFP is executed to assess the neutral axis location for all girders with sufficient strain magnitude. This compiles an array of estimated neutral axis locations corresponding to each reading which satisfies the minimum strain requirement, therefore producing an array of neutral axis estimates for a single girder. Therefore a statistical function capable of analyzing the data, and providing a conservative estimate of the girder neutral axis, was investigated. Neutral axis profiles can often contain localized increases in magnitude, as well as evident linear regions. When visually assessing a neutral axis profile, localized magnitude changes are often ignored, and evident linear regions with consistent magnitude are chosen for the in-service neutral axis location. When no linear region of consistent magnitude is evident, an approximated average of the profile is chosen. Linear regions typically occur at higher magnitudes of the neutral axis profile, therefore a function which produces results slightly higher than a simple average of the data was desired. The root mean square (R.M.S.) statistical function was investigated, and was utilized on neutral axis profiles from field tested girders to verify its applicability. It was found that the method proved reliable when used with test data, and was insensitive to irregular variations in data profiles. Final neutral axis location for test girders is therefore established using this RMS function, shown in equation 1. Figure 4a illustrates example neutral axis arrays, which are plotted along with calculated RMS values for a set of girders.

$$RMS = \left(\frac{1}{n} \sum_{i=1}^{n} (N.A.)_i^2 \right)^{1/2} \qquad (1)$$

RMS = root mean squared value

n = number of applicable data points

$(N.A.)_i$ = i^{th} applicable neutral axis reading

For each truck path, neutral axis locations are determined for each girder by the above method. Different truck paths may result in distanced girders having insignificant strain magnitudes; therefore a neutral axis location may not be calculated for that specific girder. However, other paths will likely cause sufficient strain magnitudes to produce a neutral axis estimate. Therefore, neutral axis estimates for each girder are averages for each girder from all truck paths. If a test girder does not record strain magnitudes in any of the truck paths sufficient enough to garner neutral axis calculation, the girder is neglected in the calculation of distribution. Neglecting girders without sufficient strain magnitude to calculate neutral axis will be conservative, due to this girders effect not being included in the denominator of equation (9) of Chapter 2. Disregarding this girder will produce a slightly higher distribution factor estimate for the entire bridge structure.

Once field measured neutral axis locations are established, further programming utilizes this information to determine a field measured inertia. Figure 4b details a composite girder section, and the strains induced by a test vehicle. The neutral axis is utilized to determine an effective thickness of deck relating to the measure neutral axis from test measurements. The calculated deck thickness is a conceptual measure of the amount of material acting composite with the girder, and does not directly relate to the as-built deck thickness. Calculated deck thicknesses larger than as-built conditions can be caused by barriers or sidewalks, which add additional material acting composite with the girder. Development of the expression used to calculate the equivalent deck thickness for a girder is shown in equations (2), (3), and (4). Inertia for the individual girder can then be determined from the in-service cross-sectional properties.

The general expression to determine the neutral axis of a beam/slab cross-section is:

$$c = \frac{\sum Ay}{\sum A} = \frac{A_b y_b + (B_{eff} \times t_c) y_c}{A_b + (B_{eff} \times t_c)} = \frac{A_b y_b + (B_{eff} \times t_c)\left(D + \frac{t_c}{2}\right)}{A_b + (B_{eff} \times t_c)} \qquad (2)$$

Solving for t_c from equation (2) produces a quadratic equation:

$$B_{eff} \frac{t_c^{\,2}}{2} + B_{eff} t_c (D - c) + A_b (y_b - c) = 0 \qquad (3)$$

Solving for t_c from equation (3) using the quadratic formula:

$$t_c = \frac{-B_{eff}(D-c) + \sqrt{(B_{eff}(D-c))^2 - 4B_{eff}(A_b(y_b - c))}}{2B_{eff}} \qquad (4)$$

c = Neutral axis location measured from the bottom flange of the girder
A_b = Cross-sectional area of the girder, estimated to be equal to the specified design value
y_b = Center of area for only the girder section, measured from the bottom flange of the beam
B_{eff} = Effective width of deck material acting composite with the girder section, transformed by the modular ratio to represent girder material properties
t_c = Thickness of the concrete deck, estimated to be equal to the specified design value
y_c = Center of area for only the concrete, measured from the bottom flange of the girder
D = Distance between gauges, which can be estimated as the depth of the girder

The last component required for distribution factor calculation is the strain in each girder. Strains are extracted from the data at "high" strain levels for each girder from a single truck path. These strains are used to calculate the distribution factor relating to each truck path, using equation (9) of Chapter 2. Distribution factors from appropriate individual truck paths are then combined to estimate the impact of multiple trucks on the bridge. The lateral distribution factor calculated from the combination of adjacent truck paths provides an estimate of the fraction of load transferred to a single member from two trucks. This value is then doubled to represent the percentage of a single truck that would be effectively transferred to a single member.

3.3. FIELD TEST RESULTS

Field test results were utilized in the previous section to assess the accuracy of the handheld data acquisition system. Due to changes in system components following initial the following analysis of the three tested bridges. The following analysis utilizes the DFP, however relies on field test data from the BDI collection system, due to previously mentioned issues with strain magnitude. Also, previous tests were meant to verify the system accuracy and usability, prior to development of the distribution factor improvement concept, therefore gauge location was often insufficient to properly assess distribution. However, the current system, with proper gauge installation, would be capable of sufficient data collection to utilize the DFP. Results from the DFP for the three tested bridges can be found in Fig. 5 through 7.

3.3.1. IA 92 Steel Girder Bridge

The IA 92 steel girder bridge demonstrated significant composite action, although the interior girders of the bridge were originally designed non-composite. This additional stiffness was evident in the calculation of individual beam inertia by the DFP. Distribution factor calculated by conventional methods was found to be 0.689, while the DFP calculated to be 0.690. The codified value of distribution for this bridge structure is verified through this field test. This high percentage of load transferred to a single member is caused by high respective strain magnitudes in the first interior girder. Magnitudes of strain in this girder were found to be over twice that of adjacent girders, which is reflected by the field test D.F. The field test data for this bridge is shown in Fig. 8.

3.3.2. 53rd Street Prestressed Concrete Girder Bridge

The 53rd Street Bridge utilized FRP deck panels in place of a conventional concrete deck. Due to the panels having significant voids within its cross-section, the DFP could not assess an accurate effective width for the deck. However, due to all girders having equivalent section properties, relative difference in girder stiffness was still possible, resulting in accurate field measured distribution factors. Interestingly, one of the tested girders was found to have a lower neutral axis than originally designed, even with the possibility of additional stiffness from the decking. Other girders demonstrated minimal benefit in stiffness due to the FRP decking. Utilizing conventional equations for the given bridge layout resulted in a D.F. of 0.647. The field measured D.F. for this bridge was found to be 0.854; therefore transferring 32% greater load levels to a single girder than codified equations would reflect. This increase in load effect can be partially associated with overlap of individual truck paths. This overlap would be an impossible load combination, due to both trucks occupying a fraction of the same space, therefore the D.F. could be considered conservative. However, under composite bending the FRP deck provided little additional stiffness. This lack of rigidity in the deck can be assumed consistent in the transverse direction, causing less efficient lateral distribution of loads. This additional information relating to structural performance is invaluable to a bridge load rating engineer.

3.3.3. East 12th Street Steel Girder Bridge

The East 12th Street Bridge not only demonstrated improved composite action over that of specified equations, but also distributed loads extremely effectively. Conventional equations resulted in a D.F. of 0.79, when field results produced a D.F. of 0.523. Improvement of the D.F. would result in an increase of 51% over that of the originally calculated load. This bridge is constructed of High Performance Steel, combined with High Performance Concrete. It can be verified by this example that conventional calculations are quite conservative for these high performance materials. This bridge is new to the IA DOT bridge network, therefore will not be considered deficient in strength for a significant amount of time. However, this example shows the benefit that field testing can have on Inventory and Operating rating levels.

3.4. BRIDGE LOAD RATING IMPROVEMENT POTENTIAL

There are currently over 650 girder bridges in the IA DOT bridge network. This presents a significant opportunity for the configured handheld data acquisition system to influence the maintenance decisions of the agency by collecting and analyzing field test information. By conducting field tests in conjunction with inspections which utilize snooper trucks, the inconvenience of gauge installation is minimized, and both visual and structural performance assessments of the bridge can be conducted in a limited timeframe.

The above test results present three different findings from a structural performance assessment of the structures, all which improve the owner's confidence in the bridge's structural performance. Applicability of the codified distribution factor equations was verified on the IA 92 girder bridge, which was originally constructed in 1938, and may be thought to have questionable load capacity. The subsequent field tests affected the codified load rating significantly, decreasing the load rating capacity of the 53rd Street Bridge, while allowing significant increase to the load rating for the East 12th Street Bridge. This illustrates the improvements that can be found by utilizing the presented methodology.

Girder bridges within the IA DOT network were analyzed to assess potential impacts that the direct load rating improvement could have on the bridge network. Figure 9 shows structurally deficient girder bridges within the IA DOT network, and an assessment of bridge load capacity with respect to the agency policy. The agency currently specifies an Operating rating of 36 tons for all bridges within the network; therefore the data is independent of structure size or facility carried. As can be seen in the figure, a significant number of the bridges are within 30% less than the Policy value. If it was estimated that D.F. could be improved by up to 30% on each structure, this would relate to 169 bridges which could potentially have sufficient structural capacity, which were originally thought to be structurally deficient by Pontis. These improvements to the load rating within Pontis would allow for more economical use of funds, and insure deficient bridges are selected for replacement.

A simulation was conducted to determine which bridges with strength deficiency were being selected by Pontis for strengthening or replacement. Due to the high cost associated with replacement or strengthening of bridge structures, bridges without significant truck demand are often not found to be economical by the Pontis BMS. However, it was found that 8 bridges were still being selected by Pontis for replacement due to strength deficiency, therefore judged as economical by the BMS. If these bridges were field tested, an evaluation of their load carrying capacity could be conducted, and prevention of replacement recommendations by the Pontis BMS could possibly be prevented. This would allow the programmed funds to be reallocated to truly deficient structures.

3.5. CONCLUSIONS

The proposed methodology has been expanded to further detail the interpretation of field measurements, and assess D.F. from field test results. The assumptions made in the development allow for simplified analysis, while still utilizing the value of field test measurements. The developed program was then utilized on three different bridge structures, and proved reliable and consistent with hand calculations.

The results from the bridge tests proved significant differences from conventional codified values, not only in distribution of loads, but also performance of individual beam sections. This information can be utilized to improve the accuracy of the load rating within Pontis. The potential benefit of utilizing the handheld data acquisition system is evident in this research, and could be utilized nationwide to more accurately assess the structural performance of girder bridges within a network. By confidently estimating the performance of bridge structures, bridge management can be improved for the IA DOT, and other state agencies.

3.6. REFERENCES

1. Labview 7 Express, PDA Module for Pocket PC, Version 1.0, National Instruments Corporation.

2. Labview 7.0f1, 2003 National Instruments Corporation.

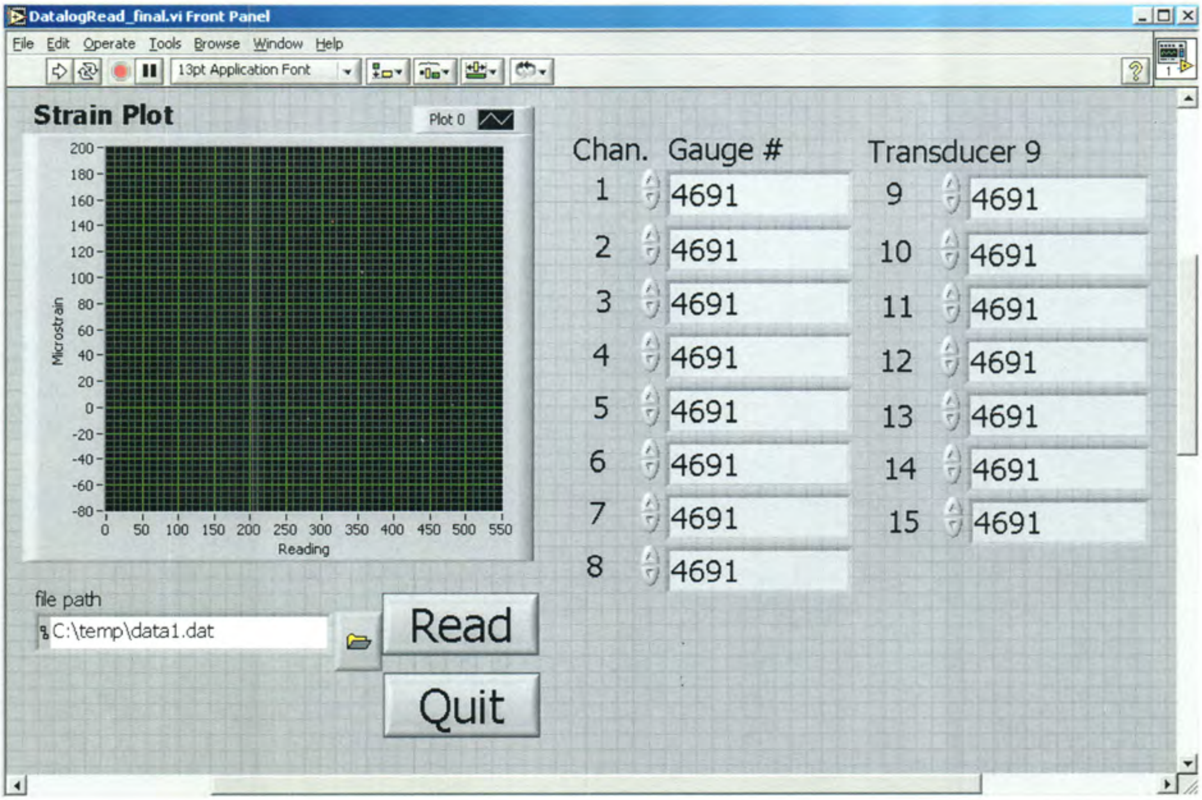


Figure 1. Labview user interface for DatalogRead program.

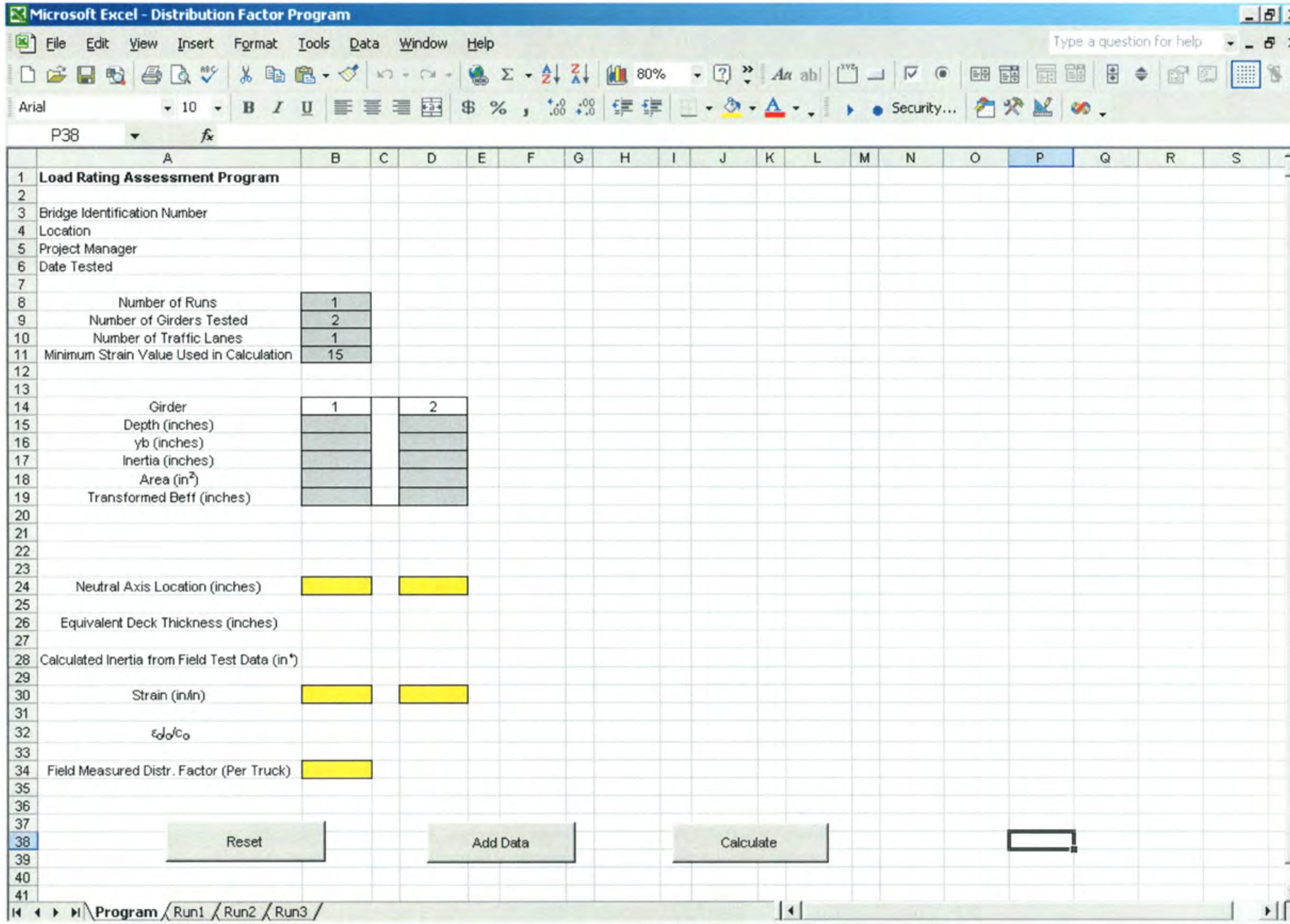
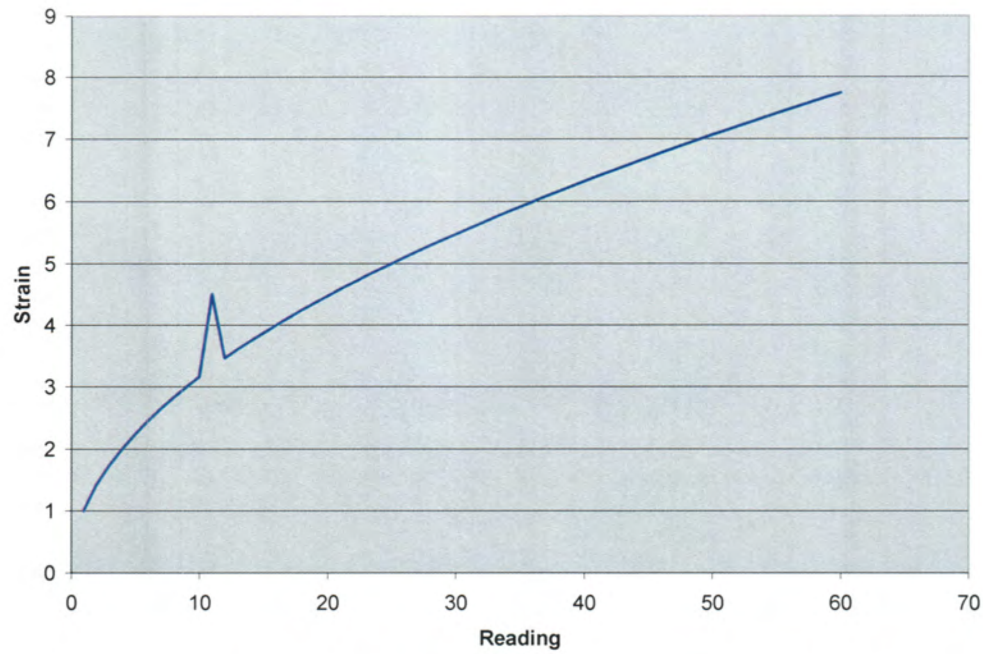
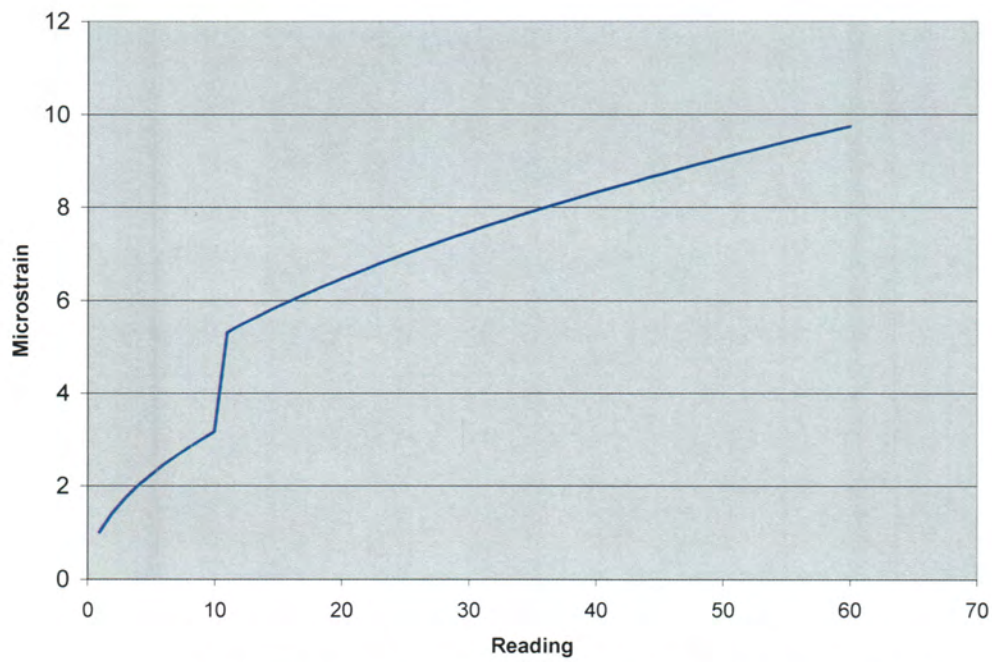


Figure 2. Distribution Factor Program user interface.

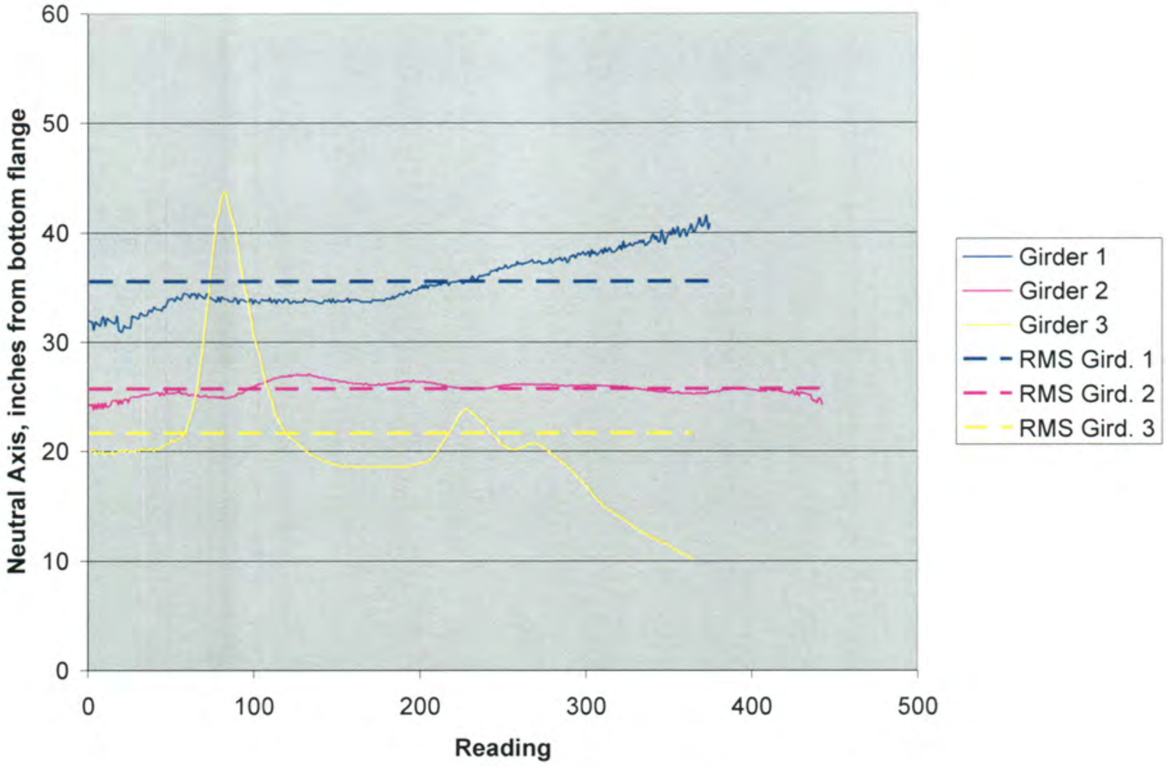


a. Example strain profile with spike

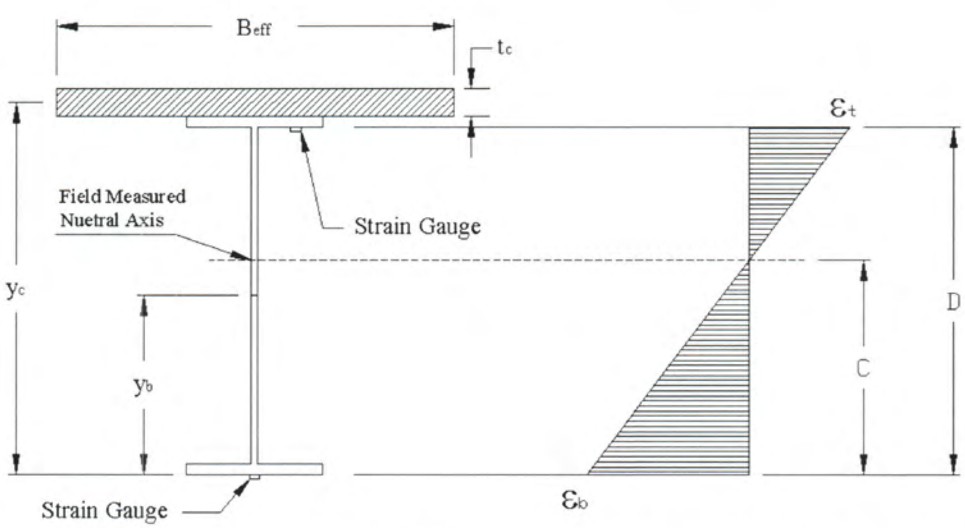


b. Example strain profile with release of stiffening mechanism

Figure 3. Example Spike Recognition.



a. Example neutral axis assessment from RMS function.



b. Idealized strain profile for composite girder under bending.

Figure 4. Composite girder property estimate details.

	A	B	D	F	H	J	L
1	**Load Rating Assessment Program**						
2							
3	Bridge Identification Number						
4	Location	IA 92					
5	Project Manager						
6	Date Tested						
7							
8	Number of Runs	3					
9	Number of Girders Tested	6					
10	Number of Traffic Lanes	2					
11	Minimum Strain Value Used in Calculation	15					
12							
13							
14	Girder	1	2	3	4	5	6
15	Depth (inches)	26.7	26.84	27	27	26.84	26.7
16	yb (inches)	13.35	13.42	13.5	13.5	13.42	13.35
17	Inertia (inches)	2850	3129.2	3446.5	3446.5	3129.2	2850
18	Area (in^2)	24.8	26.77	28.82	28.82	26.77	24.8
19	Transformed Beff (inches)	4.08	8.218	10.11	10.11	8.218	4.08
20							
21							
22							
23							
24	Neutral Axis Location (inches)	35.89793	26.94495	21.8213	25.7691	24.7851	35.9202
25							
26	Equivalent Deck Thickness (inches)	17.18	6.69	2.93	5.33	5.14	17.20
27							
28	Calculated Inertia from Field Test Data (in^4)	17208	8808	6769	8730	7585	17240
29							
30	Strain (in/in)	66.32	230.84	165.77	118.85	39.27	16.195
31							
32	$\varepsilon_o I_o / c_o$	31791	75462	51419	40266	12018	7773
33							
34	Field Measured Distr. Factor (Per Truck)	0.690					
35							
36							
37							
38	Reset		Add Data			Calculate	
39							
40							
41							

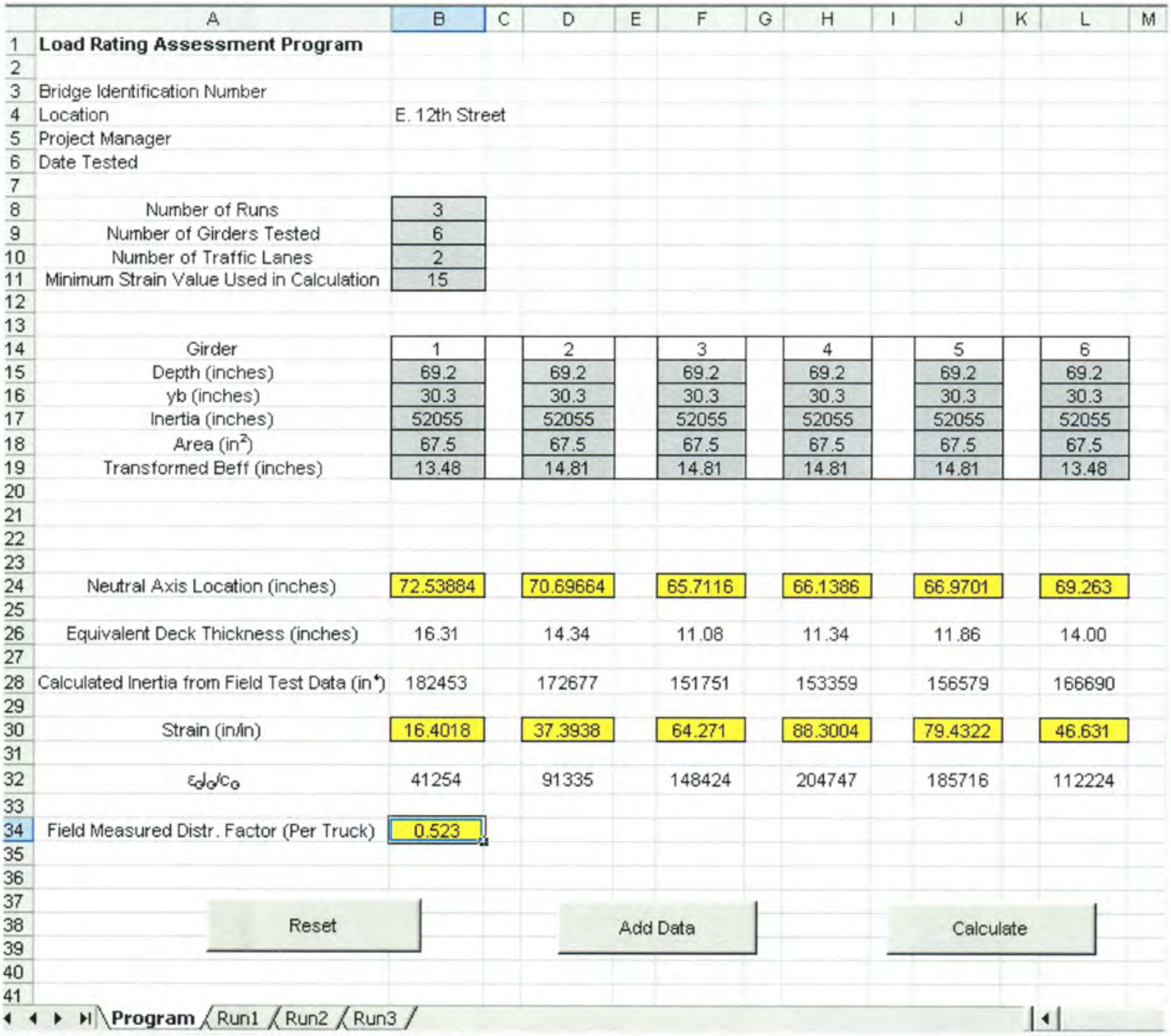
Program / Run1 / Run2 / Run3

Figure 5. IA 92 steel girder bridge DFP results.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	**Load Rating Assessment Program**													
2														
3	Bridge Identification Number													
4	Location	53rd St.												
5	Project Manager													
6	Date Tested													
7														
8	Number of Runs	2												
9	Number of Girders Tested	7												
10	Number of Traffic Lanes	2												
11	Minimum Strain Value Used in Calculation	15												
12														
13														
14	Girder	1		2		3		4		5		6		7
15	Depth (inches)	44.88		44.88		44.88		44.88		44.88		44.88		44.88
16	yb (inches)	19.45		19.45		19.45		19.45		19.45		19.45		19.45
17	Inertia (inches)	91098		91098		91098		91098		91098		91098		91098
18	Area (in^2)	424		424		424		424		424		424		424
19	Transformed Beff (inches)	44.53		44.53		44.53		44.53		44.53		44.53		44.53
20														
21														
22														
23														
24	Neutral Axis Location (inches)	25.67427		23.2673		19.1731		21.629		N/A		N/A		N/A
25														
26	Equivalent Deck Thickness (inches)	2.70		1.57				0.86						
27														
28	Calculated Inertia from Field Test Data (in^4)	158504		132315		91098		114602						
29														
30	Strain (in/in)	40.326		113.12		100.943		25.4129		3.212		2.966		0.98
31														
32	$\varepsilon_o I_o/c_o$	248958		643281		479614		134651						
33														
34	Field Measured Distr. Factor (Per Truck)	0.854												
35														
36														
37														
38	Reset			Add Data						Calculate				
39														
40														
41														

Program / Run1 / Run2 / Run3

Figure 6. 53rd Street prestressed concrete bridge DFP results.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Load Rating Assessment Program**												
2													
3	Bridge Identification Number												
4	Location	E. 12th Street											
5	Project Manager												
6	Date Tested												
7													
8	Number of Runs	3											
9	Number of Girders Tested	6											
10	Number of Traffic Lanes	2											
11	Minimum Strain Value Used in Calculation	15											
12													
13													
14	Girder	1		2		3		4		5		6	
15	Depth (inches)	69.2		69.2		69.2		69.2		69.2		69.2	
16	yb (inches)	30.3		30.3		30.3		30.3		30.3		30.3	
17	Inertia (inches)	52055		52055		52055		52055		52055		52055	
18	Area (in^2)	67.5		67.5		67.5		67.5		67.5		67.5	
19	Transformed Beff (inches)	13.48		14.81		14.81		14.81		14.81		13.48	
20													
21													
22													
23													
24	Neutral Axis Location (inches)	72.53884		70.69664		65.7116		66.1386		66.9701		69.263	
25													
26	Equivalent Deck Thickness (inches)	16.31		14.34		11.08		11.34		11.86		14.00	
27													
28	Calculated Inertia from Field Test Data (in^4)	182453		172677		151751		153359		156579		166690	
29													
30	Strain (in/in)	16.4018		37.3938		64.271		88.3004		79.4322		46.631	
31													
32	$\varepsilon_G I_G / c_G$	41254		91335		148424		204747		185716		112224	
33													
34	Field Measured Distr. Factor (Per Truck)	0.523											

Figure 7. East 12th Street steel girder bridge DFP results.

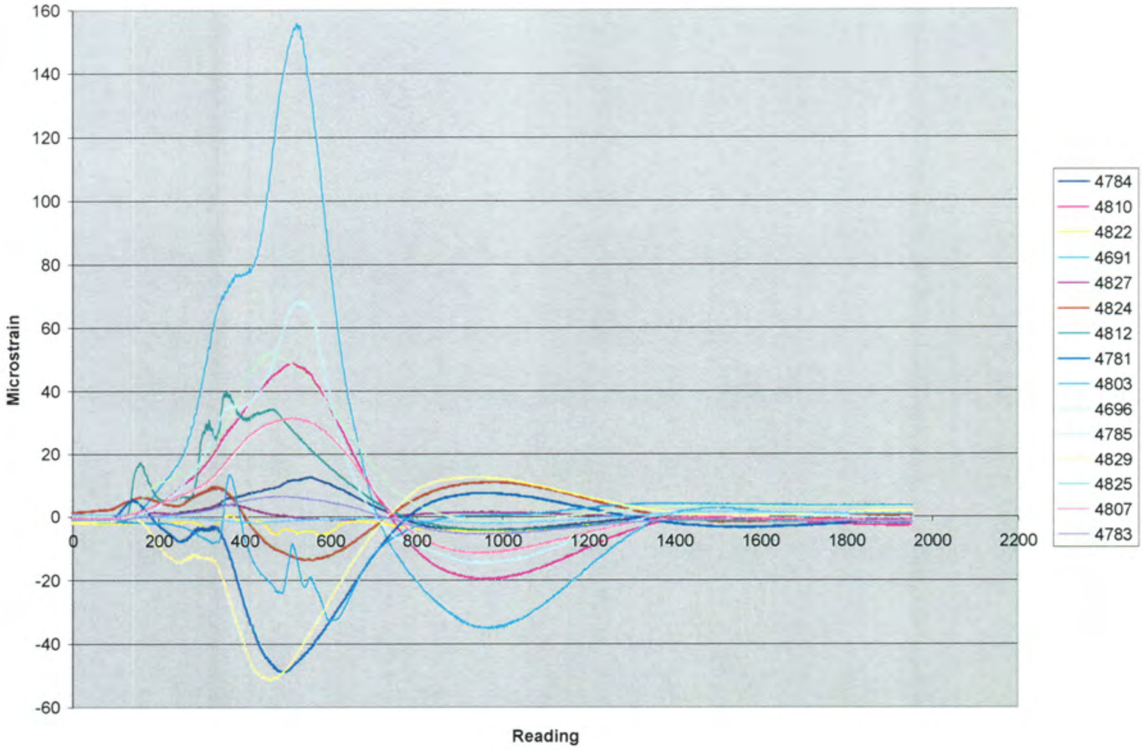


Figure 8. IA 92 steel girder bridge test results.

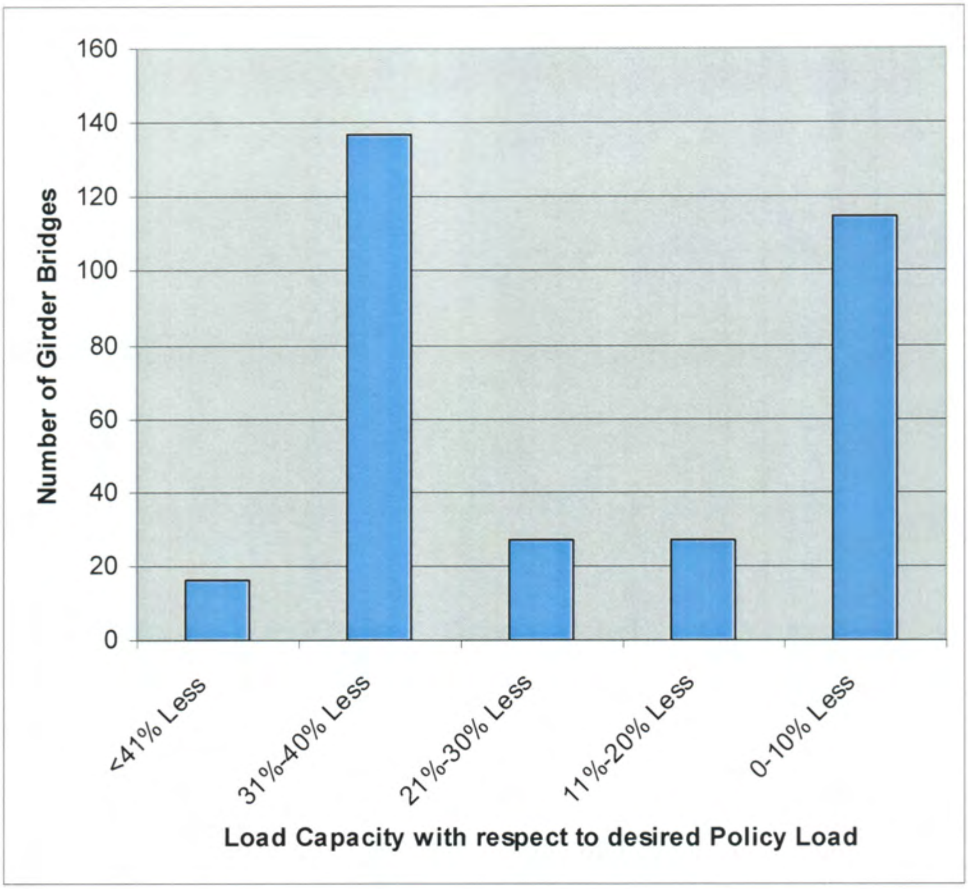


Figure 9. IA DOT girder bridge evaluation.

GENERAL CONCLUSIONS

CONCLUSIONS

Conclusions on the completed research are as follows:

- The completed research has provides the Iowa DOT with a complete Pontis database, which can now be incorporated into their evaluation of bridge structures within the network. With continual accurate inspection entry, along with updates to the policy, the implemented database will provide the foundation for improved utilization of available funds throughout the agency's bridge network.
- The Pontis BMS implementation strategies presented herein can be utilized by any agency with limited historical data.
- The completed research has provided complete assessment and assembly of a handheld data acquisition system. This system is capable of collection and storage of 15 channels of test data, and relies strictly on battery power. The handheld data acquisition system was tested and verified to insure both accuracy and field applicability. The completed system proved field capable, and the programmed device functioned consistently to different testing environments and applications.
- The developed methodology allowed for an assessment of lateral load distribution for each tested bridge. This information provides additional insight to the structural performance of an individual, which can be utilized to improve the accuracy of the load rating of the structure.
- An assessment of the potential improvements to the IA DOT Pontis database was conducted. It was shown that utilization of the system would prove beneficial in the selection of bridge structures which are truly deficient in strength, and prevention of rehabilitation to bridges which have sufficient capacity.
- This development is an initial attempt to improve Pontis through integration of structural performance parameters. Various methods have been used to assess bridge performance, and this research presents only one method to improve a bridge management system's evaluation of bridge rehabilitation or replacement. This research can act as the building block for further integration of field testing information, and its inclusion into the Pontis database.

RECOMMENDATIONS FOR FUTURE RESEARCH

- Storage of the data collected from field testing could be stored within the Pontis database. This would allow organization of bridges which were tested, and could allow assessment of bridges within the network which may benefit from field testing. This database could act in sequence with the current visual inspection database, allowing comparison of field test results and visual condition over the bridge lifespan.
- Basic bridge parameters, which may include girder properties, transverse spacing, deck thickness along with span length, could be stored for each bridge structure within the Pontis database. This information could then be accessed and utilized in conjunction with field test data, to assess structural performance of the bridge.
- Further development of the Pontis database could include built in functions which analyze entered field test data. A standardized testing procedure could be presented to insure consistent evaluation of the structural performance of bridge structures. This concept could then be implemented nationwide, improving bridge management in all state agencies by utilizing field measurements.
- Further research should be conducted to assess bridge configurations not addressed within this research effort. This includes skewed structures, as well as structures without longitudinal girder superstructures.
- Continual evaluation of testing procedures should evolve in accord with advancements in handheld technologies, and gauge capabilities. This could include wireless gauges permanently installed on bridge elements, with the ability to collect strain readings wirelessly on the PDA as the truck passes over the bridge.
- Further programming effort which allows automatic reformatting and analyzing of data, along with updating of the Pontis database could be completed through additional research. This was felt out of the scope of this research, however would prove beneficial to personnel with limited computer experience.

APPENDIX A. HANDHELD DATA ACQUISITION SYSTEM USERS MANUAL

USERS MANUAL

Field Data Collection

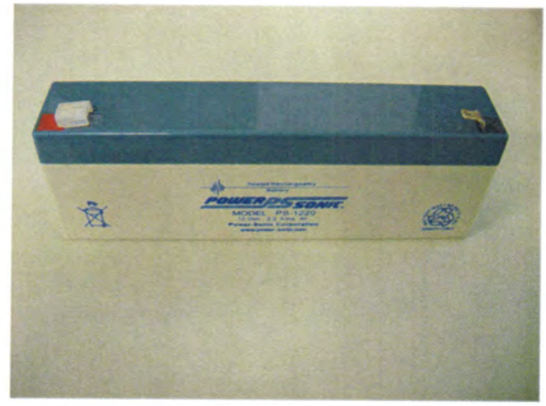
This section will be formatted as to take the reader through an entire field test process, starting with acquisition and ending with load rating determination. System components are shown in Figure 1. These components will be referred to throughout the manual, therefore should be familiar to the reader. Following gauge installation at midspan, gauges should be connected to the connector block, as shown in Fig. 2a. To reduce possibility of error, it is required that gauges are connected to the connector blocks in such a way that the first girder is collected by channel 1 and 2, with 1 representing the top flange reading, and 2 representing the bottom flange reading. The second girder should be connected to channels 3 and 4, with the same top flange/bottom flange pattern. When all test girders are instrumented in this way, further analysis of the data if significantly simplified. Connector block cables should then be connected to the signal conditioning unit, as shown in Fig. 2b. The PDA with the expansion pack should now be connected to the signal conditioning unit. To complete this connection, the DAQ card must first be connected to the data cable, and then inserted into the PDA expansion pack. Details of the data cable connection to the DAQ card is shown in Fig. 3a, with details of the insertion of the card into the expansion pack shown in Fig. 3b. Final connections of the data cable should be as shown in Fig. 3c. The final system configuration should resemble Fig. 4a. Notes should be made detailing which specific gauge number relates to each channel number, and which girder number the gauges apply to.

The system can now be powered on, which will be indicated by the LEDs. Fig. 4b details the powered system. The battery is connected by matching the colored terminals of the battery with the colored leads from the signal conditioning unit. When the LEDs are illuminated, the signal conditioning unit is providing voltage to the installed transducers, as well as providing power to the signal conditioning unit to process the data and send information through the data cable to the PDA. Although this battery will support extended acquisition, it is advised to keep the system powered off until the test truck is prepared for the load test.

As the test truck prepares for load test, the PDA can be turned on and test parameters can be entered. The program, "PDA_15Chan_" must be booted from the PDA, as shown in Fig. 5a. The program is located within the "My Documents" folder, which is the folder that synchs data between the PDA and host computer. Fig. 5b shows the PDA synched to the host computer. Any data that is modified or added within this folder, will also be modified and added to the host computer when the PDA is synched. The data acquisition program is located within this folder to allow any updates to the software to be automatically changed upon synching to the host computer. To open the application, tap the program name, which will load the initial file input screen, shown in Fig. 5c. The initial screen requires a specific name for the test run, which should relate to the test, and the specific truck path that data will be collected for. It is recommended that the file path My Documents\ remains unchanged. This will allow saved data to by synched to the host PC without further file relocation. It is imperative that each file be named uniquely, for files with identical names will be overwritten by the latest data. File extension must also remain .DAT, due to the driver only functioning with this data type. Following file name entry tap the OK button to continue. The screen which follows is shown in Fig. 5d. Data representing the specific test details should be entered into the respective field. Data for the span length or sample rate can be entered using the shown toggles; however utilization of direct data entry may be more efficient for these specific fields. To enter values directly, tap within the data field, and highlight the default value. Then tap the up-arrow symbol located in the lower right corner of the PDA screen, and select keyboard. This command allows entry directly from the displayed keyboard. Following entry, simply tap the keyboard symbol in the lower right corner. If mistakes are made, a backspace button is included, located in the upper right corner of the keyboard display. The default sample rate is sufficient for all tests conducted at crawl speed. The DAQ card is capable of attaining data readings at 20hz, which is more applicable for dynamic tests. However, the DAQ card is limited to 200 total samples per second, therefore can acquire a maximum of 10 channels of data at this rate.

Following data entry, the PDA is ready for the load test. It should be insured that the signal conditioning unit is powered on. When the truck is prepared for the test, the RUN button should be tapped on the PDA screen, initiating data collection. The truck should proceed to cross the bridge at the specified speed. Once the collection has begun, the data screen will become inactive until the test is complete. The screen may darken to save power, however the test will not be affected by this function. Following test completion, plots of the collected voltage will be plotted on the graph. Basic profiles of the data will be shown, and data collection can be verified. To close the program, or to begin a new test, tap the EXIT button. This will end the program, and return you to the My Documents folder. The new file that was created will be saved in the folder, and the test procedure can be repeated for additional tests. The EXIT button is not equivalent to tapping the "x" in the upper right corner of the screen. By tapping this symbol, the program window closes, however the program remains activated. This program being left activated will consume significant processing power, leaving other PDA functions, including file browsing, very slow and unresponsive. To deactivate the program, it should be reopened, and the EXIT button should be tapped to shut the application off.

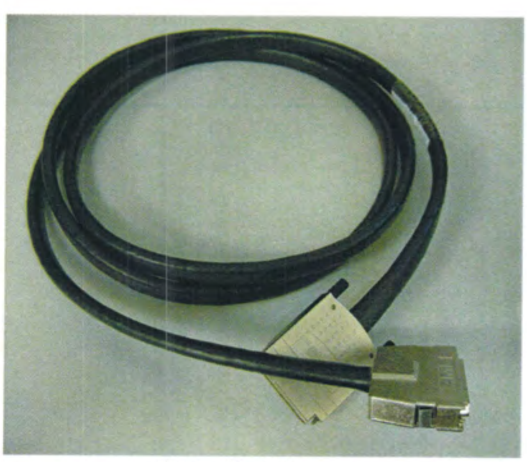
Signal Conditioning Unit



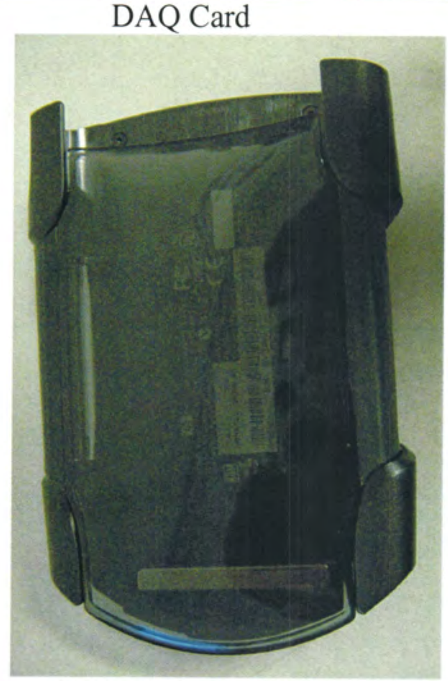
Battery

Connector Block with Cable

DAQ Card

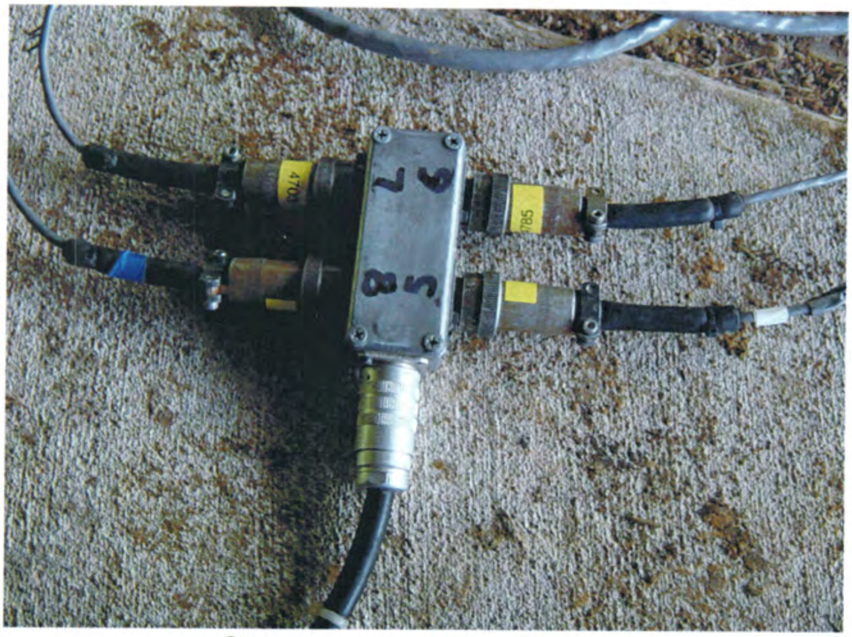


Data Cable

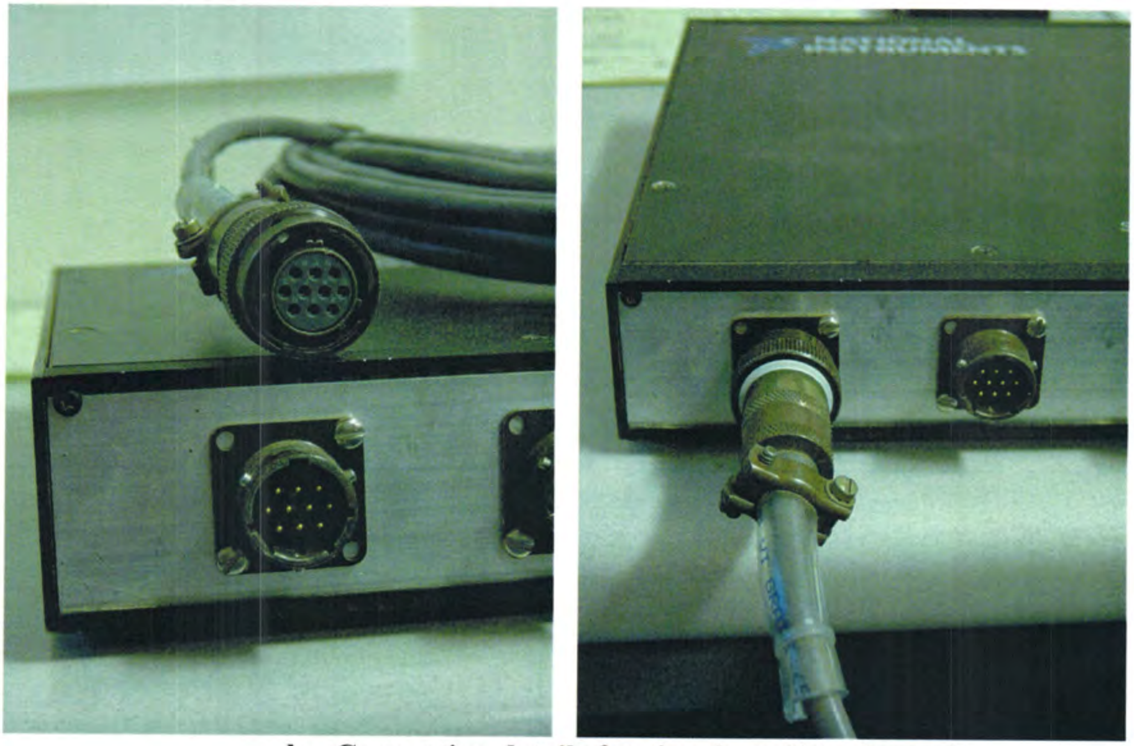


PDA Expansion Pack

Figure 1. System Components.



a. Gauges connected to connector block

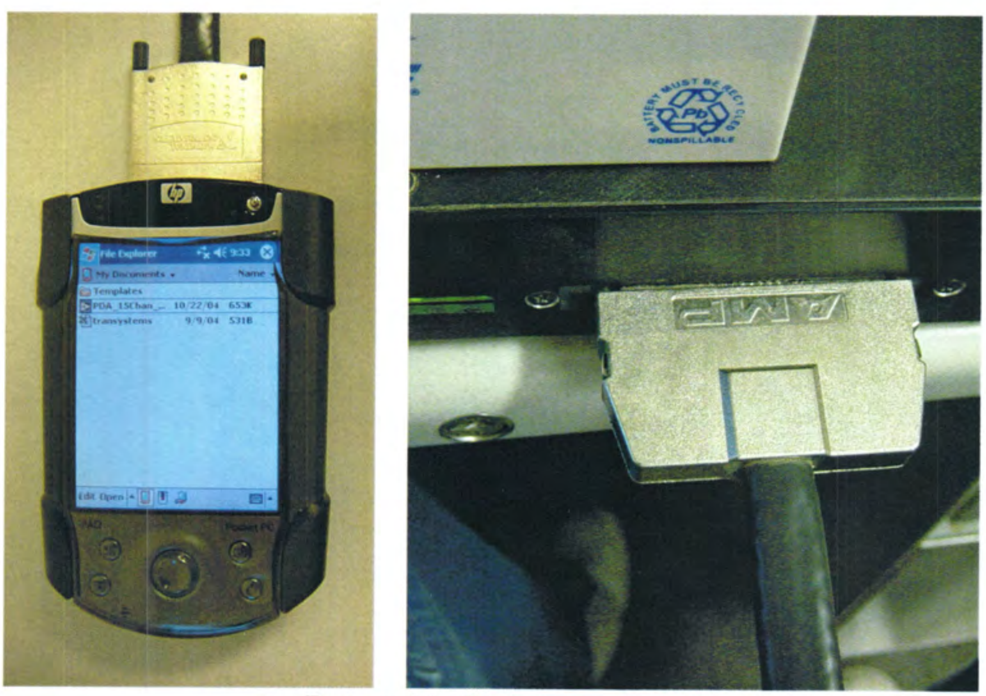


b. Connection details for signal conditioning unit

Figure 2. Connector Block details.

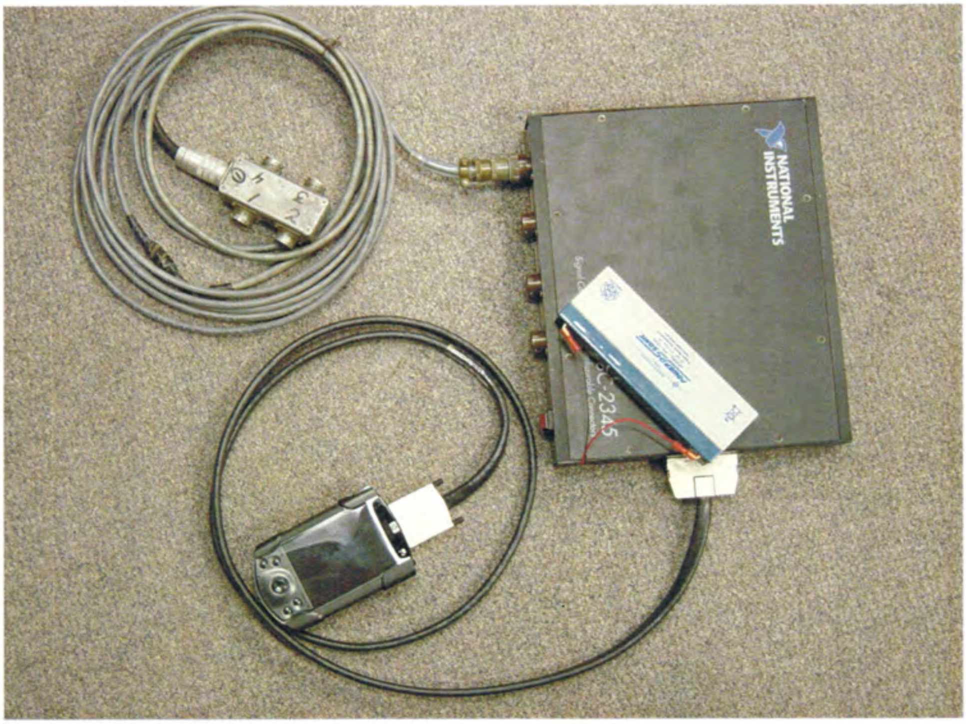
a. DAQ card – data cable connection

b. Insertion of DAQ card into PDA expansion pack

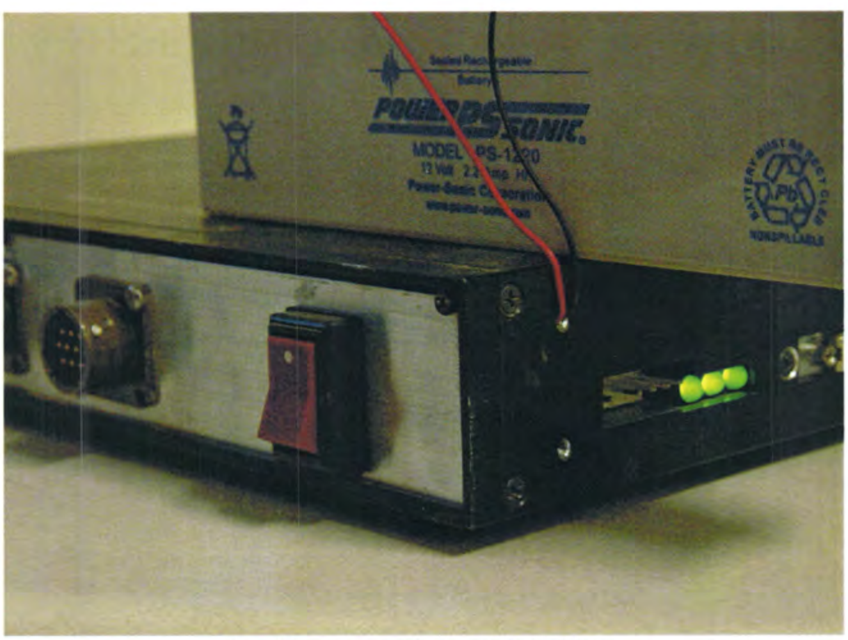


c. Data cable final connection details

Figure 3. Data Cable connection details.

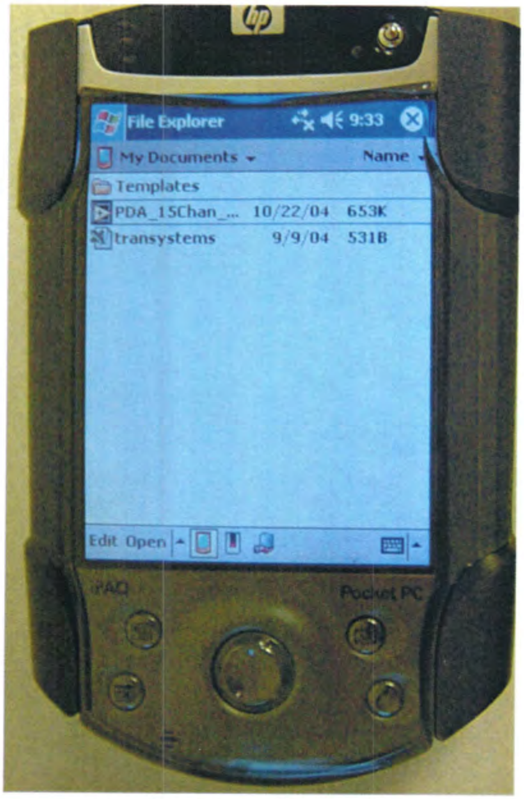


a. System configuration

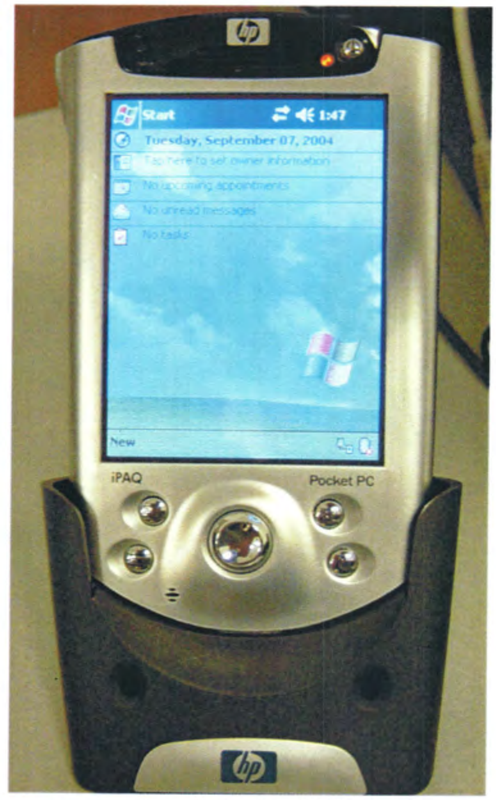


b. Power switch with LEDS

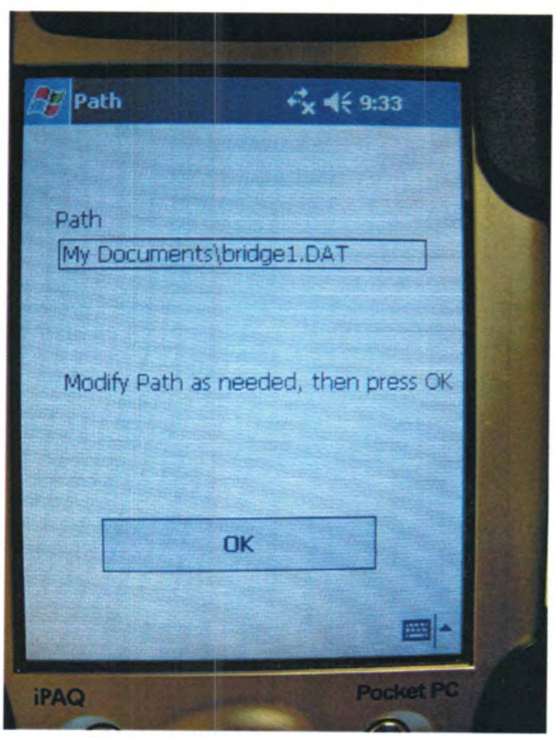
Figure 4. System configuration layout and power recognition details.



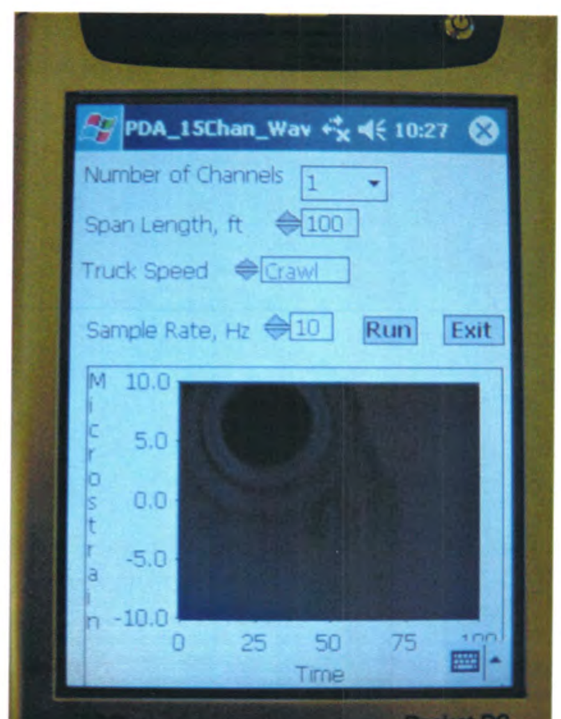
a. Program file location



b. Synched PDA



c. Initial file input screen



d. Test Parameter input screen

Figure 5. PDA user interface details.

Troubleshooting Guide
This guide includes example mistakes or problems that may be encountered using the PDA data acquisition system, and their corresponding solution. Although all possible instances may not be covered, this is the author's compilation of all experiences and foreseen issues with the system.

System Component Assembly
Incorrect system component assembly will not negatively affect future system performance in any way. However, mistakes in component assembly can cause limited data acquisition, or prevent any useful data collection at all. The PDA is incapable of recognizing most system component assembly errors, therefore will continue to attempt data collection, regardless of component assembly status.

If there is **data plotted is invalid or limited** following a field test, possible reasons may be:

- System power is not turned on; check that power LED's are on and battery is connected correctly.
- Data cable is not connected correctly to the signal conditioning unit.
- Connector block cables not attached properly to the signal conditioning unit.
- Gauges not properly connected to the connector blocks.
- Number of channels was not entered correctly, therefore less data was collected than desired.
- Sample rate is too high for the selected amount of channels. Reduce channel number or sample rate to insure less than 200 total readings per second.
  $(\#Chan)*(Sample\ Rate) \leq 200$

PDA Screen Errors
An **Error Window** appears on the PDA screen:

Error: LabVIEW PDA/DAQ-PPC: Error code: 90001
Cause: This error occurs when the DAQ card cannot be accessed by the Labview for PDA driver.
Solution:

- The DAQ card is not properly inserted into the PDA expansion pack.
- The expansion pack is not properly connected to the PDA.
- The extended battery is not connected to the expansion pack properly, or is discharged completely; reconnect battery or recharge extended battery.

Error: Extended Battery Very Low
Discription displayed: "To prevent possible data loss, replace or recharge your extended battery according to the owner's manual"
Cause: The extended battery is located within the expansion pack, and has significant electrical load during a field test. This can cause this warning message to appear, even though adequate charge was provided to the battery prior to testing. No data will be affected nor lost due to this message.
Solution:

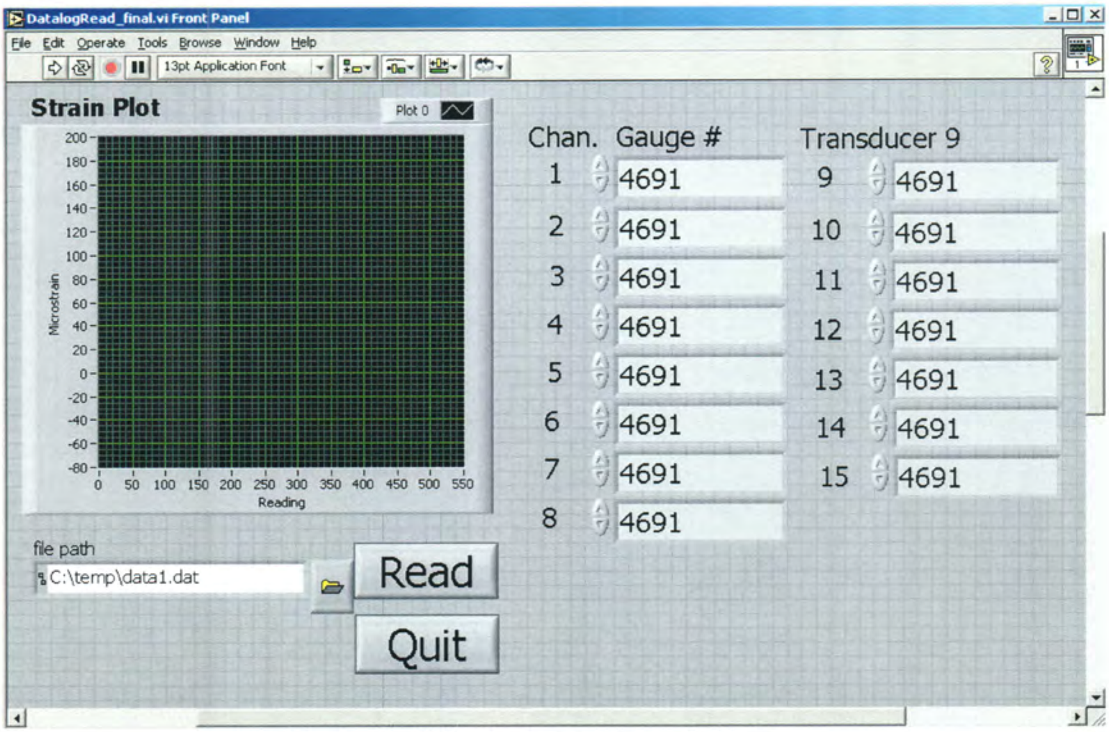
- Click OK and continue with further testing.

Error: Extended Battery Fault
Discription displayed: "Your Extended Battery has become critically low. The expansion pack will be powered off. To continue using this expansion pack, you will need to charge it."
Cause: The extended battery is located within the expansion pack, and has significant electrical load during a field test. Data cannot be collected while the expansion pack is powered off.
Solution:

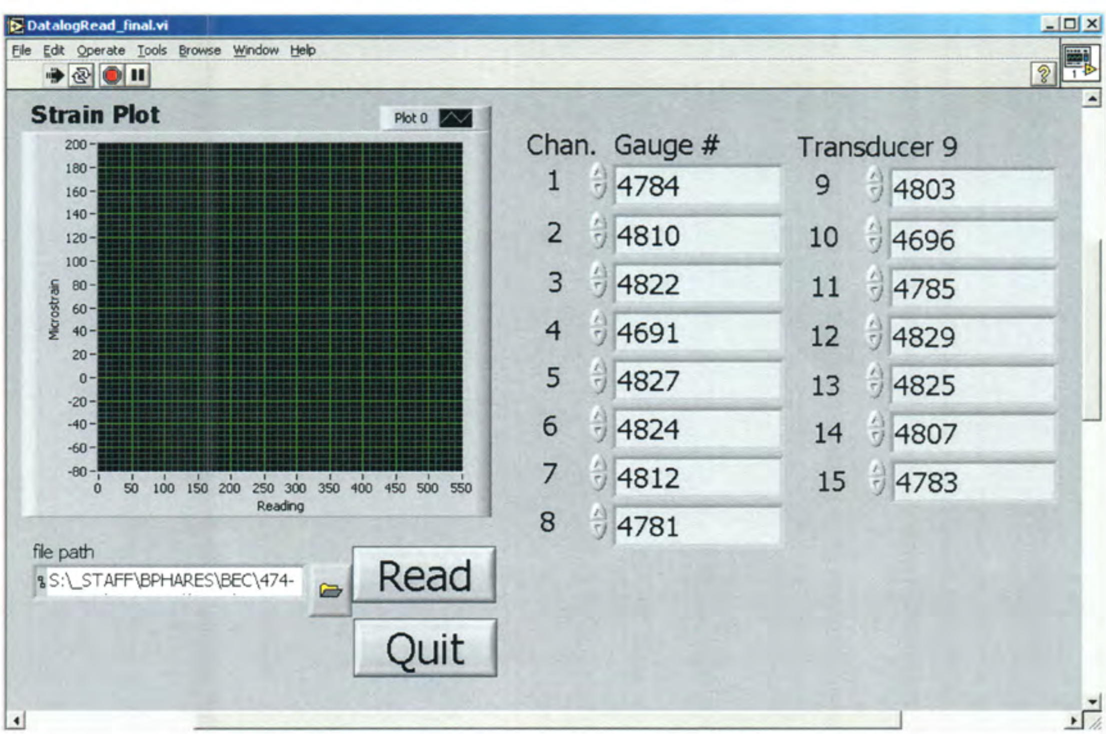
- Recharge extended battery.

Data Reconfiguration and Storage

Following the collection of data from a field test, the PDA must be synched to the host computer. Synching the PDA will transfer the stored data files to the PC hard drive, and can then be reconfigured into Microsoft Excel format. To accomplish this, a Labview application was created. This application, named "Datalogread", should be opened when analysis of the data is desired. The initial screen layout is shown in Fig. 6a, with a default file location and default gauge numbers. To browse for the file to be reformatted, click the folder button, located to the right of the file input bar. A browser window will appear, and the file can be found and saved. Correct gauge numbers, relating to the testing channels should be entered in each field. The list of possible gauges is included in a drop-down list for each gauge number. Following all gauges being entered, click the RUN button, which is located within the task bar in the upper left corner, and is shown by a right pointing arrow. Once clicked, the arrow will turn from white to black, indicating the program is ready to run. Figure 6b shows an example screen layout with gauge numbers selected, file location entered, and the RUN button selected. The program will account for the number of gauges that collected data; therefore additional channels can remain as the default gauge number value with no impairment to the program or output. After the RUN button is clicked, no changes can be made to the file location or gauge inputs. The only activated buttons are READ and QUIT. By clicking QUIT, the program stops and changes can be made to the input. Clicking READ will reformat the input data into Microsoft Excel format, plot the information on the graph, as well as open a save window. Figure 6c shows a typical screen layout following the READ button being initiated. The name of the file to be written should be sufficient to describe the bridge that was tested, as well as what specific truck path this information stemmed from. The extension of the saved file should be .xls, to insure that the file will default to Microsoft Excel. An example file name would be "IA92steelgirder_run1.xls". Clicking OK will write this file into the specified folder, which can then be opened and manipulated using Microsoft Excel. Following the file writing procedure, the QUIT button should be selected to stop the current program. This will allow the file location to be changed, and the program may be rerun for additional truck paths. An example of this completed program screen layout is shown in Fig. 6d. The gauge numbers will be saved in accordance with initially entered data, until the program is closed. Once closed, all values will return to the default value.

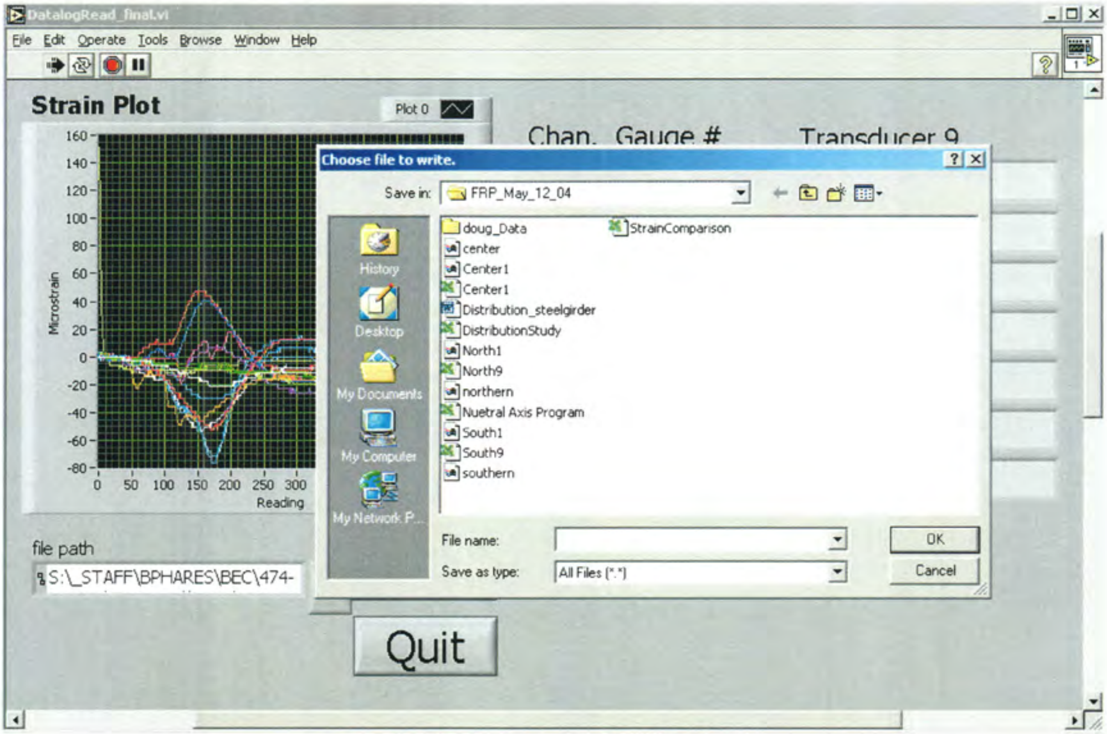


a. Initial program screen layout

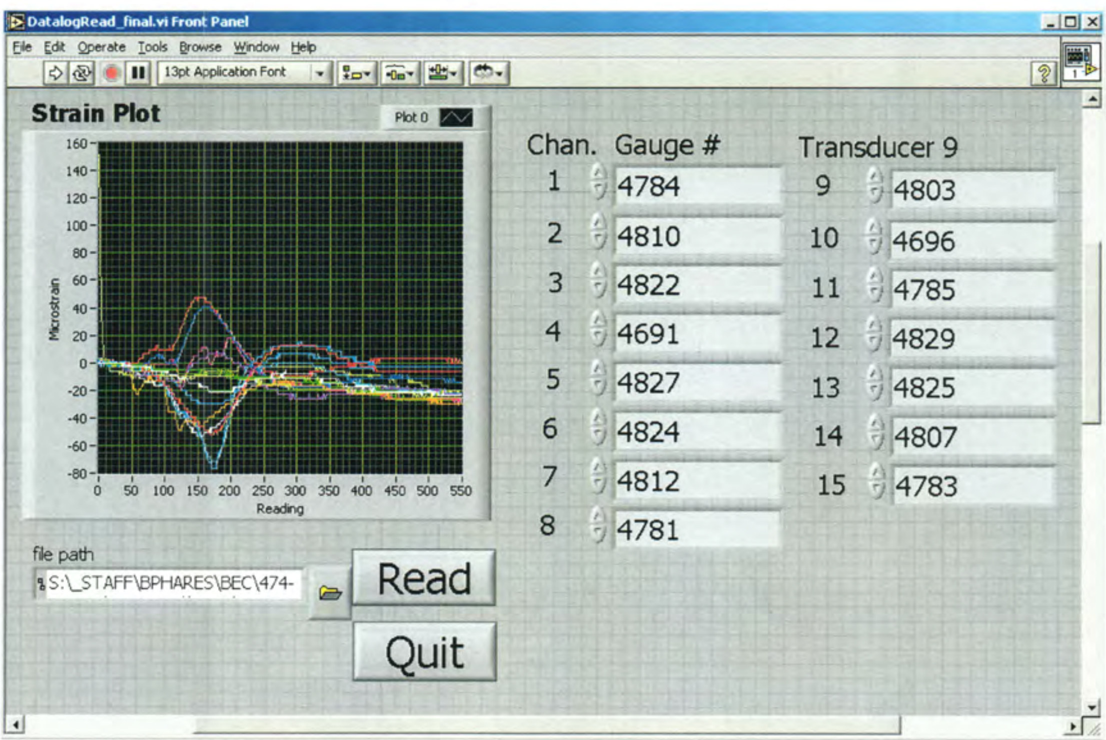


b. Example gauge and file location entry

Figure 6. DatalogRead program screen layout examples.



c. **Example "write file"**



d. **Completed program layout**

Figure 6. (continued)

Distribution Factor Determination

The field test distribution factor can be determined by running the Distribution Factor Program (DFP). Prior to opening the program, Macros must first be enabled. This can be verified in Excel by selecting Tools>>Macros>>Security. Ensure that the security level is set to medium, enabling Macros to function, and select OK. The DFP can now be opened in Microsoft Excel. The initial screen will be the user interface, shown in Fig. 7. This screen contains fields to describe the specific field test, basic bridge parameters, along with fields that will be entered by the program following analysis of field test data. Raw field test data has been written into separate Excel files by Labview software previously mentioned. This data should be copied from these files, and pasted into the sheets labeled Run1, Run2, and Run 3. These additional sheets can be opened by clicking the labeled tab in the lower left corner of the spreadsheet. A blank Run1 sheet is shown in Fig. 8. Although the specific truck path order is insignificant, entered data within each sheet must be in the order shown. If the test was conducted according the above section, the data will already be formatted correctly, and can simply be pasted into the sheet. If readings from top and bottom flanges of individual girders are entered improperly, calculated values will be incorrect.

Return to the "Program" sheet by clicking on the labeled tab in the lower the left corner of the spreadsheet. Bridge parameters relating to the in-service condition of the bridge should now be entered in the labeled fields. The number of runs allows the program to neglect the sheet "Run 3" in the event that a third truck path was not used in the field test. The "Minimum Strain Value Used in Calculation" field should not be changed from the default of 15 unless confidence in the data justifies a lower estimate. Figure 9 shows example bridge parameters for the IA 92 Bridge entered into the respective fields. After general bridge parameters have been entered, click the "Add Data" button located at the bottom of the spreadsheet. The number of girders, and all respective fields, will be increased to the value entered in the "Number of Girders Tested" field.

After general bridge parameters have been entered, and the Add Data function has been executed, specific design values for each tested girder must be entered in the appropriate field. Each girder number relates directly to the three "Run" files which contain the field test data. Therefore, girder one properties should reflect the properties relating to test data in the Girder 1 columns. In the occasion that all girders have equivalent design properties, information can be entered only for the first two girders. Following data entry for the first two girders, click the "Add Data" button again, and properties will be copied to all applicable cells. Once all information has been entered for each test girder, the program is ready to be run. Figure 10 shows the IA 92 Bridge information entered for each test girder. Click the "Calculate" button near the bottom of the spreadsheet to execute the program. Calculation of field test properties will begin, as seen by the comprehensive scanning of data throughout each sheet. Following program completion, field measured values will be automatically entered into the respective fields, and a field measured D.F. will be calculated. This D.F. can be compared to that found through conventional equations, and an assessment of the improvement of load rating can be made. Results from the IA 92 Bridge are shown in Figure 11.

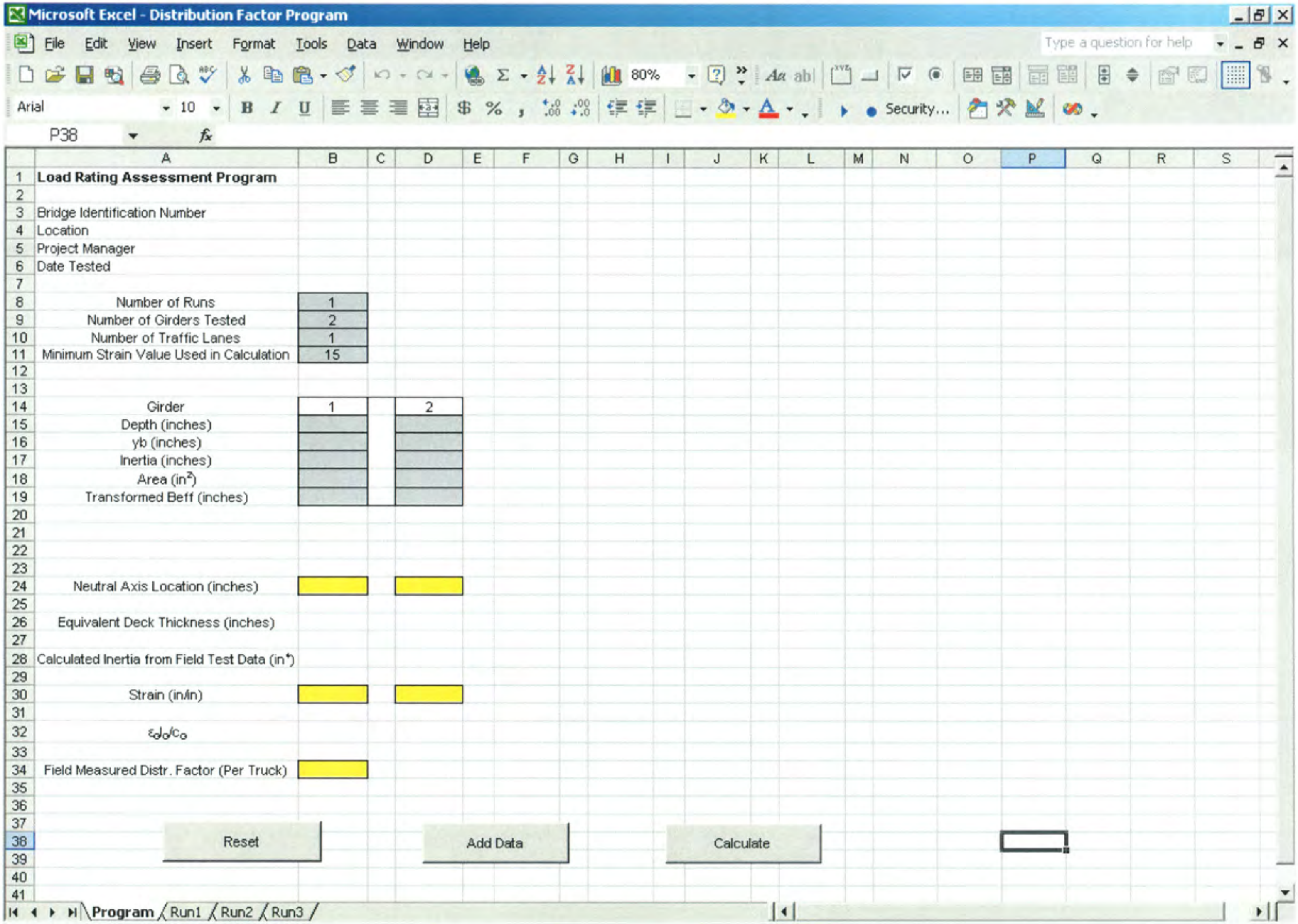


Figure 7. Distribution Factor Program user interface.

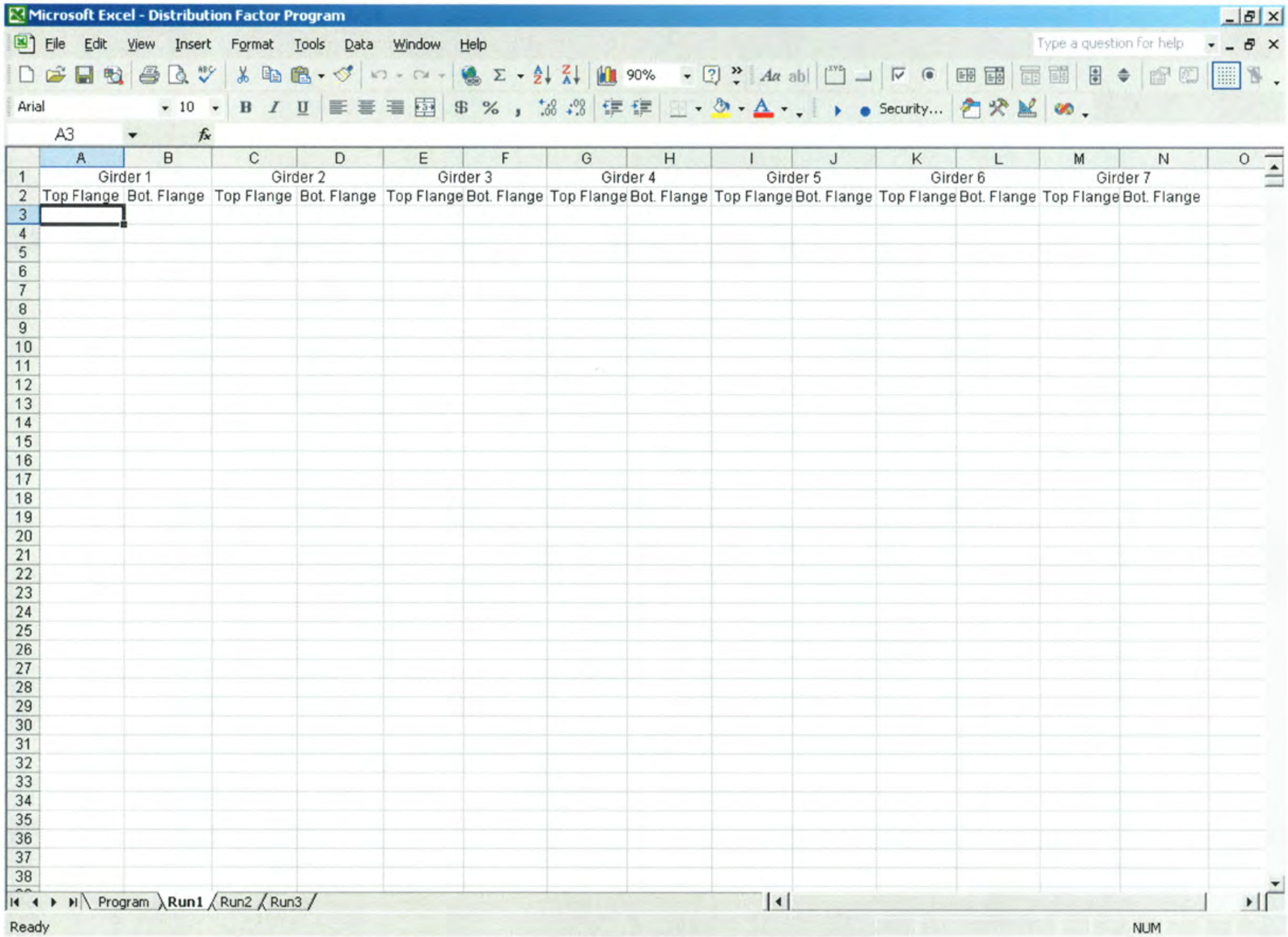


Figure 8. Blank data input screen.

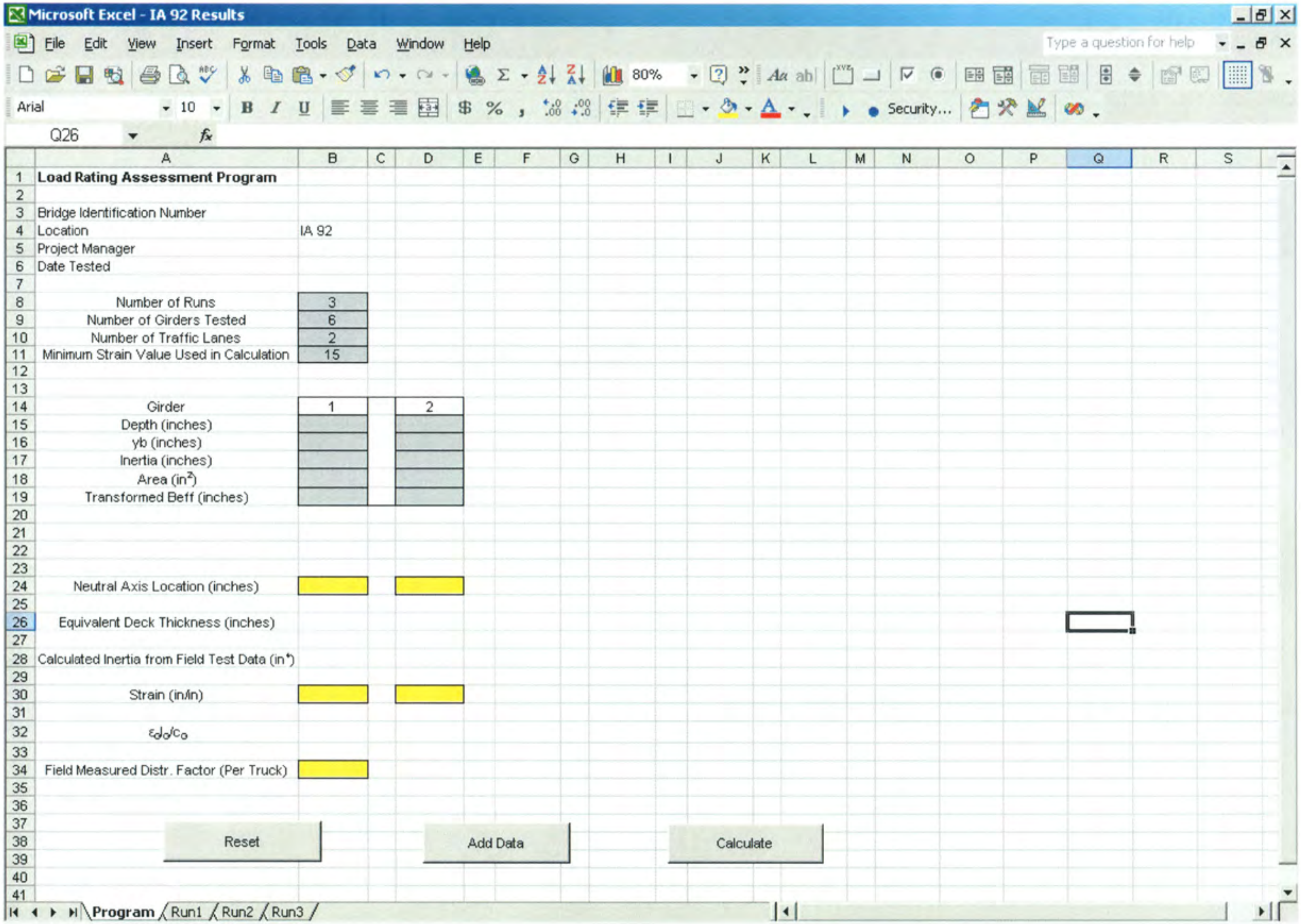


Figure 9. IA 92 Bridge basic parameter entry.

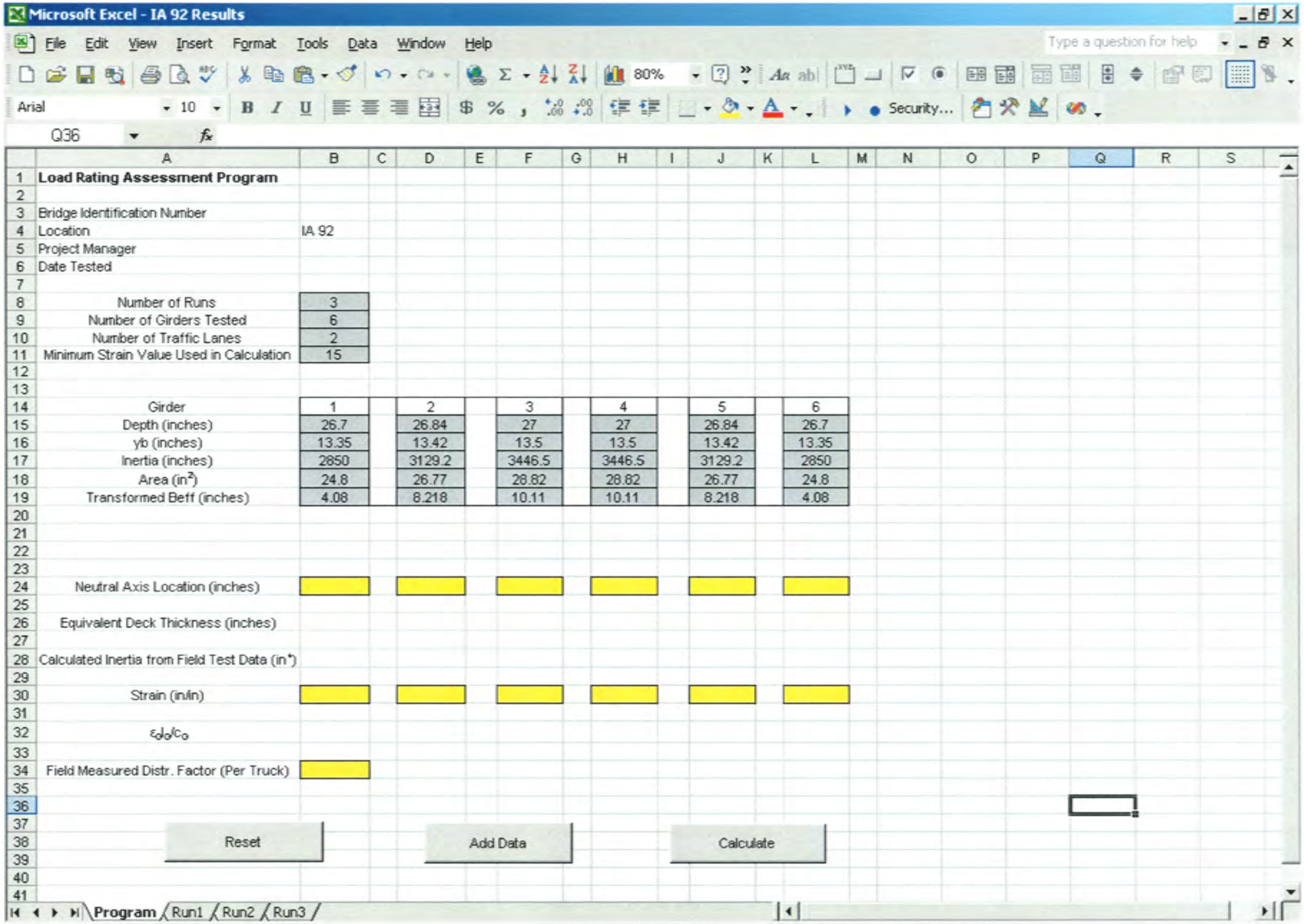


Figure 10. IA 92 Bridge completed girder property entry.

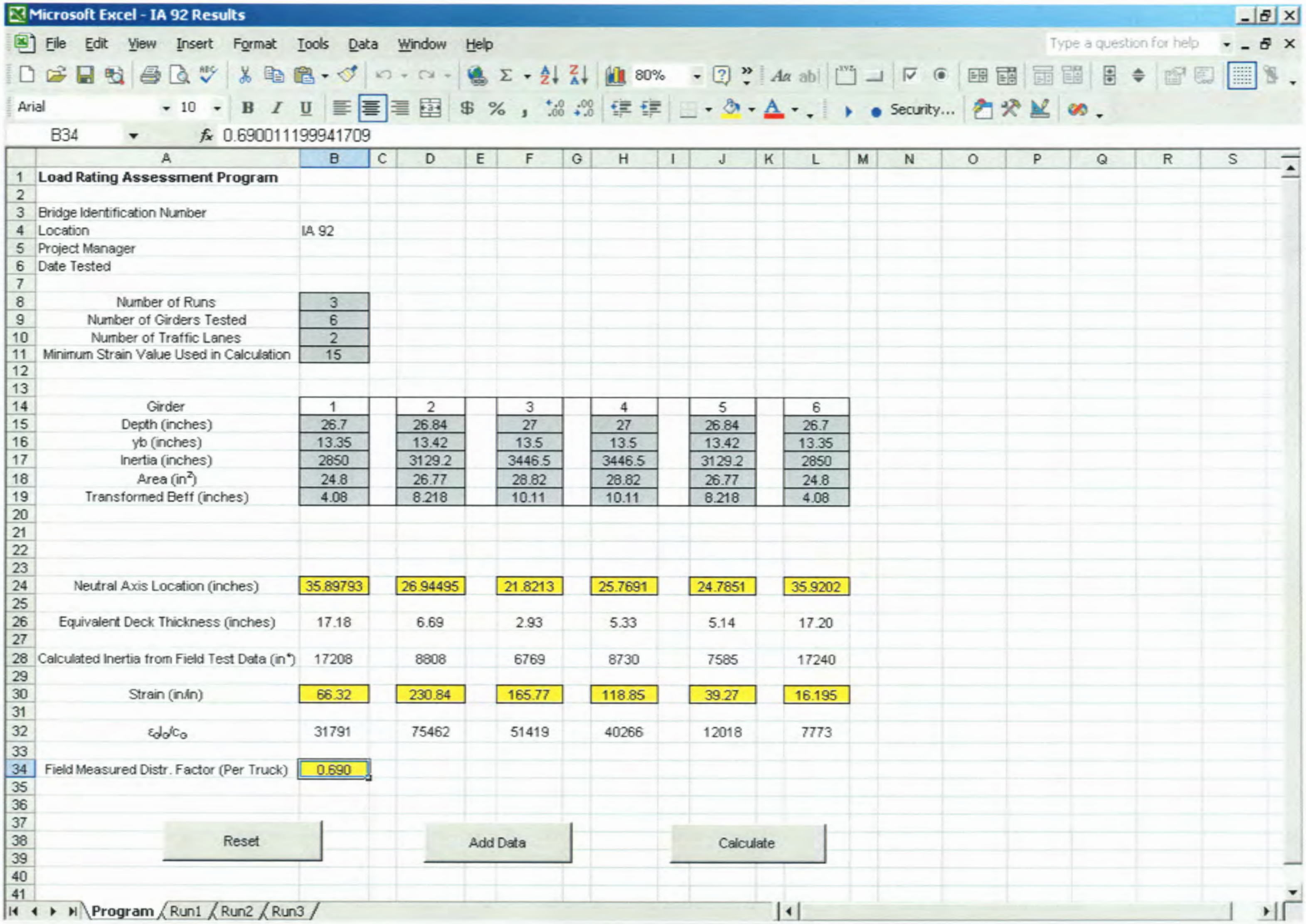
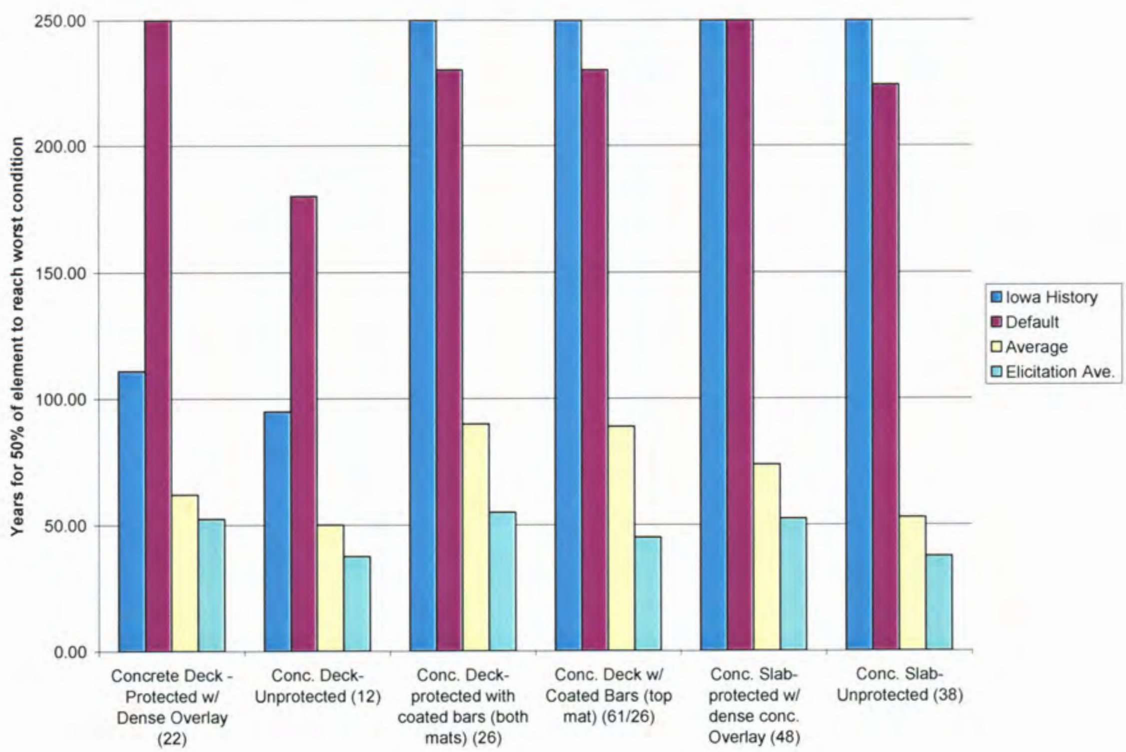


Figure 11. IA 92 Bridge DFP results.

APPENDIX B. ADDITIONAL TABLES AND FIGURES

Table 1. Final cost assessment sheet.

Element #	Elem. Discription	Unit of Measure	Kansas Pontis Data Metric Unit	Kansas Pontis Data English Unit	Wisconsin Pontis Data Metric Unit	Wisconsin Pontis Data English Unit	Default Pontis Values Metric Unit	Default Pontis Values English Unit	2001 F.D.O.T. English Unit	2003 F.D.O.T. English Unit	2001 Iowa D.O.T. English Unit	2003 Iowa D.O.T. English Unit
12	Bare Concrete Deck	m^2 / S.F.	$323	$30	$251	$23	$302	$28	$30	$32	$10	$11
13	Unprotected Conc Deck w/Asphalt Overlay	m^2 / S.F.	$323	$30	$251	$23	$331	$31	$31	$33	$11	$12
22	Conc Deck w/ Rigid Overlay	m^2 / S.F.	$323	$30	$317	$29	$347	$32			$13	$14
26	Conc Deck w/ Coated Bars	m^2 / S.F.	$323	$30	$317	$29	$188	$17			$10	$11
27	**Conc Deck w/ Cathodic Protection**	m^2 / S.F.	none	none	$191	$18	$431	$40				
28	**Steel Deck w/ Open Grid**	m^2 / S.F.	$323	$30	$352	$33	$344	$32	$35	$37		
31	**Timber Deck (bare)**	m^2 / S.F.	$108	$10	$281	$26	$10	$1	$10	$11		
38	Concrete Slab (Unprotected)	m^2 / S.F.	$377	$35	$452	$42	$482	$45	$30	$32	$26	$28
39	Unprotected Concrete Slab w/ Asphalt Overlay	m^2 / S.F.	$377	$35	$452	$42	$702	$65	$31	$33	$27	$29
48	Protected Conc. Slab w/ Rigid Overlay	m^2 / S.F.	$377	$35	$480	$45	$484	$45			$29	$31
52	Conc. Slab w/ Coated Bars	m^2 / S.F.	$377	$35	$452	$42	$300	$28			$27	$29
53	**Conc. Slab w/ Cathodic Protection**	m^2 / S.F.	none	none	$402	$37	$466	$43				
54	**Timber Slab**	m^2 / S.F.	none	none	$402	$37	$9	$1	$1	$1		
105	**R/C Box Girder**	m / L.F.	$1,312	$400	$15,314	$4,668	$6,493	$1,979				
106	Unpainted Steel Open Girder	m / L.F.	$1,312	$400	$663	$202	$939	$286			$525	$562
107	Painted Steel Open Girder	m / L.F.	$1,312	$400	$1,601	$488	$1,197	$365	$900	$964	$525	$562
109	Pre-Cast Open Girder	m / L.F.	$1,312	$400	$1,656	$505	$673	$205	$370	$396	$120	$129
110	R/C Open Girder	m / L.F.	$984	$300	$1,546	$471	$927	$283	$370	$396	$120	$129
111	**Timber Open Girder**	m / L.F.	$492	$150	$919	$280	$2,220	$677	$150	$161		
113	Painted Steel Stringer	m / L.F.	$984	$300	$613	$187	$227	$69	$210	$225	$120	$129
117	**Timber Stringer**	m / L.F.	none	none	$61	$19	$194	$59	$114	$122		
121	**Painted Steel Bottom Chord Through Truss**	m / L.F.	$1,640	$500	$613	$187	$2,625	$800	$800	$857		
126	**Painted Steel Through Truss excluding Bottom Chord**	m / L.F.	$2,461	$750	$3,313	$1,010	$3,117	$950	$950	$1,018		
131	**Painted Steel Deck Truss**	m / L.F.	$2,461	$750	$3,063	$934	$2,953	$900	$900	$964		
141	**Painted Steel Arch**	m / L.F.	$2,461	$750	$15,314	$4,668	$2,953	$900	$900	$964		
152	**Painted Steel Floorbeam**	m / L.F.	$820	$250	$613	$187	$2,050	$625	$460	$493		
156	**Timber Floorbeam**	m / L.F.	none	none	$306	$93	$4,940	$1,506	$114	$122		
161	**Painted Steel Pin &/or Pin-Hanger Assembly**	each	$10,000	$10,000	$2,801	$2,801	$4,906	$4,906	$100,000	$107,123		
202	Painted Steel Column or Pile Extension	each	$10,000	$10,000	$4,040	$4,040	$4,494	$4,494	$20,000	$21,425	$1,500	$1,607
204	P/S Conc. Column or Pile Extension	each	$12,000	$12,000	$3,267	$3,267	$9,429	$9,429	$20,000	$21,425	$1,600	$1,714
205	R/C Column or Pile Extension	each	$12,000	$12,000	$5,050	$5,050	$11,884	$11,884	$20,000	$21,425	$2,588	$2,772
206	Timber Column or Pile Extension	each	$3,000	$3,000	$4,040	$4,040	$2,140	$2,140	$1,000	$1,071	$1,080	$1,157
210	R/C Pier Wall	m / L.F.	$4,921	$1,500	$3,313	$1,010	$9,743	$2,970	$3,000	$3,214	$1,090	$1,168
215	R/C Abutment	m / L.F.	$4,921	$1,500	$4,969	$1,515	$2,560	$780	$820	$878	$1,400	$1,500
216	**Timber Abutment**	m / L.F.	$492	$150	$3,313	$1,010	$4,399	$1,341	$620	$664		
231	**Painted Steel Abutment Cap**	m / L.F.	$984	$300	$6,125	$1,867	$1,796	$548	$460	$493		
234	R/C Pier Cap	m / L.F.	$6,562	$2,000	$4,969	$1,515	$1,577	$481	$460	$493	$1,961	$2,100
235	**Timber Pier Cap**	m / L.F.	$492	$150	$1,656	$505	$584	$178	$150	$161		
240	Unpainted Steel Culvert	m / L.F.	$656	$200	$5,207	$1,587	$2,546	$776			$130	$139
241	Reinforced Concrete Culvert	m / L.F.	$656	$200	$5,207	$1,587	$2,370	$722			$500	$536
300	**Strip Seal Expansion Jt.**	m / L.F.	$1,640	$500	$497	$151	$658	$201	$122	$131		
301	**Pourable Joint Seal**	m / L.F.	$656	$200	$61	$19	$244	$74	$26	$28		
302	**Compression Joint Seal**	m / L.F.	$656	$200	$187	$57	$350	$107	$152	$163		
303	**Assembly Joint/Seal (modular)**	m / L.F.	$3,281	$1,000	$6,125	$1,867	$1,287	$392	$420	$450		
304	**Open Expansion Jt.**	m / L.F.	$574	$175	$635	$194	$997	$304	$304	$326		
310	**Elastomeric Bearing**	each	$5,000	$5,000	$467	$467	$1,055	$1,055	$527	$565		
311	**Movable Bearing**	each	$6,000	$6,000	$1,616	$1,616	$1,360	$1,360	$527	$565		
313	**Fixed Bearing**	each	$6,000	$6,000	$1,495	$1,495	$1,759	$1,759	$527	$565		
314	**Pot Bearing**	each	$10,000	$10,000	$2,801	$2,801	$1,808	$1,808	$1,800	$1,928		
315	**Disk Bearing**	each	$10,000	$10,000	$467	$467	$300	$300				
321	Concrete Approach Slab	each	$15,000	$15,000	$6,464	$6,464	$14,400	$14,400			$5,333	$5,713
331	R/C Conc. Bridge Railing	m / L.F.	$246	$75	$166	$50	$300	$91	$50	$54	$50	$54
332	**Timber Bridge Railing**	m / L.F.	$82	$25	$123	$37	$205	$62	$34	$36		
333	Other Bridge Railing	m / L.F.	$246	$75	$153	$47	$426	$130	$60	$64	$105	**$112**
335	Steel Bridge Railing	m / L.F.	none	none	none	none	none	none	none	none	$45	$48
357	Pack Rust	each	none	none	none	none	$426	$426	none	none	none	none
358	Deck Cracking	each	none	none	none	none	$426	$426	none	none	none	none
359	Bottom of Deck, Slab, or Box Cracking	each	none	none	none	none	$426	$426	none	none	none	none
361	Scour	each	none	none	none	none	$426	$426	none	none	none	none
362	Traffic Damage	each	none	none	none	none	$426	$426	none	none	none	none
365	Steel - Fatigue Cracks	each	none	none	none	none	none	none	none	none	none	none



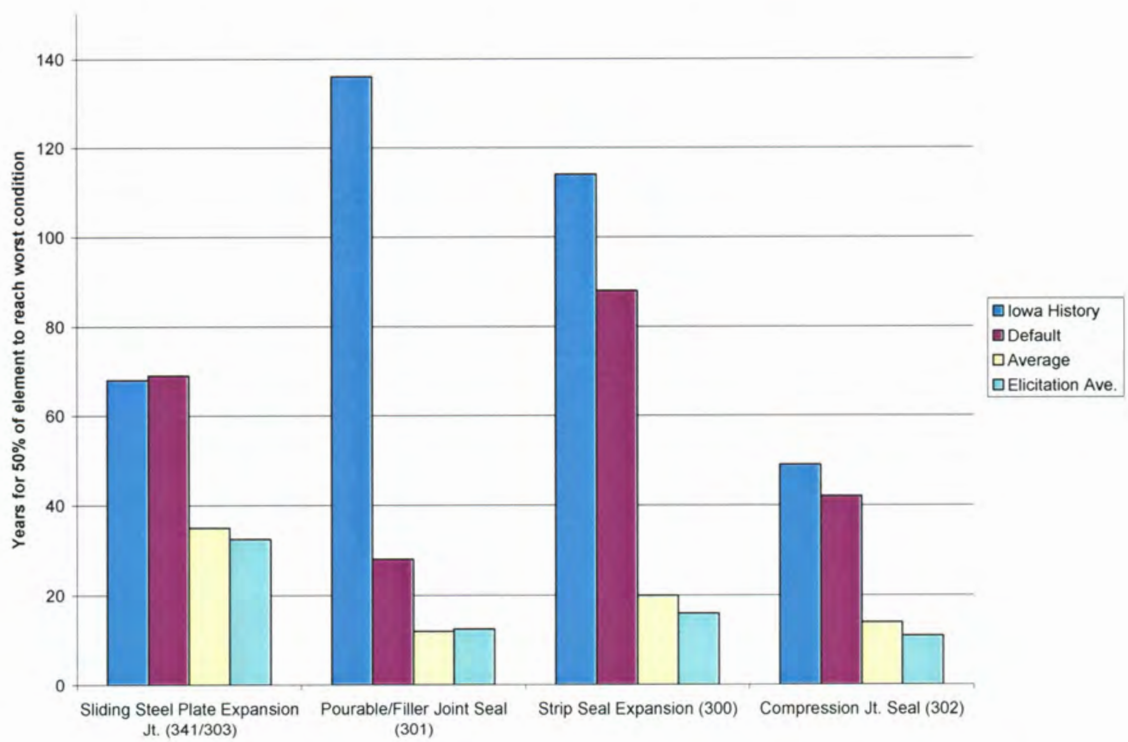
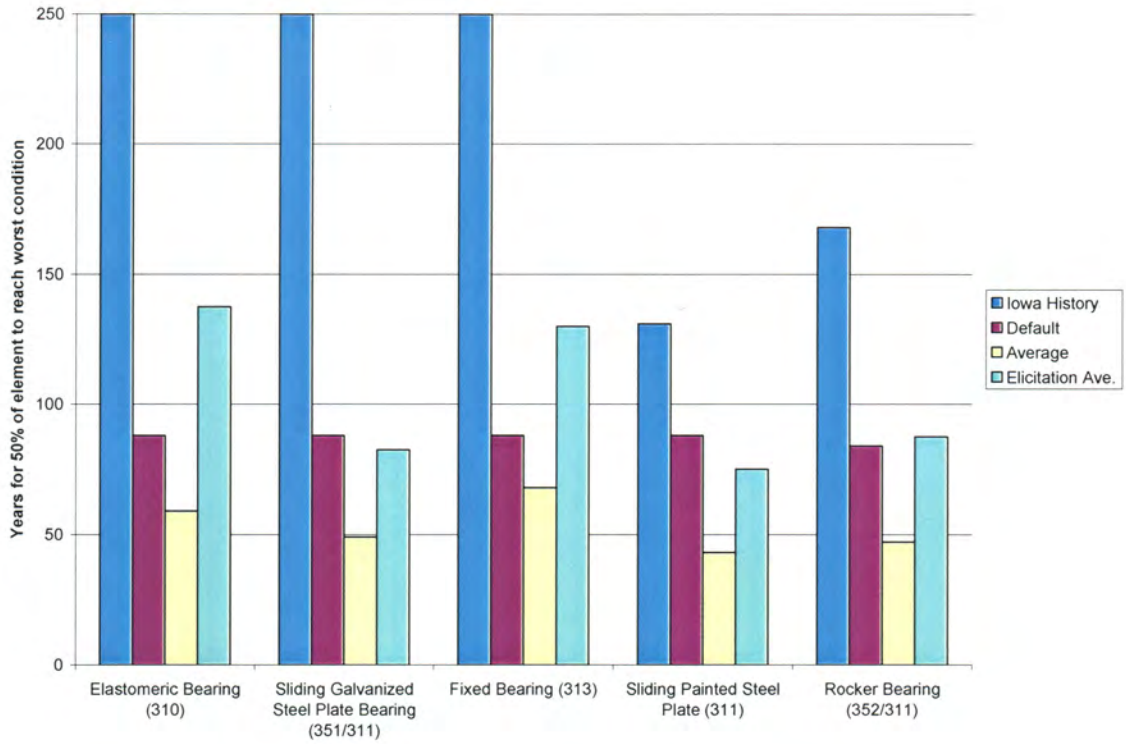


Figure 12. Completed deterioration elicitation forms.



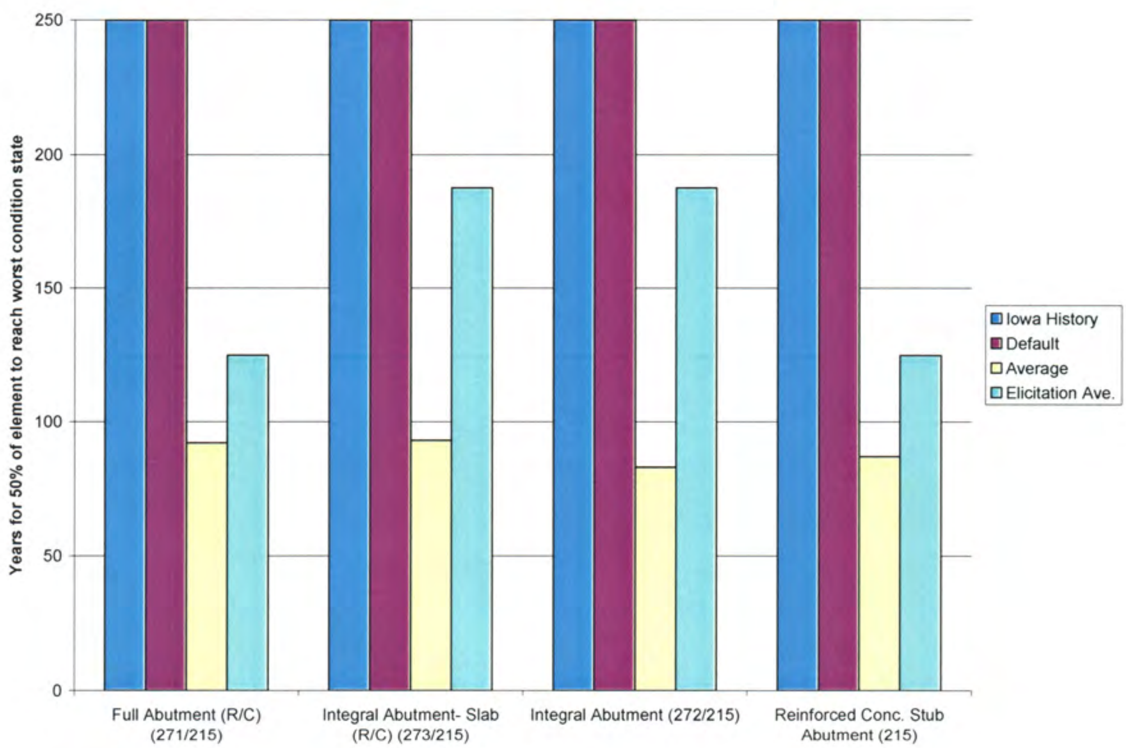
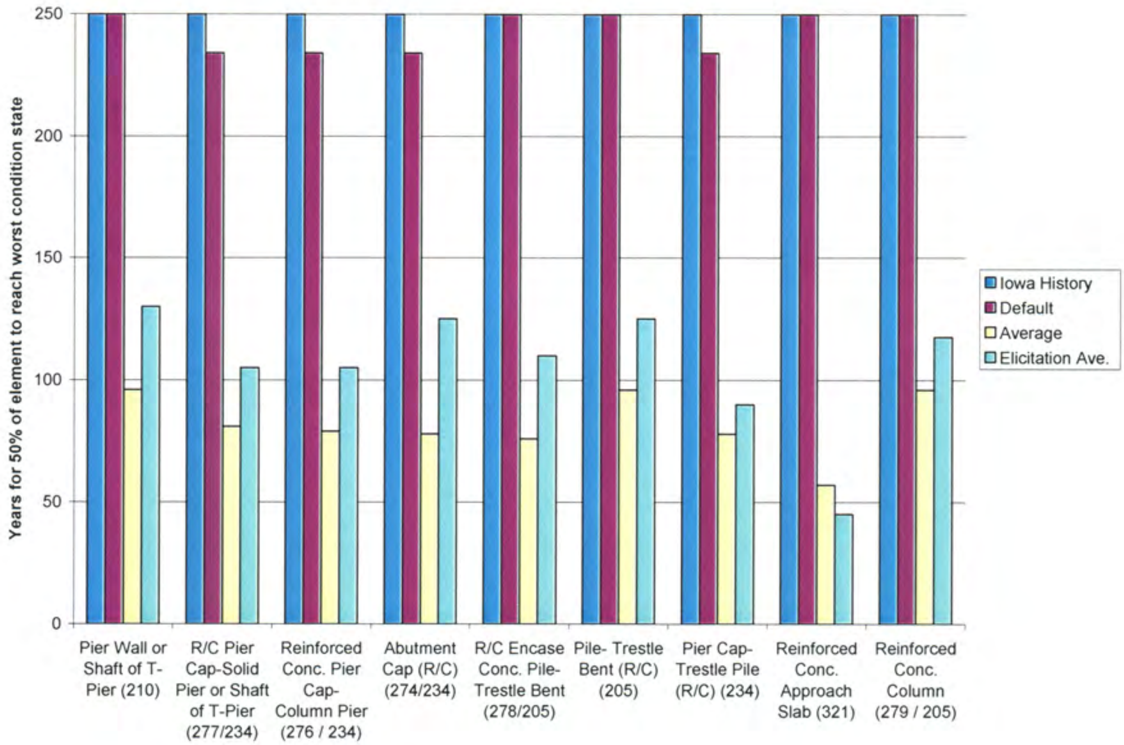


Figure 12. (Continued)



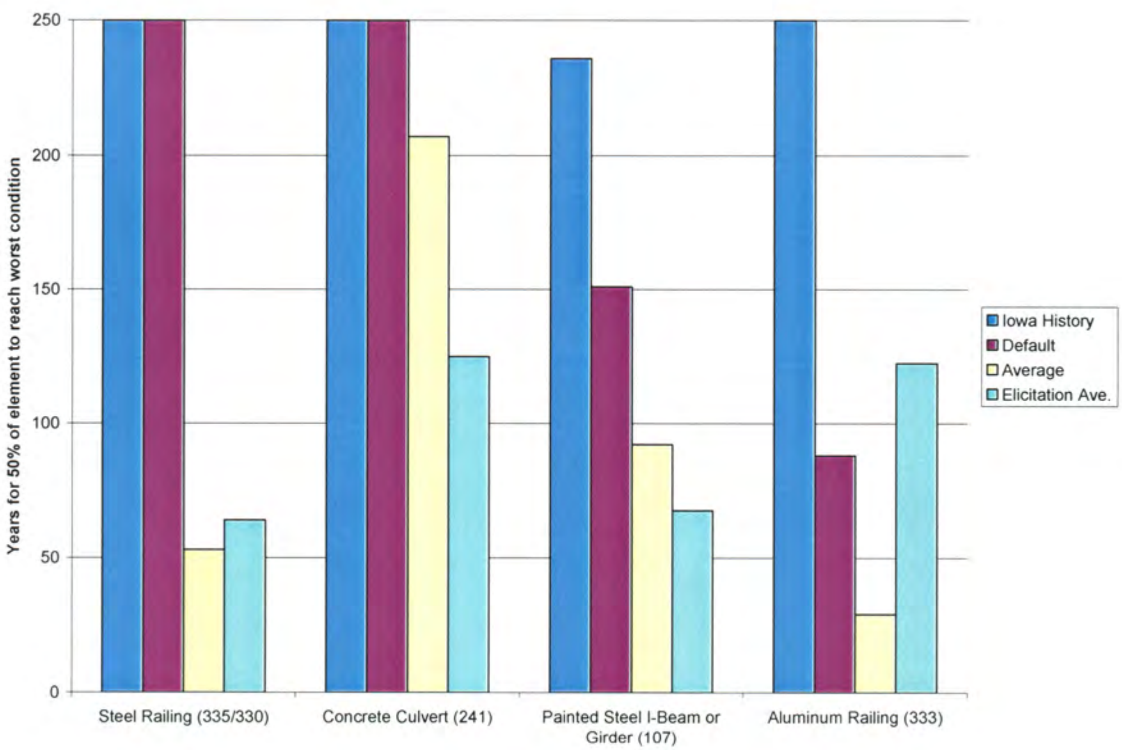


Figure 12. (Continued)

DEFINITION OF WORST CONDITION STATE IN PONTIS FOR VARIOUS ELEMENTS

Concrete Deck Elements – 12, 22, 26, 38, 48, 61
- Repaired areas and/or spalls/delaminations exist in the deck surface. Advanced deterioration. Heavy leaching and/or rust staining exist on the bottom side. Reinforcing bars are corroding with areas of section loss.

Bearings – 310, 311, 313, 351
- Corrosion is advanced with section loss. There may be loss of section of the supporting member sufficient to warrant supplemental supports or load restrictions. Bearing alignment may be beyond tolerable limits. Shear Keys may have failed. The lubrication system, if any, may have failed.

Deck Joints –
- 300 – Signs of leakage along the joint may be present. The gland possibly has failed from the abrasion of tearing. The gland has pulled out of the extrusion. Major spalls may be present in the deck and/or header adjacent to the joint.
- 301 – Major adhesion and/or cohesion failures may be present. Signs or observance of leakage along the joint may be present. Joint may be heavily impacted with debris and/or stones. Major spalls may be present in the deck and/or header adjacent to the joint.
- 302 – Major adhesion failure may be present. The gland may have failed from abrasion or tearing. Signs or observance of leakage along the joint may be present. Major spalls may be present in the deck and /or header adjacent to the joint. If joint is armored, the anchorage has failed.
- 303/341 – Corrosion is advanced. The assembly may be loose because of anchorage failure. There may be deck spalling adjacent to the joint.

R/C elements – 205, 210, 234, 274, 276, 277, 278, 279, 321
- Advanced deterioration. Corrosion of the reinforcing and/or loss of concrete section is sufficient to warrant analysis to determine the impact on the strength and/or serviceability of either the element or the bridge. The cracks are moderate with a "typical size" greater than 1/8 inch, and they have heavy leaching.

Steel Railing – 330
- Corrosion is advanced. Section loss is sufficient to warrant analysis to ascertain the impact on the ultimate strength and/or serviceability of the element.

Concrete Culvert – 241
- Major deterioration, spalling, cracking, major distortion, deflection settlement, or misalignment of the barrel may be in evidence. Major separation of joints may have occurred. Holes may exist in floors and walls. Settlement of roadway may have occurred.

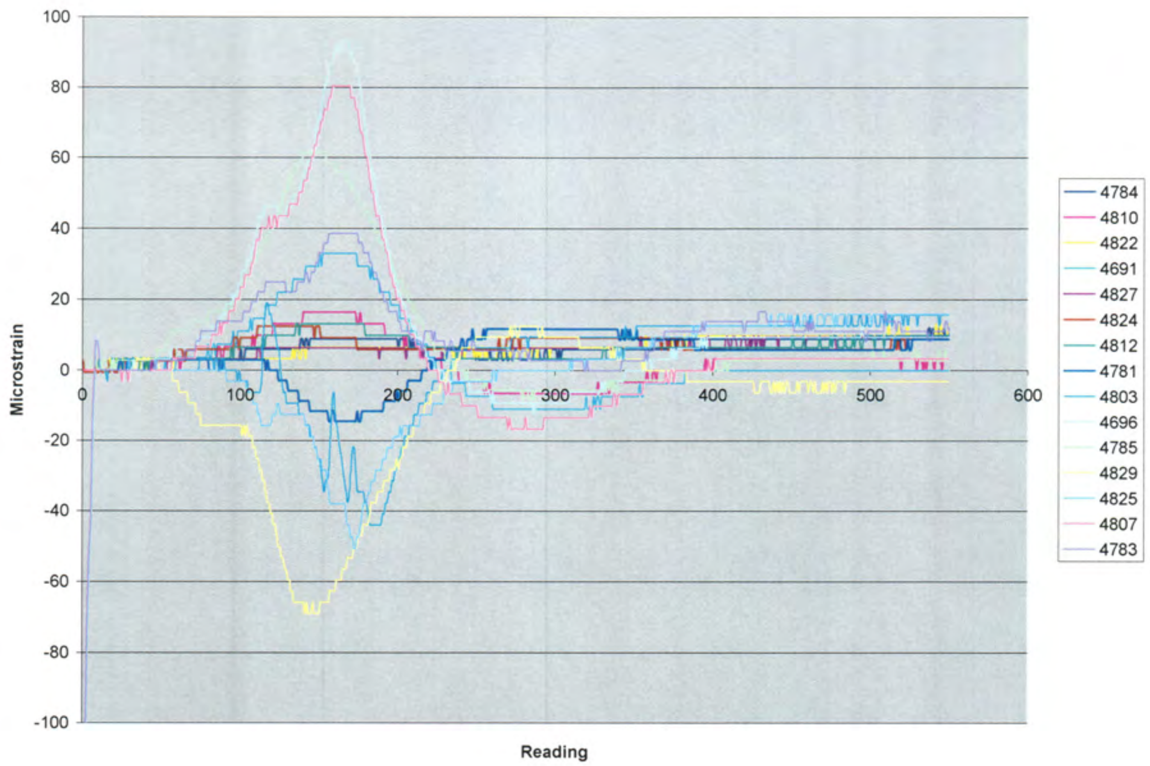
Painted Steel I-beam/ Girder – 107
- Corrosion has caused section loss and is sufficient to warrant structural analysis to ascertain the impact on the ultimate strength and/or serviceability of either the element of the bridge.

Aluminum Railing – 333

- The railing is damaged beyond repair.

Figure 13. Definition of worst condition state used in deterioration elicitation process.

Figure 14. Details of gauge installation for various girder materials.



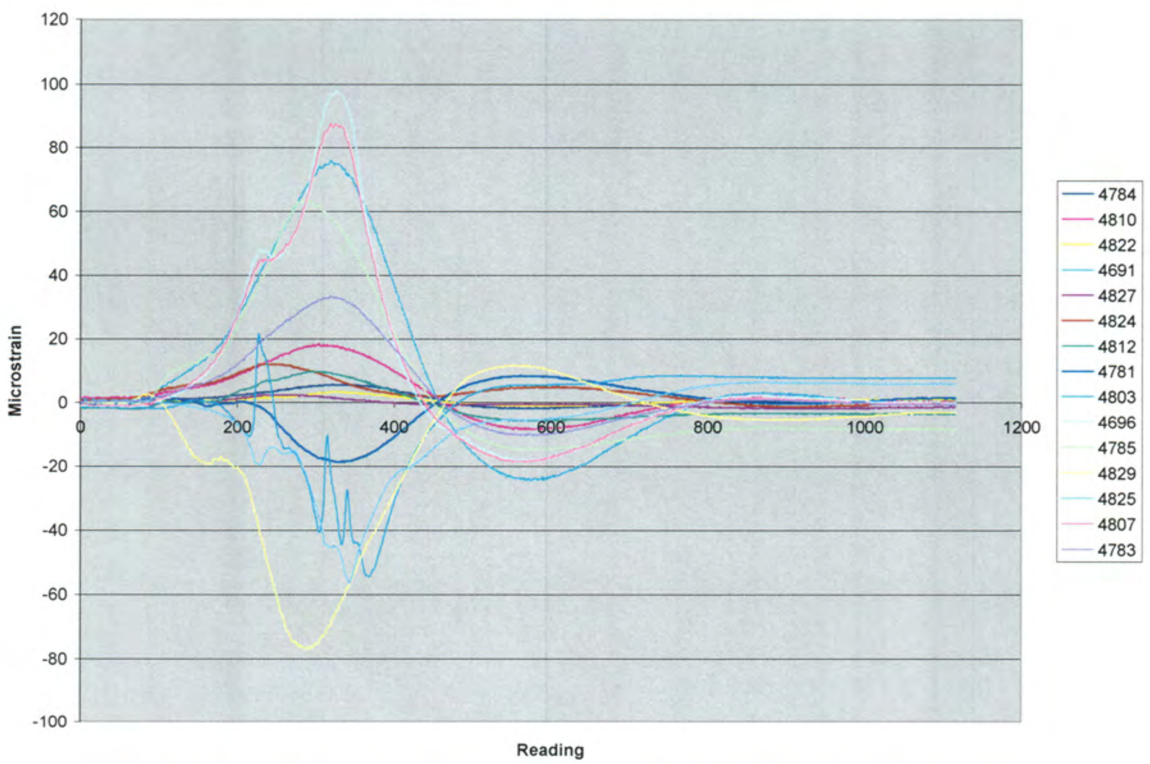
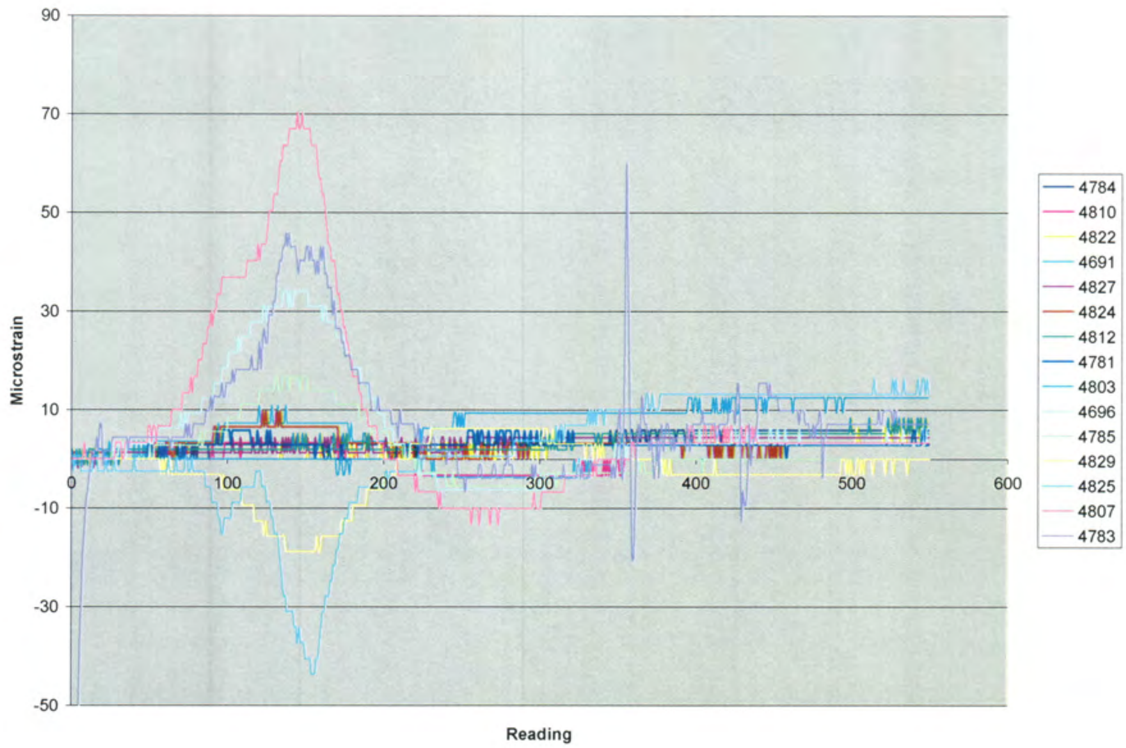


Figure 15. IA 92 Strain Profile Comparison, Center Truck Path.



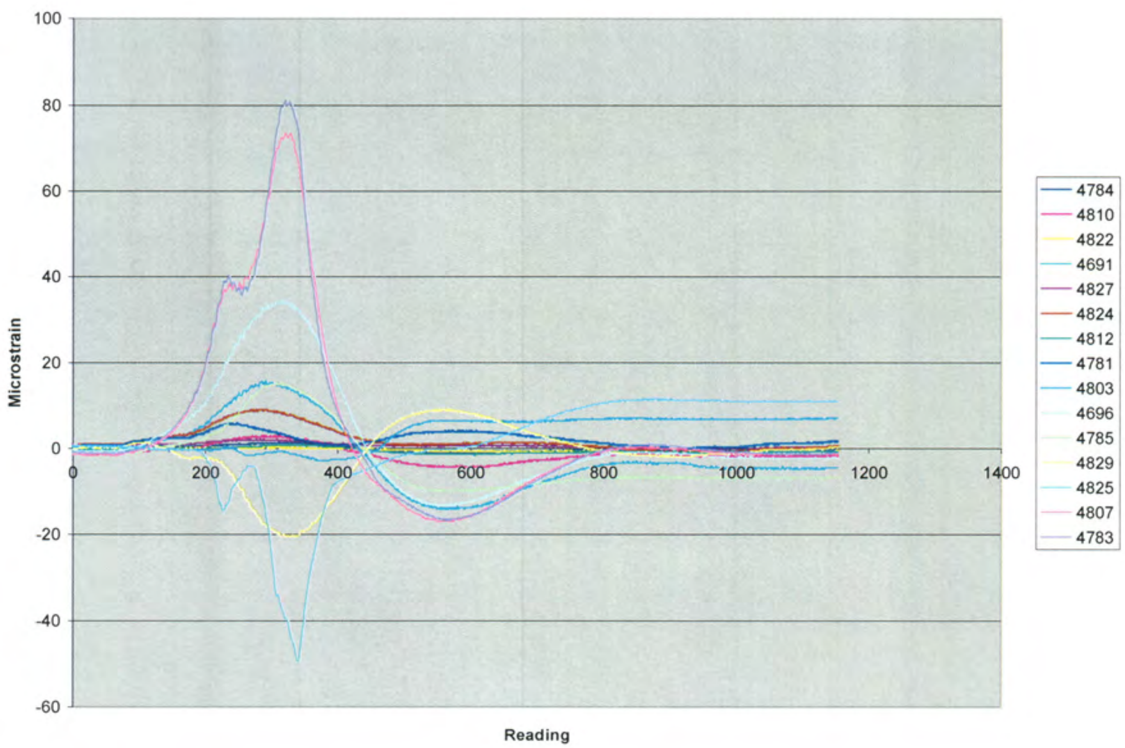


Figure 16. IA 92 Strain Profile Comparison, North Truck Path.

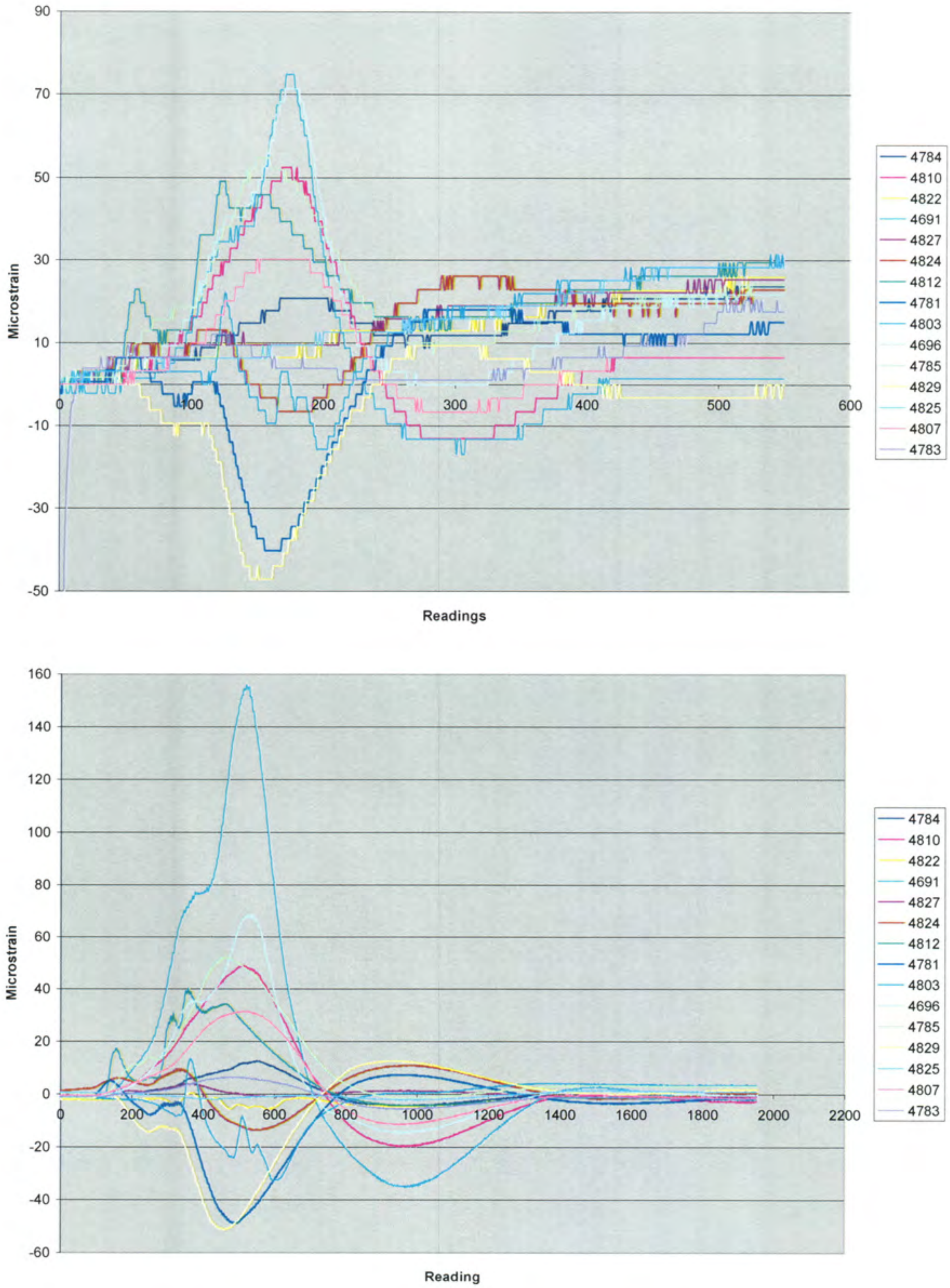


Figure 17. IA 92 Strain Profile Comparison, South Truck Path.

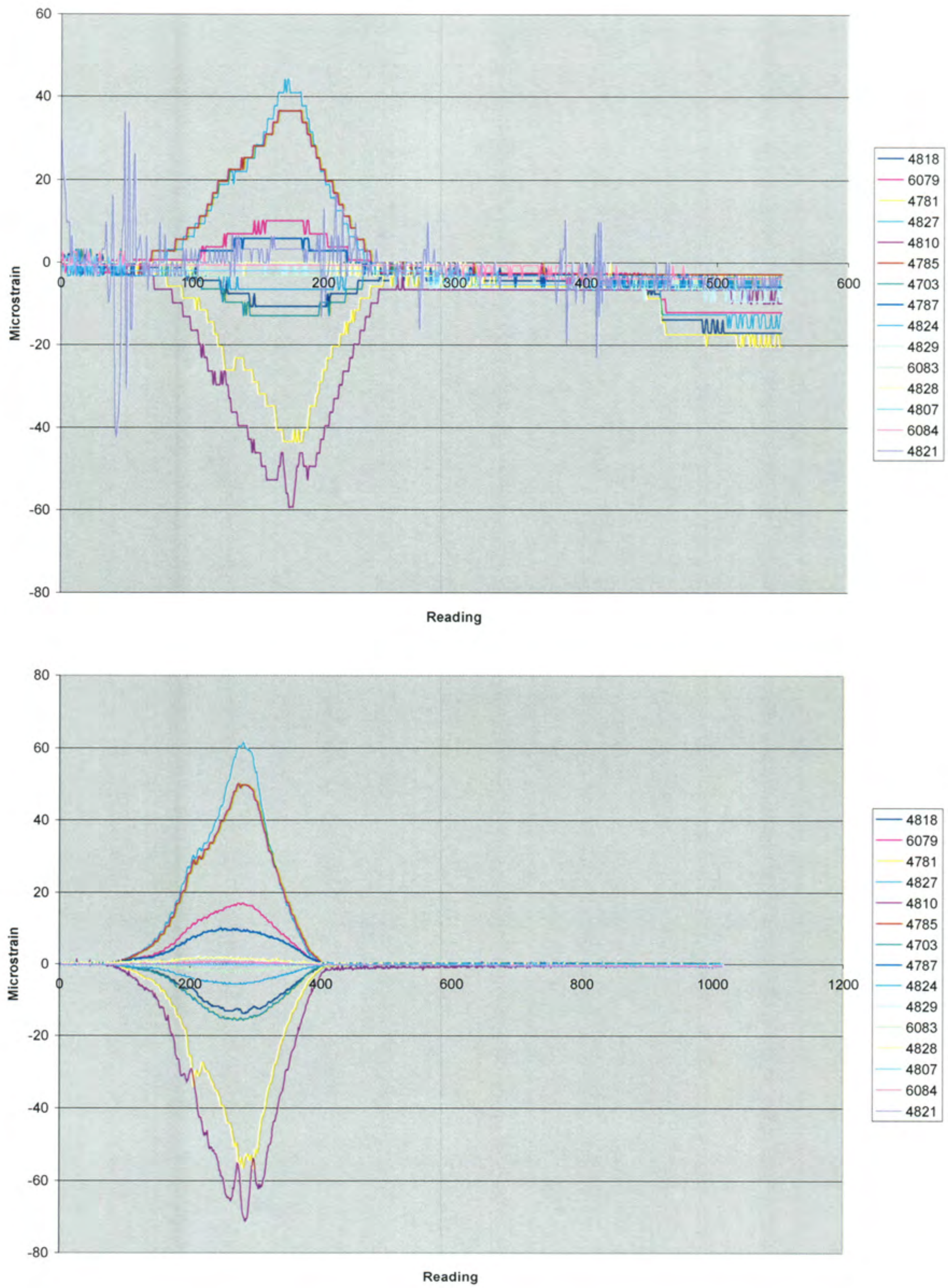
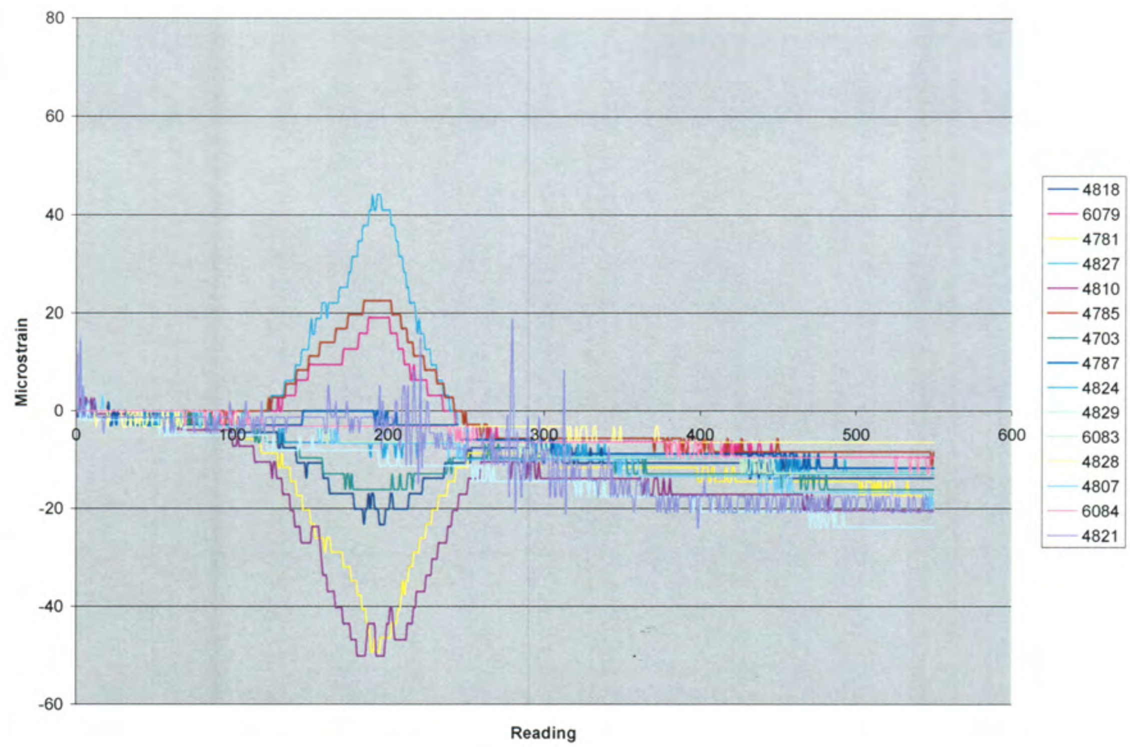


Figure 18. 53rd Street Bridge Strain Profile Comparison, Center Truck Path.



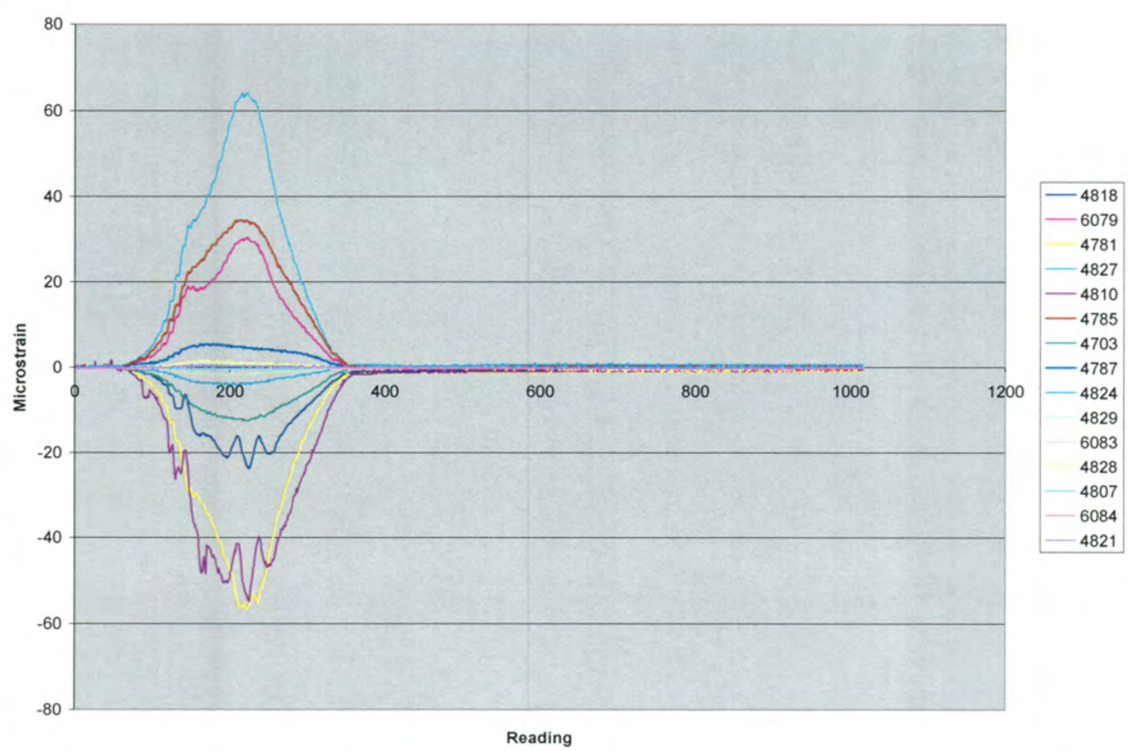
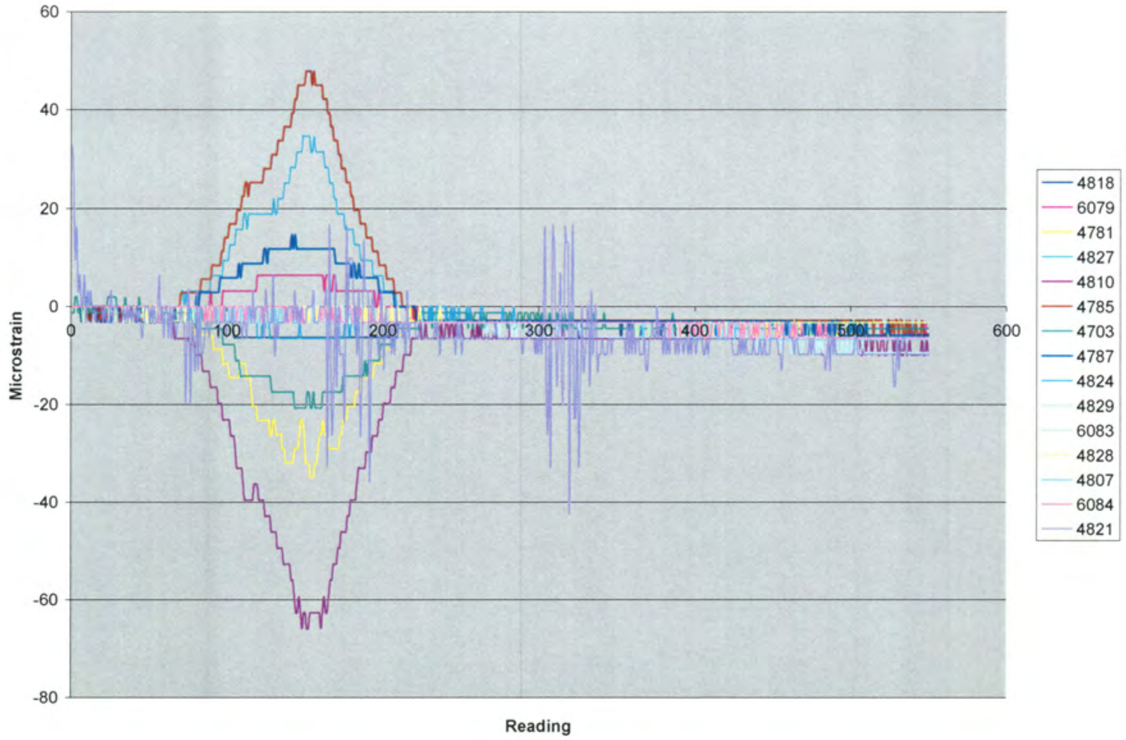


Figure 19. 53rd Street Bridge Strain Profile Comparison, North Truck Path.



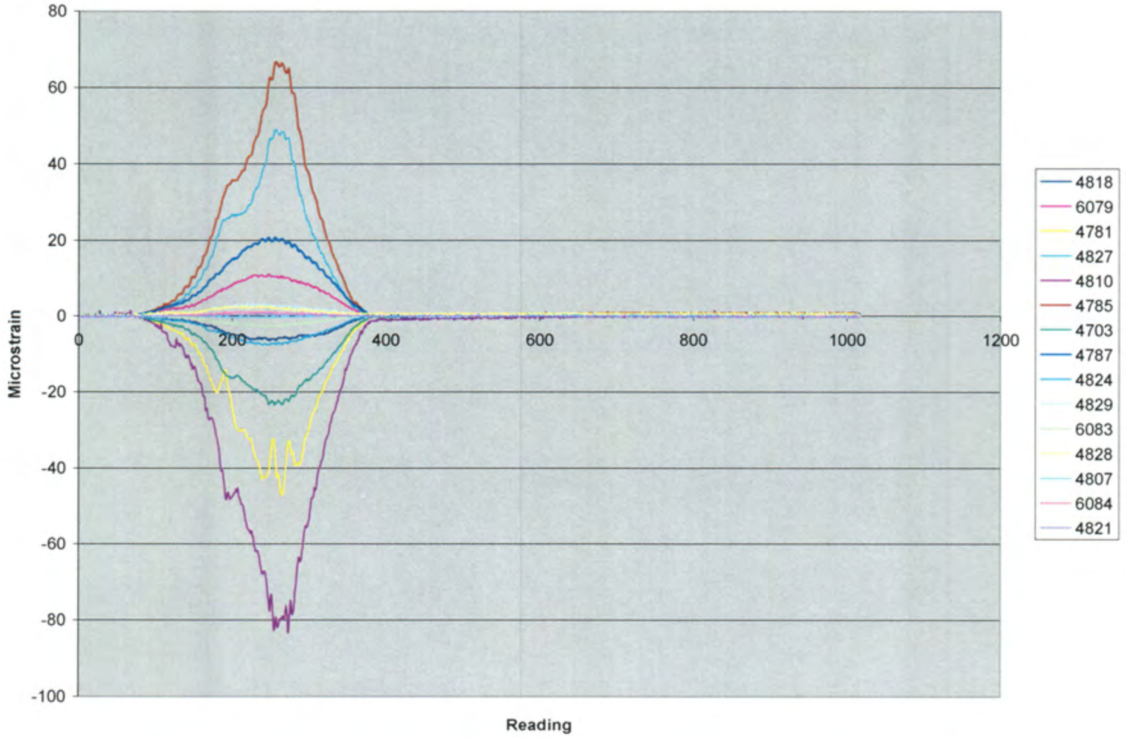
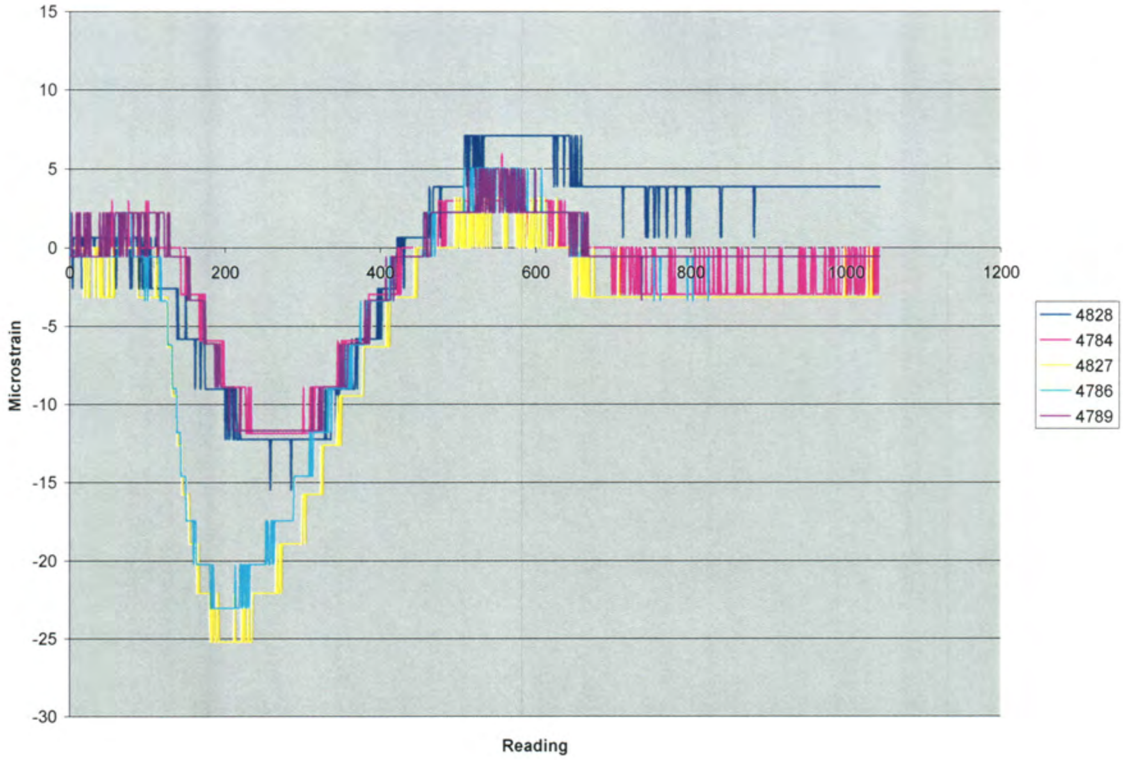


Figure 20. 53rd Street Bridge Strain Profile Comparison, South Truck Path.



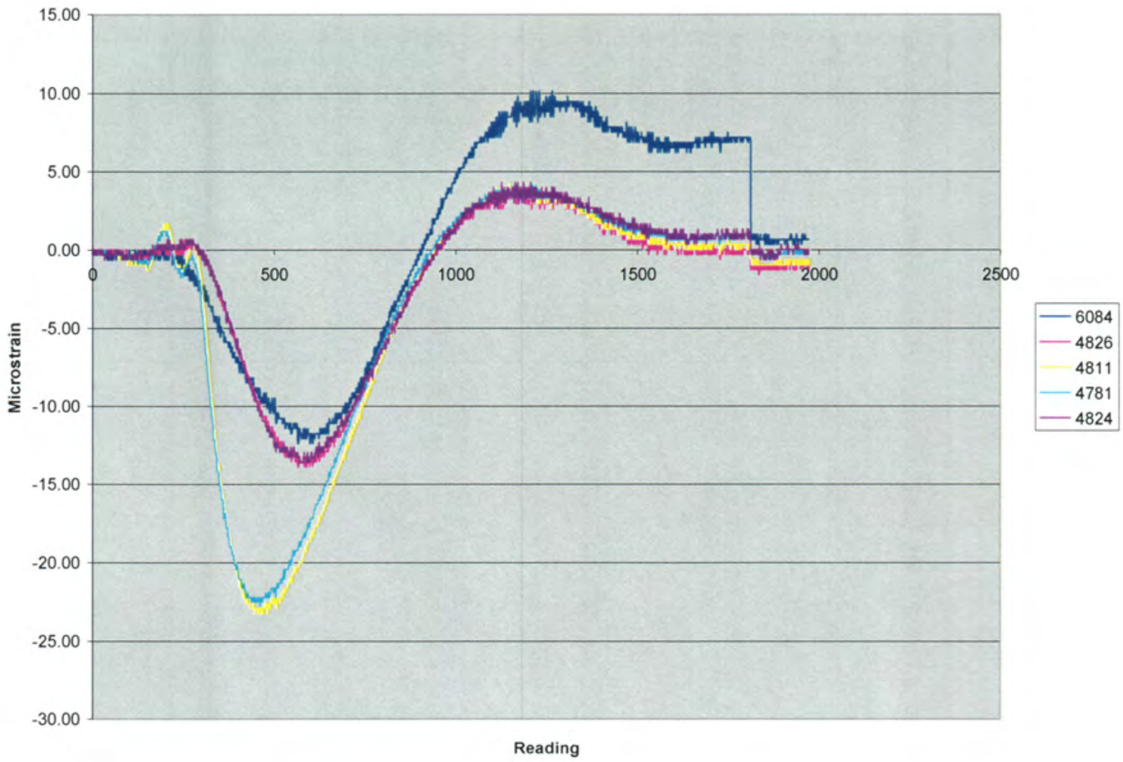
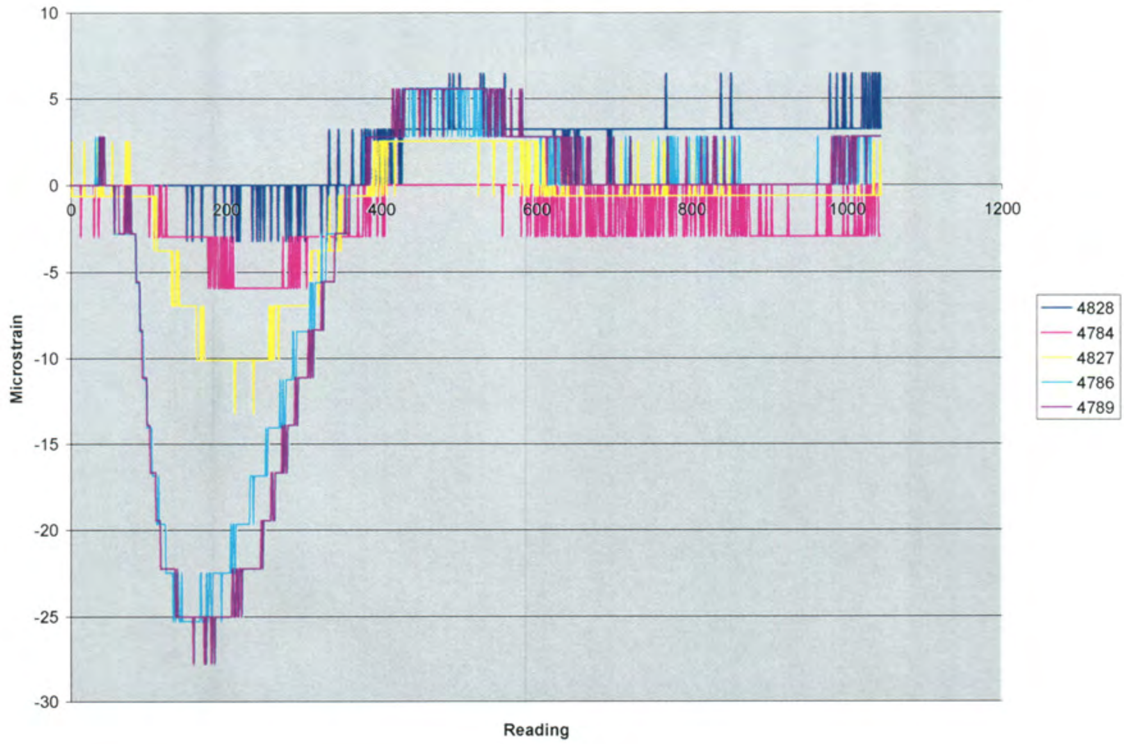


Figure 21. East 12th Street Bridge Strain Profile Comparison.



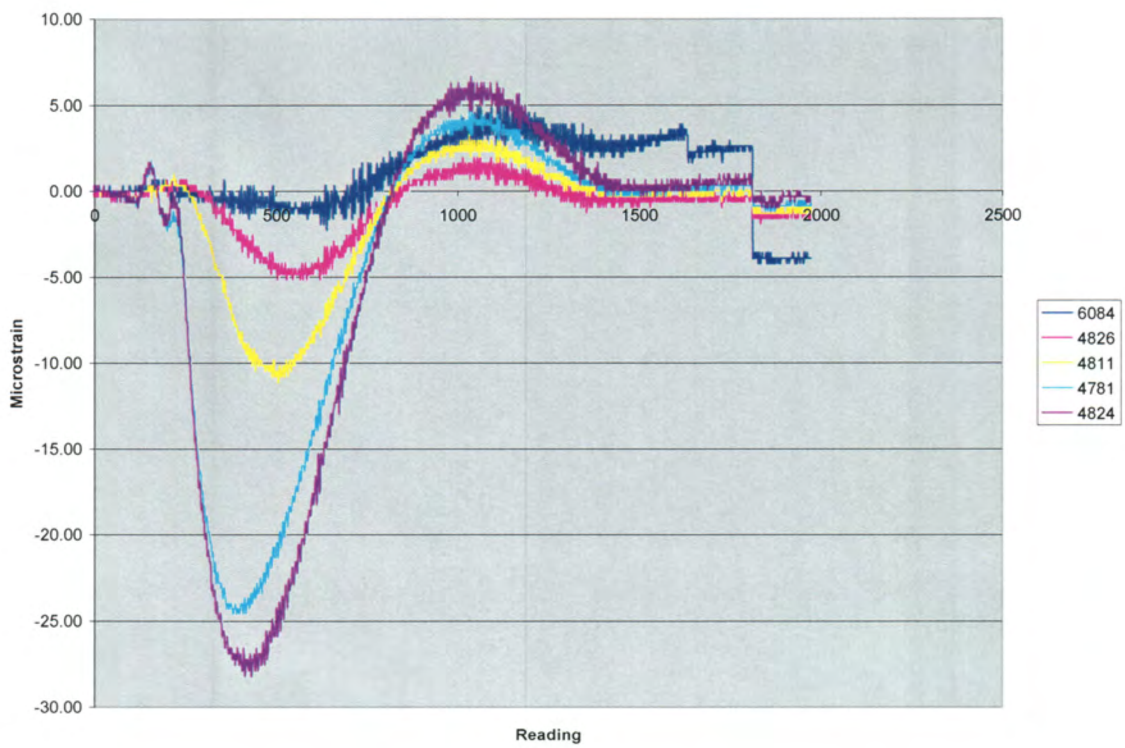


Figure 21. (Continued)