Quarterly Progress Report

TPF-5(039)	**Falling Weight Deflectometer (FWD) Calibration Center and Operational Improvements**

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Reporting Period:	**October 1, 2005 through December 30, 2005**

Project Status: **(Tasks 1-5)**	Work completed through end of period:	51.7%
	Project funds expended (pct. of funds obligated):	61.0%
	Expected completion date:	September 6, 2006

Status of the Project

The project is moving along well. The main focus of our activities during the quarter was on the development of new software for FWD calibration, populating a database of calibration test results, and design and evaluation of a multi-sensor geophone holder. Additional effort was required for Task 1 to get a nearly complete set of information from the FWD manufacturers. Continuing progress was made on Tasks 2, 3 and 4 during the quarter. After 15 months of activity, we estimate that we are somewhat behind schedule, but probably no more than three or four weeks. We are still confident that the project will be completed on schedule.

The details of the project are described in FHWA's Statement of Work which is posted at the TPF-5(039) Web site

Activity during the reporting period

Among the accomplishments during the reporting period were the following.

- Completed development of a Windows version of the FWDREFCAL computer program that is adapted to the Keithley KUSB-3108 data acquisition (DAQ) board.
- Completed conversion of the DOS version of the RELCAL 4 computer program to a Windows version, and temporarily named it FWDRELCAL.
- Defined an improved PDDX file format that can be used with FWD calibration activities.

- Began modifying the FWDRELCAL program to read PDDX data files from the FWDs. This activity will be concluded in the next quarter.
- Concluded a series of interviews with the Calibration Center Operators seeking their suggestions for procedural improvements in FWD calibration and documenting their experience with using the current procedure for non-Dynatest FWD brands. While the contract does not require it, this information is being integrated into the Task 1 report.
- Continued a series of interviews with the FWD manufacturers to identify important operating characteristics of the various types of equipment. Several items are still missing, but we have revised the Task 1 report on the findings based on what we have.
- Developed a computational method for double integrating digitized data from an accelerometer to obtain time history data. This gives precise peak displacement data.
- Populated a database of calibration results according to the SHRP protocol for later use in verifying and validating new calibration equipment and procedures. Fourteen reference and relative calibrations were completed with the geophones, and fifteen calibrations with the load cell. Some problems were encountered while doing this and they will be discussed in the next section. This work will be completed early in the next quarter.
- Designed, manufactured, tested and evaluated a multi-sensor geophone holder for the nine sensors on our Dynatest FWD. The horizontal platter design exhibited too many problems and it did not prove to be feasible. This will be discussed in the Problems Encountered section.
- Began the design and manufacture of a columnar multi-sensor holder.
- Borrowed a relative calibration stand from each of the FWD manufacturers. This will help our understanding of the sensor mounting methods used, and enable us to adapt the designs to a multi-sensor holder for use in deflection sensor calibration.
- Developed an experiment to characterize the frequency response of the Silicon Designs model 2220 5g accelerometers and the Lucas-Schaevitz model GCD-121-125 LVDTs that we are using. Found an MTS shaker table on campus that we can use. Designed and built an apparatus for holding two accelerometers and three LVDTs while they undergo test at multiple frequencies and displacements. Developed a LabView program for data acquisition and data analysis. The experiment will be concluded early in the next quarter.
- Did some preliminary investigative work on measurement of temperatures close to the accelerometer; sensitivity of accelerometers to magnetic fields and shielding effectiveness; anti-aliasing filtration of accelerometer signals; signal conditioning of accelerometer output; and alternate reference load cell designs.
- Met with the Technical Advisory Committee and gave several presentations about this project at the FWD Users Group meeting in Austin, Texas.

Problems encountered during the reporting period

<u>FWD Errors</u>

Near the end of the previous quarter we encountered a problem when we began populating a database of replicated FWD calibration results. The purpose of the database is to provide a baseline for comparison of new equipment and procedures to the current ones. The problem was repeated timeout error messages when running the FWDwin field program with our Dynatest FWD. The net result of the error messages caused the collected data to be lost, and the calibration trial had to be repeated. This was a more common problem when we were doing geophone calibration than with load cell calibration.

We received good support from the Dynatest firm in an effort to help us diagnose and correct the problem. They provided us with an updated version of the FWDwin program, and later a special edition of the program. They also suggested that we try a rebuilt microprocessor, and they loaned us a unit for that purpose. They helped to identify additional possible sources of the problem including the laptop computer, the operating system, and the RS-232 cable that connects the microprocessor to the laptop.

We ran ten calibration trials using different combinations of software, computer/operating system, cable, and microprocessor before we felt we had isolated the problem. For each trial we did a complete set of reference calibrations and two relative calibrations. Stringent limits on beam movement were imposed, notably more stringent than is routinely used at the Calibration Centers, to assure that we had good quality data.

The microprocessor was identified as the primary source of the error messages.

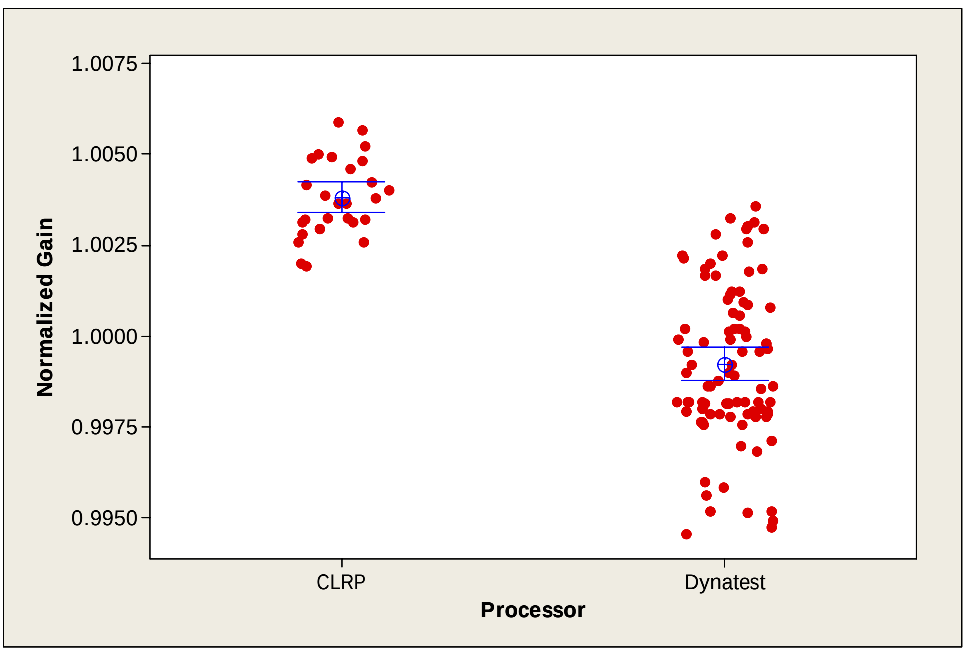

Fig. 1 Comparison of results using the Cornell and loaned Dynatest microprocessors.

Figure 1 shows an interval plot of the results. The red dots depict a calibration factor for each individual geophone. A small amount of "jitter" has been added by the plotting routine so that the data points will not fall in a single, vertical column. The mean result and the 95% confidence interval on the mean are shown in blue. While the two populations overlap slightly (in terms of gain factor), clearly the two means are not the same. A rigorous statistical analysis of the data showed the two means to be very significantly different, with an F-ratio of 110. The difference in the two means was very small, only 0.0046.

We elected to continue the database development using the rebuilt microprocessor. This required us to repeat all of the work that had been done using the Cornell microprocessor. We had to discard all of the load cell calibration trials and half of the deflection sensor trials in our database. Unfortunately work that spanned several months was lost.

We gained some benefit from the investigation, however, as it did give us a good estimate of the repeatability of the geophone and load cell calibration procedures. With this information we determined that an optimum number of calibration trials is 9 for the geophones, and 15 for the load cell calibration trials. A smaller number of trials is required for the geophones because each trial includes data from a set of nine geophones.

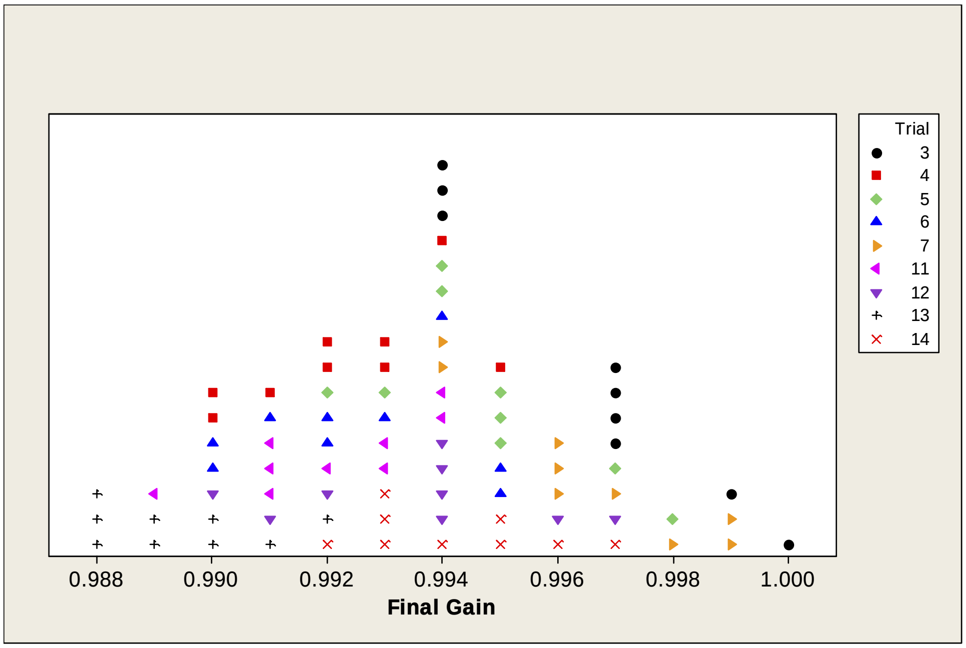

Fig. 2 Scatterplot of nine geophone calibration trials.

The nine geophone calibration trials using the rebuilt microprocessor have been completed, and the results are shown in Figure 2. Note that the range of the data is only 0.012 units wide, which is why the problem we experienced with the microprocessor was so important.

The fifteen load cell calibrations will be completed early in the next quarter.

<u>LVDT Errors</u>

We had planned to use our LVDT as the reference device for evaluating the Silicon Designs accelerometer. However, during the previous quarter we compared the response of four LVDTs, two belonging to Cornell and two loaned to us by the PennDOT Calibration Center. We found a 1.3 percent spread in the dynamic response of the LVDTs. An investigation of why this is the case is on going, meanwhile we are using only one LVDT in our work.

All four LVDTs were calibrated statically using the same micrometer calibrator, so they were expected to give the same dynamic response. One of the LVDTs was new, having been purchased especially for use in this project. One might expect it to give the biggest response, since it had experienced little or no friction-causing wear. However the opposite was true, the oldest LVDT gave the largest dynamic response and the newest one gave the least.

Discussions with the LVDT manufacturer did not provide any insight concerning reasons for the differences between units. Our hypothesis is that the frequency response of each unit is slightly different, and the frequency rolloff may be much more severe than we expected.

We have found a suitable shaker table that we are able to use without charge. We have designed an experiment and built a holder that will allow us to simultaneously characterize the frequency response of three LVDTs and two accelerometers at the same time. We were able to buy a highly-accurate laser displacement device at a fraction of the retail price, and we will use it as the reference device in the comparisons.

While we had not originally planned to use a shaker table to evaluate the accelerometers, this new plan is a much better way to proceed. We recently discovered that the Silicon Designs accelerometers are sensitive to magnetic fields. The shaker table study will allow us to look at the effect of electromagnetic fields, and to evaluate the efficacy of EMF shielding. We may also try to assess the influence of temperature on the accelerometer response using the shaker table.

We began the shaker table tests at the end of the quarter. We expect the investigation to be completed midway through the next quarter.

Multi-sensor Holder Trials

Our first design of a holder for multiple geophones was unsuccessful, but we learned a lot in the process. We designed and built a platter-type holder, which was bolted to the test pad using the same holes that are used for the old, single-sensor geophone holder (Figures 3a and 3b).

(a)

(b)

Figure 3 Platter-type multi-sensor geophone holder.

We tested the assembly with an array of sensors orthogonal to the FWD, as shown in the photo, and also with the sensors oriented at 45 degrees to the FWD. We felt this design would be very useful if it would work. By placing the sensors on a horizontal platter, the position of the sensors could easily be changed by simply rotating the platter on a vertical shaft. Our concern, however, was whether the platter would rotate as the ground wave from the FWD passed beneath it. The test data show that the platter did rotate (Figure 4).

The peak displacement of the sensor closest to the FWD (sensor #1 in the photo and the grey line at X = 100 on Figure 4) shows about the same deflection as the center sensor (green line). Its counterpart at the rear of the plate (sensor #9 in the photo and the yellow line at (X = -100) on the chart) shows the largest peak deflection. The red and blue lines (sensors #3 and #7) show there was also some transverse plate rotation.

If the plate rotations had not been so large (a 100-micron differential), they might not have posed a big problem. For our next design we planned to array the nine sensors in a circle. By rotating the circle horizontally in nine equal increments, each sensor would be in every position. We expected any differences attributable to position would average out. However, in addition to plate rotation, another complication was encountered.

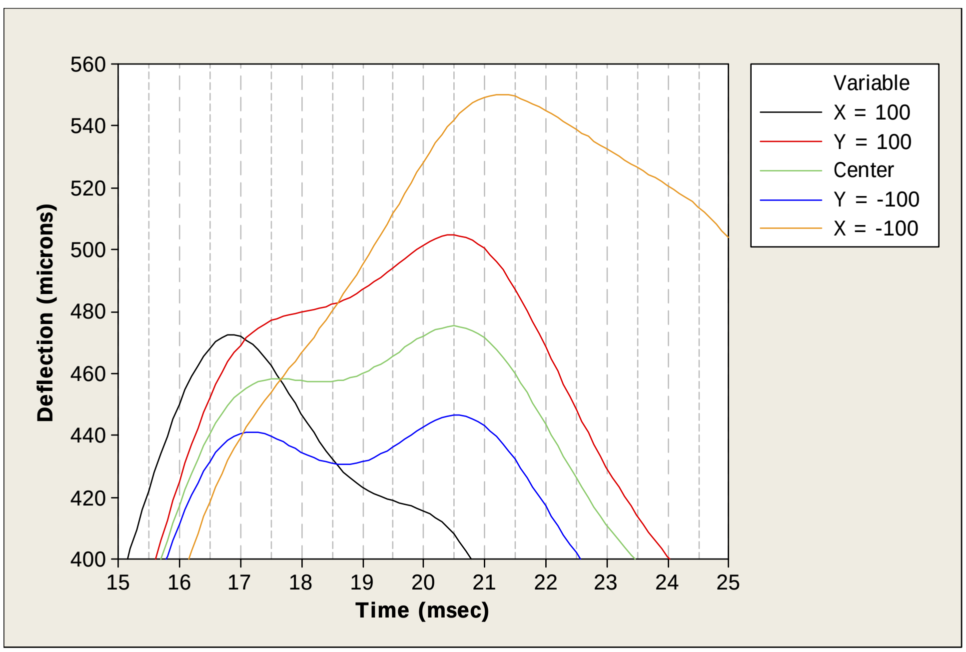

Figure 4 Time histories of 5 geophones on the platter due to one drop.

For statistical reasons, a large number of drops are made during relative calibration (currently 45 drops). We found that as we proceeded through the drop sequence, the test pad deflection steadily increased, probably due to subgrade liquefaction. With both plate rotation and increasing deflection taking place *simultaneously*, each sensor would not be subject to the same average deflection. So the platter design could not be used.

In a way, we were fortunate to encounter the liquefaction problem early in the game, before we put a lot of time into investigating the platter design.

We have determined that a columnar design will overcome both problems. If liquefaction (or compaction) occurs, each deflection sensor will be affected equally. So the average result will be satisfactory. We plan to investigate a columnar design in the next quarter. To this end, we have a relative calibration stand to work with from each of the four FWD manufacturers.

Work completed by task

The six tasks referred to below are described in detail in the Statement of Work on the TPF-5(039) pooled-fund web site. Our strategy is to work simultaneously on Tasks 2 and 3. We feel that both the hardware upgrades and the software upgrades interact, and thus it is more efficient to work on the two tasks together. Progress was also made on Task 4 during this quarter.

Task 1. Communication, Coordination and Reference Resources

Task 1a is complete. All protocols, software, and drawings of the currently used FWD equipment that are available are in hand. One set of this information will be transmitted to the COTR.

Task 1b will continue throughout the project. This task provides for a dialog with the FWD manufacturers and the calibration center operators. We feel this dialog should continue for the duration of the project.

During the reporting period we continued our interviews with the FWD manufacturers and the Calibration Center Operators. At the FWD Users Group meeting in Austin we were able to interview John Ragsdale, the Center Operator for the Texas Calibration Center, and we were able to interview three representatives from Carl Bro face-to-face. Good progress was made on getting the information that we needed.

The additional information is being integrated into the Task 1 report, and the report will be submitted early in the next quarter. We are still missing a small amount of information about the Carl Bro equipment, but we feel we have enough now for our report.

Task 2. Modify Calibration Process

Task 2a is continuing. Our revised calibration procedure combines reference calibration and relative calibration into a single procedure, with electronic data transfer from the FWD computer to the Calibration Center computer. The software is being modified to support this approach.

Our work to date indicates that we will be able to use an accelerometer instead of the LVDT as our reference sensor. Using our double integration technique, the precision afforded by the accelerometer appears to be as good, or nearly as good, as the LVDT. A final decision on whether to use the accelerometer has not been made, however, pending the outcome of the frequency response characterization of the LVDTs and accelerometers that will be completed early in the next quarter. Additional concerns involve the sensitivity of the accelerometer to electromagnetic fields and to temperature. We will investigate those issues during the coming quarter.

While it appears that the accelerometer will be highly accurate and repeatable, it does not seem to offer a level of accuracy sufficient to justify elimination of the relative calibration part of the procedure. Our interviews with the equipment manufacturers have led us to understand they have improved the measurement precision of their FWDs over the past decade. The accelerometer precision is quite good, but it is not a lot more precise than the geophones, and thus we will continue to need to use a statistical approach in the calibration procedure, as the current calibration procedure does. We believe we can combine the two parts of the procedure in a relatively seamless way.

A goal for streamlining the calibration procedure was established at the April 2005 meeting of the Technical Advisory Committee (TAC). The Committee asked that we expedite the procedure so it can be completed within three hours, and we believe that goal can be achieved. We are doing reference calibration on all deflection sensors simultaneously, rather than sequentially as it currently is done. This saves a lot of time.

While the first multi-sensor holder that we studied was not successful, we believe that a columnar design will work. It has already been shown to be satisfactory for relative calibration.

Another way to save considerable time is to electronically transfer the data from the FWD computer to the calibration computer. To accomplish this, the new software is being written to read the FWD data from a PDDX file format, as specified by the American Association of State Highway and Transportation Officials (AASHTO). We have learned from our interviews with the manufacturers that one FWD brand does not have a PDDX output option and the others have minor departures from the AASHTO standard. The Calibration Center Operators have told us that many FWD owners do not have up-to-date software in their computer, thus we should not expect that all (or even a majority) of existing FWDs will be able to create a PDDX output file.

Thus a major barrier to electronic communication between the FWD and the calibration center computer has been encountered. There is a wide variety of native file formats that the various FWD brands currently produce. We are developing a file conversion program, based in large part on a program that FHWA has already produced, that can accept input from the several types of FWDs and produce a PDDX file that meets the needs of the calibration software. This would be a stand-alone product that could be used by FWD owners for a variety of reasons. Work on the file conversion program is currently underway.

Our interviews with the Calibration Centers have alerted us to the fact that total reliance on *wireless* data transfer between the FWD computer and the calibration computer may not be possible for several reasons. First, many of the FWD computers that are presently being used are not adaptable to wireless technology, or the FWD owners may be resistant to installing wireless support in their computer. Second, the Information Technologies (IT) people in the hosting DOTs (where the Calibration Centers are located) will need to be consulted and involved. Use of wireless technology may raise some concerns about security. So we plan to allow for several different ways that the FWD data can be transferred in addition to wireless methods. This may include using a thumb drive, a CD-R, or perhaps a 3.5 inch floppy disk.

Our work has shown that the custom load cell that is currently used is satisfactory for the job. Several of the Calibration Centers have replaced the top plate on their load cell, increasing its thickness from 0.625 inch to 1.0 inch. This was done to improve the long-term stability of the reference load cell calibration factors. For the load cells that have not yet received a thicker top plate, we plan to make that modification.

During the quarter we continued our effort on gathering a database of calibration test results. As noted, we experienced some problems and delays with this. The problems have been isolated and overcome. At the end of the quarter we had completed a full set of nine geophone calibrations, and the data appear to be sufficient and satisfactory. We will repeat the load cell calibrations, doing fifteen calibrations early in the next quarter.

The database of calibration results will prove to be very useful when we assess whether the revised calibration procedures meet or exceed the accuracy and precision of the current procedures. Using statistically designed experiments, the evaluation of any particular modification will require only 4 geophone calibration trials or 8 load cell calibration trials to make the assessment. This represents about one week of effort for each parameter under study.

Task 2b will not be necessary. In FWDREFCL we have been successful with developing "about triggering" for the Keithley KUSB-3108 DAQ board. This means that an event such as the falling mass striking the load plate can be used to detect the release of the falling mass. We have found that this technique will work with both load and deflection sensor calibration. Thus it will not be necessary to establish an automated mechanism to trigger data acquisition at the release of the mass.

"About triggering" works in conjunction with three buffers that operate under the control of the Keithley DAQ board. More than three buffers could be used, but we have found that three are sufficient for our needs. We are collecting data at 15,000 samples per second on each of two 16-bit channels (LVDT and accelerometer). Each buffer holds one second of readings. After the buffer is filled, the data are transferred to a temporary array in the computer memory, while the next buffer is filling.

If the desired event is detected among the data, then a specified amount of pre-event data are saved, and sampling continues until the desired number of readings have been obtained. If the event is not detected, the data in the buffer are overwritten, and the cycle continues. This allows a substantial amount of data to be collected before the event, without the need to retain an excessive amount of data.

Task 2c is continuing. Our work to date indicates that an accelerometer can be used to eliminate the LVDT/beam/block assembly. We will continue to assess this during the next quarter. At this time it appears that a means of measuring beam movement will not be necessary.

Task 3. Hardware and Software Upgrades and/or Development

Task 3a is continuing. This task was begun in three phases, using the services of two part-time computer programmers. A fourth phase was added during the reporting period.

Phase 1. Convert the DOS-version of FWDREFCL to a Windows program. For compatibility with the Keithley KUSB-3108 DAQ board, we have elected to use Visual Basic 6 for our Windows language. We refer to the new program as FWDREFCAL. This phase has been completed.

Phase 2. Replace the calls to the DAS-16G DAQ board in FWDREFCAL with calls to the new Keithley KUSB-3108 DAQ board. About triggering is being used. This phase has been completed.

Phase 3. Convert the DOS-version of FWDRELCAL to a Windows version, adding a PDDX file reader. Merge FWDREFCAL and FWDRELCAL. Modify the combined program to reflect the changes in the calibration protocol that are developed by the study. For instance, a subroutine that double integrates the accelerometer signal must be added. This phase is on going and will be completed in the next quarter.

Phase 4. Develop a file conversion program so that the FWDs can communicate electronically with the Calibration Center computer. This work will be completed during the next quarter.

No effort was made on Task 3b during this reporting period. We do not plan to purchase hardware for distribution to the Calibration Centers until the COTR has accepted the modified procedures. We expect to schedule the visits of the COTR for review and acceptance of the modified calibration procedures near the end of the coming quarter. Tentative dates for the reviews will be determined early in the next quarter.

Task 4. Calibration System Testing, Installation and Operator Materials/Training

Task 4a is continuing. It is an open question whether the development of a calibration database is a Task 2a or a Task 4a activity. In any case, the database will prove to be very useful for evaluating the new procedures, software, and equipment. It has taken longer than we expected to gather the calibration results for the database (as explained in a previous section), but from this point forward it will save time by reducing the number of calibration tests that we must do to demonstrate whether the new procedures meet or exceed the requirements.

To assess the new procedures we will perform a limited number of calibration trials, as explained under Task 2a. This will be termed the "assessment data set." To evaluate *accuracy* we will check for a significant difference in the *means* of the assessment data set versus the database that we have collected using the current calibration procedure. To evaluate *precision* we will check for a significant difference in their *variances*. Statistically-based data analysis methods will be used for this purpose.

During the reporting period we devised an efficient way of demonstrating whether the new procedures work with the various brands of FWDs. We plan to arrange a visit in March to several of the Calibration Centers to use the new equipment and software with the JILS, KUAB, and Carl Bro FWDs. This will avoid the need to pay for the various FWDs to come to Ithaca, with all of the attendant scheduling complications. It will also give the Calibration Center Operators the opportunity to provided feedback on the new features, and give them a bit of training in the use of the software. The COTR has agreed to this approach.

Task 4b is continuing. We are documenting the Windows versions of the FWDREFCAL and FWDRELCAL software, developing flow charts keyed to the software. We expect the activity to be concluded during the next quarter. As various activities are concluded, we prepare brief internal reports for the file, which will expedite the writing of the software and hardware documentation.

No effort was made on Task 4c during this reporting period. Installation of the new equipment and training for its use will not proceed until the COTR has accepted the modified procedures. We expect that the visits to the Calibration Centers described under Task 4a will reduce the time required for training.

Task 5. Presentation and Reporting

There were several activities during the reporting period.

- A progress report was given at an informal meeting of the Technical Advisory Committee (TAC) on Sunday, October 16, immediately prior to the FWD Users' Group meeting.
- A brief project report was given at a meeting of the Calibration Center Operators on Sunday, October 16, immediately prior to the FWD Users' Group meeting.
- A formal presentation was made during the FWD Users Group meeting on Monday, October 17.

During the TAC meeting, tentative plans were made to hold the next committee meeting in late April 2006. A specific date and location for the meeting was not made. A decision from the COTR on this is needed soon.

Task 6. Miscellaneous Support for TPF-5(039)

This task is not included in the current contract. Effort on this task is not anticipated before fall 2006. It will require separate task orders.

Work planned during the coming quarter

By the end of the next quarter we expect that the bulk of the research component of this project will be completed. Near the end of the quarter we plan to seek the COTR's acceptance of the modified calibration procedures.

Under Task 1 we will continue to maintain a dialog with the FWD manufacturers and Calibration Center operators. The Task 1 report will be submitted.

Under Task 2 we will complete the development of a data base of calibration test results.

We will continue to evaluate designs of multi-sensor holders to facilitate doing reference calibration and relative calibration of up to twelve sensors simultaneously. We will finish merging the reference and relative calibration into the modified procedure using the new sensor holder.

We will complete the characterization of the frequency response of the accelerometers and LVDTs.

Under Task 3 we will complete the software development efforts, modifying FWDREFCAL as needed. We will complete work on the PDDX file converter program.

Under Task 4 we will continue to document the new software and work on users manuals. We expect to complete the modifications to the software and hardware during the period. Testing of the modified procedures is expected to continue throughout the quarter.

Near the end of the quarter we expect to begin drafting the final report.

Near the end of the quarter we expect to go to three or four Calibration Centers to try out the modified equipment and procedures on the various brands of FWDs.

Under Task 5 we plan to meet with the COTR during the TRB Annual Meeting in January.

We also plan to arrange for a meeting of the Technical Advisory Committee. The meeting will be scheduled to be held during the following quarter, perhaps near the end of April.

Task 6 – Not included in the current contract.

Transportation Pooled Fund Study TPF-5 (039)
Progress Report for July 1 – September 30, 2005

Table 1. Work Schedule and Completed Work

WORK COMPLETED

Year	2004			2005											
Month	October	November	December	January	February	March	April	May	June	July	August	September	October	November	December
Task															
1 Communication and Coordination	**TASK 1**														
2 Modify Calibration Processes					**TASK 2**										
3 Hardware and Software Upgrades										**TASK 3**					
4 Testing, Installation, and Training														**TASK 4**	
5 Presentation and Reporting															
6 Miscellaneous Support															

Year	2006									2007	2008	2009	**Percent of Task Completed**
Month	January	February	March	April	May	June	July	August	September	FY	FY	FY	
Task													
1 Communication and Coordination													**98**
2 Modify Calibration Processes													**85**
3 Hardware and Software Upgrades													**87**
4 Testing, Installation, and Training	**TASK 4 cont'd**												**25**
5 Presentation and Reporting			**TASK 5**		**Draft Report**		**TASK 5**		**Final Report**				**0**
6 Miscellaneous Support (not in this contract)											**TASK 6**		**Not in contract**