QUALITY MANAGEMENT OF PAVEMENT PERFORMANCE DATA

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ABSTRACT

While the principles of statistical quality assurance, including quality control, acceptance and independent assurance, are well developed, their application to the collection of pavement management data is quite different. In most cases, these statistical tools are applied to processes in which the desirable product is known and the purpose of the control measures are to ensure the efficient production of that product. However, in the case of pavement management data, the ***right*** product is not known. The product itself is data indicating the actual variability in the condition of the roadway. Thus, the control limits are not constant and are a function of the data itself. It is extremely important to identify the sources of variability in each form of data, and to isolate those that can be controlled in the process from those that must be reflected in the data.

If systematic quality control, independent quality assurance, and acceptance procedures are not implemented for pavement management data, the recommended treatments may be compromised, and the effectiveness of and confidence in the pavement management process may be undermined. The sources of variability in distress and roughness data are examined. An overall process scheme for quality assurance is recommended and illustrated. An example of application to independent quality assurance checks of pavement distress data is provided. The importance of limits based upon appropriate sample sizes greater than one is emphasized.

In establishing the requirements for the Inventory Condition and Asset Survey (ICAS) project, the Virginia Department of Transportation set the goals necessary for providing reliable pavement management information. Major challenges were provided to the automated data collection industry. To date, virtually all of these challenges have been met.

Key words: pavement management data, quality control, quality assurance, distress index, pavement profile, pavement roughness

INTRODUCTION

Highway agencies throughout the world have adopted pavement management systems, and pursued the collection of pavement performance data to support those systems. Several types of data are typically collected, including rutting, roughness and distress information. Early efforts were conducted by manual survey techniques, but to improve the safety and efficiency of these operations, automated data collection systems have been developed over the past three decades.

These automated systems have resulted in agencies possessing a rapidly increasing wealth of data. However, issues have arisen as to how to manage this mass of information. Pavement management systems have been prepared to process it. So, we have all this information and can produce reports from it describing the condition and needs of our highway systems. But how accurate is the information? How reliable are the reports? Should we accept it on faith that it is what we hope it to be? Or, should we raise the questions: “How good is our pavement management data?” “Is it really telling us what we think it is?”

The Virginia Department of Transportation (VDOT) raised these issues in the development of pavement management data collection specifications included in the Inventory Condition and Asset Survey (ICAS). This project, built upon preceding efforts, has resulted in an increased understanding of pavement data quality, including how it should be measured. Significant improvements have been made in data process control, quality assurance, and acceptance, particularly with respect to distress information.

Like any other production process, the collection of data for pavement management systems should be a controlled process. Due to the nature of the data, the means and methods for achieving this process control are not straightforward. However, process control can, and should, be accomplished. To achieve the real goals of pavement management, it is imperative that process control and quality assurance procedures become a routine part of the data collection process. In some respects, quality control of pavement management data collection has the potential to have as great an impact on overall pavement condition, as does quality control of the pavement construction processes.

Controlled collection of pavement management data allows for the development of acceptance criteria and an overall quality assurance plan for data collection contracts. This provides an important basis for the development of specifications for privately contracted data collection, and for confidence in the delivered data.

While the principles of statistical quality assurance, including quality control, acceptance and independent assurance, are well developed, their application to the collection of pavement management data is quite different. In most cases, these statistical tools are applied to processes in which the desirable product is known and the purpose of the control measures are to ensure the efficient production of that product. However, in the case of pavement management data, the ***right*** product is not known. The product itself is data indicating the actual variability in the condition of the roadway. Thus, the control limits are not constant and are a function of the data itself. Thus, it is extremely important to identify the sources of variability in each form of data, and to isolate those that can be controlled in the process from those that must be reflected in the data.

VARIABILITY IN DISTRESS INFORMATION

Distress information collected for pavement management applications inherently can include a wide range of variability from a wide number of sources. These sources include:

- Pavement condition
- Data collection method
- Rater consistency
- Inter-rater uniformity
- Time
- Transcription, referencing and data entry

Without full understanding and control of these sources of variability, erroneous conclusions can be reached regarding the quality of the data or regarding the condition of the pavement.

The first source of variability, ***pavement condition***, results in the variability inherent in the condition of the pavement itself, as inspection moves linearly along a roadway. That is, the cracking type and extent may vary significantly. This variability reflects the "true" variability of the pavement system, and is, in essence, important information to be stored in the pavement management system. Thus, it differs from the remaining sources of variability that represent the "noise" in the measurement system. However, the degree of this variability significantly complicates the quality control procedures designed to minimize the variability from the remaining sources.

The second source of variability results from the ***method of data collection*** used. On-site inspection may provide a different perspective from automated distress imaging methods. Lighting is a known significant factor influencing both types of data collection, as is surface moisture. Historical efforts to provide distress information using camera technology have been limited by the resolution capability of camera equipment. Recent advances in both digital camera and computer data handling and storage capacity have improved distress imaging to the desired level. Digital imagery has been verified, together with VDOT staff, to identify cracking of a fraction of one millimeter in width. On-site raters, depending upon environmental conditions, may easily miss cracks of that width.

The data collection sampling rate, and sample size, is also significant. Continuous rating can produce different results than sampling. If sampling is to be used, studies are needed to verify the extent of variability as inherent in the sampling rate, and to identify the appropriate sample interval and size to be used.

Uniformity, or lack of rating variation, produced by a single rater over time, including consistent interpretation of distress for various roadway conditions is also a vital to quality data. Continuous process monitoring can identify and help control variability from this source.

Variation between raters is another significant source of variability. This is best addressed by a process beginning with careful distress extent and severity definitions. These definitions must be clear to raters, and should clearly delineate all conflicts in interpretation. For example, from the Long Term Pavement Performance (LTPP) study of distress variability, one of the larger sources of variability was the distinction between longitudinal and low-severity alligator cracking *(1)*. VDOT removed this ambiguous issue by defining any longitudinal crack within a wheel path as a low-severity alligator crack *(2)*.

Distress training must be used to develop consistency among raters, and to assure that individual raters remain consistent over time as well as maintain consistency among a group of raters. The quality control procedures should also be set up to provide control on the variation between raters, and to identify any consistent bias by a single rater.

Many organizations conduct inter-rater checks in an attempt to limit variation between raters. However, without a statistically valid means of defining excess variability, comparing rater results, and identifying unacceptable variation, the effectiveness of such checks is limited.

It is a well-recognized fact that pavement condition changes with ***time***. Often this is true over short time intervals affected by seasonal climatic changes, as well as over long-term evaluations. The variation of pavement condition with time is an important factor to be included in the pavement management database, and is the basis for the development of performance models. However, it confounds quality assurance or acceptance procedures by requiring the ratings be done near the same time in order to comparable.

Data referencing, processing, and handling errors are equally detrimental to data quality as any other source of variability. Frequently, errors in fundamental processes, or manual data handling, these errors do occur and must be eliminated from the final data deliverable.

VARIABILITY IN PROFILE AND ROUGHNESS DATA

Similarly, it is important for information collected using automated sensors such as roughness or longitudinal profile and rutting data to be consistent and reliable. Excess variability results in low reliability of the data and, again, a potentially improper assessment of pavement conditions.

Accepted control for longitudinal profile data is defined in ASTM E950-98 *(3)*. This specification requires that repeated runs of roughness data should be within five percent. The consequence of this is that the reported roughness result can be considered reasonably accurate. If, however, greater variability is present, the reported average value may result in an unrealistic representation of the roadway smoothness.

The accuracy of sensor data reported for a given section of road can be sensitive to many things including:

- Pavement roughness
- The type of device used
- Condition of the pavement surface
- Consistency of the line measured on the pavement surface
- Reliability of the equipment used
- Time
- Transcription, referencing and data entry

Each of these items must be adequately addressed to assure reliable roughness information is reported. As discussed for distress measurements, the actual roughness of the roadway varies over the roadway system, both over the roadway lengths and with time. Transcription, location referencing and data entry may also lead to errors and variability.

Assessments of roughness information gathered by various ***types of equipment*** have repeatedly shown that different devices, while providing consistent results unto themselves, provide widely varying results. In an unpublished comparison of roughness devices to evaluate equipment for replacement of the original LTPP profilers, it was determined that the many devices evaluated produced widely varying roughness numbers. Inspection of the information lead to the conclusion that two factors were significant in this result: the frequency and the processing (filtering) of information gathered. If the data collection interval used by two devices is different, they are very likely to produce different results. Some devices collect data at an interval of one inch, others three inches, and still others six inches. Similarly, some systems process data as a moving average over six inches, one foot, or three feet. Obviously, reported results will vary. If the filtering process is different, again, two devices are likely to produce different results.

This "device" variability is not limited to electronic devices alone but extends to manual devices, such as the Dipstick, as well. In fact, the result reported is a function of the measurement and processing technique used to gather the information. The "true" roughness value of a roadway can only be ascertained within the limitations of the methodology used to collect and process it. Each methodology defines its own "truth." (Much in the same way as the roughness of a roadway can be said to vary with the vehicle and passenger. A healthy young adult driving slowly in a luxury automobile at slow speeds with having a different "truth" of the road roughness than an ill and elderly passenger in a fast-moving ambulance.)

Certainly the ***condition of the pavement surface*** will affect the results measured by these electronic sensor devices. It is well recognized that the pavement surface must be dry, but measurements can also be affected by dirt-filled cracks as compared with open cracks.

Similarly, it has been found that the ***line followed along the pavement*** by the sensors can significantly affect results. One example is the presence of a longitudinal crack along the outer edge of a wheel path. If one pass avoids intersecting the crack, a smooth pavement will be reported. On the other hand, if the vehicle wanders repeatedly across the crack, a much rougher pavement surface will be reported. If the two sets of data are averaged, the reported result will consist of a weighted average of the result of multiple runs, and lie somewhere between the extremes measured. While this is particularly important when repeat runs of data are collected, such as calibration runs, it is clear that the reported roughness results are quite sensitive to measuring a consistent line along the pavement.

The ***condition and repeatability of the equipment*** is another important element in achieving reliable data. Following calibration procedures is important to ensuring that data is reliable. Checking the calibration of equipment that appears to be operating properly can identify electronic or sensor problems. Frequent calibration checks during data collection can help ensure reliable data is obtained. For example, a faulty sensor will result in inaccurate results. Equipment must be recalibrated following any repair work, such as replacement of a faulty sensor.

VARIABILITY IN ELECTRONIC DATA AND AUTOMATION

This class of data includes all information collected by automated electronic sensors. Most recently, laser sensors have become the preferred tools for this type of work. Information collected by these means can include distress, rutting, roughness and joint faulting. The application of laser sensors to collect rutting and roughness information has become fairly common. Three-dimensional laser systems have been developed to capture distress information. All of these systems provide sophisticated means of gathering pavement management information, at relatively high speeds. While these sensors represent the capability of greatly improved resolution and the potential for highly consistent results, it is important to note that their use does not eliminate variability or guarantee accurate data.

Once again, statistically-based comparisons can be used to verify that unreasonable variability does not exist in data collected for pavement management applications. However, the process control is significantly complicated if a different device is used for control/assurance checks than for production data collection.

Significant work has also been conducted in attempts to automatic pavement management data collection processing. These efforts have advanced to a high level, with the exception of distress data. The rudiments of a pavement management system automated distress interpretation system are available for evaluation, with various algorithms being developed by different researchers. Currently, only distress types can be processed by the available systems. The reliability of the automated processes remains to be validated. Once again, unique processes are to be used if manual reviews are to be used to verify automated results. Therefore, it is necessary to statistically reconcile the acceptable limits of differences between the processes before this approach can be effectively used. As interpretation technology is developed for additional distress types, the validation process must be extended to include them.

ACHIEVING THE FUNCTIONS OF A PAVEMENT MANAGEMENT SYSTEM

Pavement management systems were conceived to provide system management tools for engineers and managers charged with maintaining highway and road systems. They are useful for tracking pavement performance over time, and for projecting system needs from the perspectives of pavement strategies and associated costs. These projections allow for better advance planning, and for improved allocation of available funds over time.

Obviously having accurate information input into a pavement management system can be vital to obtaining accurate projections of both short and long term needs, but how critical is data accuracy?

Preventive Maintenance

One key to successfully maintaining a functional highway system is to appropriately select and apply maintenance and rehabilitation treatments to specific pavements, and for recognizing the consequences of delaying treatment. The development of a truly cost-effective pavement management system requires the inclusion of preventive maintenance strategies. However, an anomaly exists for those agencies claiming to utilize preventive maintenance strategies, but whose pavement management process cannot identify the hairline cracks necessary to initiate preventive maintenance strategies. Recognizing one-millimeter and even sub-millimeter cracking is necessary to get the most benefit from investment in the roadway system.

Preventive maintenance can only be effective when the combination of early identification of damage and timely application of treatments can be accomplished. VDOT has set on the course to achieve preventive maintenance as a roadway management objective. The requirement for identifying one millimeter cracking is the first step in achieving that objective. This goal has been met through the use of digital imagery with appropriate resolution.

Timely processing of information, using a carefully controlled process for which the range and consequences of variability are understood as a part of that process is also vital. The systems for achieving this objective have been developed. To date, timely implementation remains an objective.

Appropriate Repairs

Consider the long-debated concern about a longitudinal crack that is a low-severity fatigue crack, versus one that is actually a fatigue crack. This distress call resulted in a very high coefficient of variability in the LTPP assessment of distress variation *(1)*. If the crack is determined to be a fatigue crack, it triggers major structural repair. Applying crack sealing will probably not benefit the pavement. If, on the other hand, the crack is actually a longitudinal crack, this is a far less significant functional type of distress for which crack sealing is very appropriate. This distinction is particularly critical if preventive maintenance is an objective. Early identification of fatigue cracking, and any associated structural problems can result in cost effective measures, while improper identification will result in continued pavement deterioration and ineffective expenditure of funds.

In another case, quality assurance checks of pavement rating identified widespread fatigue cracking, not identified by the initial evaluation. Again, the incorrect identification of this major structural distress would ultimately have resulted in incorrect projection of the needed treatment and funding for this section of highway.

CONTROLLING VARIABILITY

It is vital to the successful application of information for pavement management applications that the overall variability of this information be controlled within known, and acceptable limits. Several steps are necessary to accomplish this. In this section, the application of statistical process control methods to pavement distress data is briefly discussed. Similar processes can be applied to other pavement management data as well.

Impact of Distress Variability

The pavement management application should be examined to determine the sensitivity of decision-making to variation in results, as discussed in the previous section. Each agency must define the distress type, severity, and extent combinations that significantly affect the results of their pavement management system decision-making. This influence is a function of the types, severity, and extent of distresses common within the climatic regimes and loading conditions present within the agencies boundaries. It is also a function of the action triggers used in the agency's pavement management process to determine the type of corrective action recommended. Evaluating the sensitivity of the particular pavement management system to distress interpretation variability is another important element in arriving at appropriate sampling rates and suitably uniform results.

The effect of these multiple, compounded sources of variability is that the "true" distress condition of a roadway is never known. How then can a reference for controlling pavement management data processing be developed? The answer is that statistical evaluation of distress results must be established which includes all the potential sources of variability inherent in a particular process. Using this approach, it is possible to effectively define an acceptable range of variability, within which results should be maintained. A change in any of the conditions of a distress survey may adversely affect the reliability of the results. As an example, comparing field-collected information with distress interpreted from imaging is analogous to comparing apples and oranges. Each is a different process, and therefore can be expected to produce different results. Neither inherently represents the "truth."

If data is being collected and data quality checks are not being performed, there is a high probability that the data is unreliable, and will result in incorrect treatment and budgetary projections.

Control of Distress Variability

First, it is important to identify the acceptable variability of distress information. This should be designed for the specific PMS system for which data is being collected. An assessment of the significance of distress variability is needed to do this. It must incorporate the sensitivity of individual distress types and severities on pavement management recommendations. It must also incorporate the elements of the data collection and interpretation process to be used.

Next, it is important to have a reliable means for controlling distress results, to assure that acceptable variability is not present in the final data used for pavement management applications. For the VDOT project, the concept of D2S limits defined by ASTM was applied *(4)*. Figure 1 provides an example of the use of these limits as a Quality Assurance filter for the distress data process. The authors have previously documented the developed of the control limits for process control and quality assurance for the VDOT distress indices of LDR, load-related distresses, and NDR, non-load-related distresses *(5)*. Those calculations and the statistical underpinnings of the D2S limits for reproducibility of test results are not reproduced here.

Finally, a well-defined process must be developed for collecting and reporting distress information. This process must include quality control/quality assurance activities for all phases of the process. By integrating all of these elements, the ICAS project has served as the model for data quality management for distress data.

In Figure 1, used for quality assurance checks, it can be clearly seen that for high values of LDR and NDR indices, the process was well controlled. However, for lower index values, there were significant differences between the quality assurance checks and the reported production values for the indices. This result in a quality assurance check should trigger a forensic evaluation of the causes for the bias.

Such a forensic check is only likely to be valuable if regular production process control is being performed. Otherwise, the quality assurance checks may frequently indicate out-of-range values due solely to high variability in the production process, beyond the variability in the roadway itself. Independent quality assurance checks are most valuable when the checks are performed on in-control data, and that is the statistical assumption underlying the establishment of the control limits.

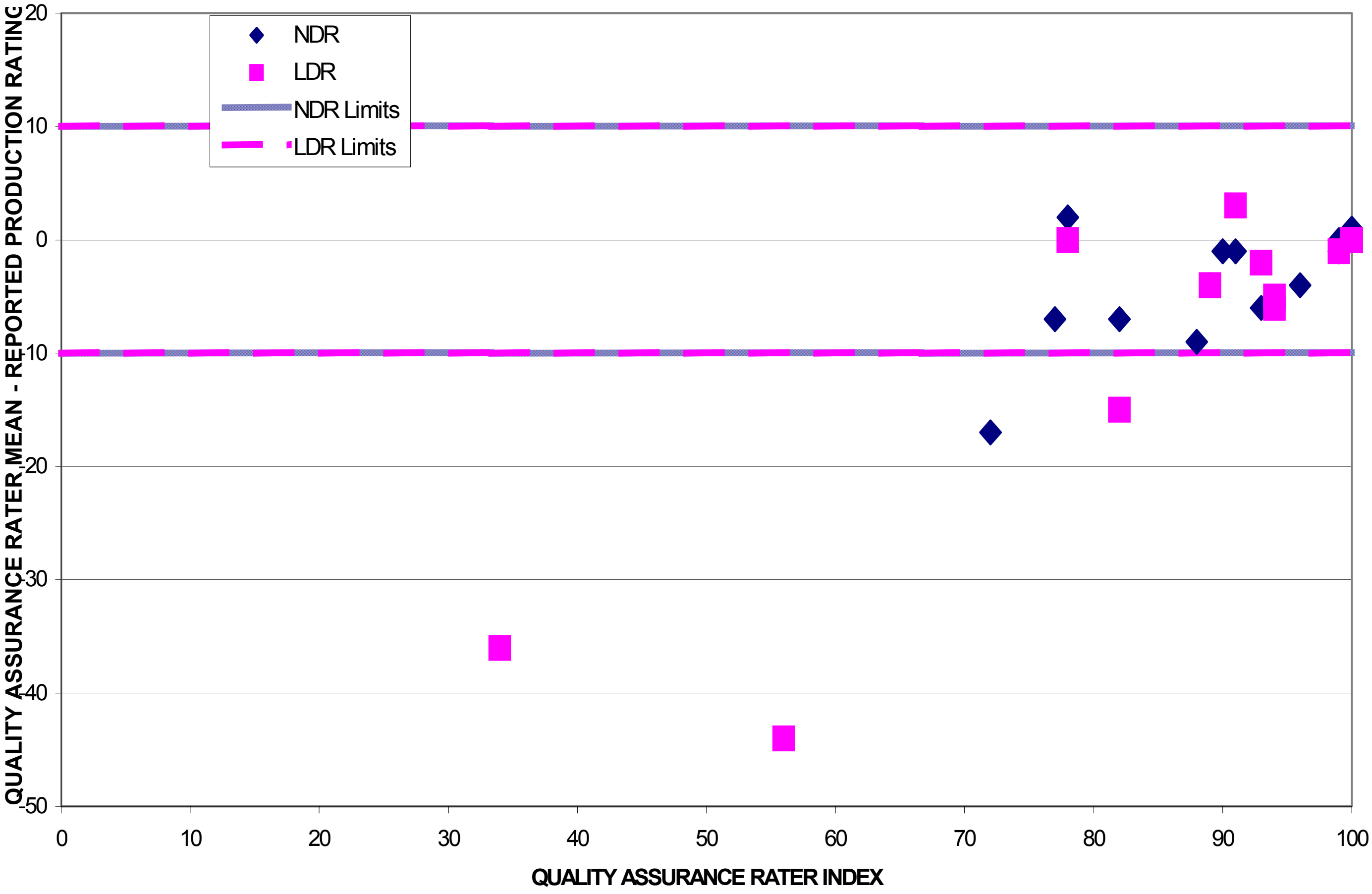

Figure 1 Example of control chart for quality assurance checks on pavement distress data, based on Virginia DOT distress indices

In order for the independent quality assurance checks to be statistically valid, they must have a sample size greater than one. Since the roadway distress is varying along its length, this means that the quality assurance check must include ratings of the same pavement by at least two different raters at the same point in time. This establishes the statistical basis for comparison to the production values. A single quality assurance check value compared to a single production value does not inherently provide meaningful information. *It is more important to provide ratings by at least two individuals on each individual section, than it is to increase the sampling rate for quality assurance checks.* Better checks should be performed on few sections, if necessary. The balance between control limits, quality assurance limits, sampling rates, and sample sizes must be statistically established for each type of pavement management data, collection process, and selected agency index.

QUALITY MANAGEMENT PROCESSES

Quality management of pavement management data must consist of a systematic approach to data collection and processing. Accomplishing this requires experienced and organized project managers for both the agency and the data collection team, who understand the obstacles to timely data delivery, as well as the steps necessary to achieve it. For the quality management system to work properly, everything from effective data collection procedures and training, to efficient data processing and quality control/quality assurance reviews must be performed in a timely manner. Steps in the quality management process include:

1. Distress definition
2. Rater training
3. Systematic data collection process management
4. Systematic data handing and processing
5. Timely, effective quality control system
6. Timely, effective quality assurance check system
7. Timely identification and implementation of corrective actions
8. Timely report development and delivery of results to the owner agency

Several of these steps should be prepared in advance of survey activities. These include development of appropriate distress definitions, rater training procedures, and systems for completing the other activities listed above. Certain other elements of the process must be developed based on the team who will perform the work. This includes identifying acceptable process variability limits to be used as control guidelines. Data handling systems need to be prepared, but may need to be customized to the specific PMS process prior to beginning the rating process. A recommended flow chart for quality control and quality assurance activities for pavement management data is illustrated in figure 2.

Putting all these vital pieces in place prepares the team to begin, but what happens when the QC/QA process identifies deficiencies? Raters must be normalized again, so that all rating work remains within the acceptable limits of variation. This may include additional rater training. It is vital to establish uniformity among raters and QC/QA raters. Some evolutionary development in distress interpretation may be required. If so, it is necessary for all parties to the process, including any agency acceptance reviewers, to be immediately aware of and act in implementing any changes.

Correction of distress information and re-review of data through process QC systems is essential. All data represented by deficient samples must be reviewed. Corrective actions may take many forms, but are important to passing information through the QC/QA process. Once corrections are complete, the dataset should be able to pass quality checks, and be prepared for delivery to the owner agency.

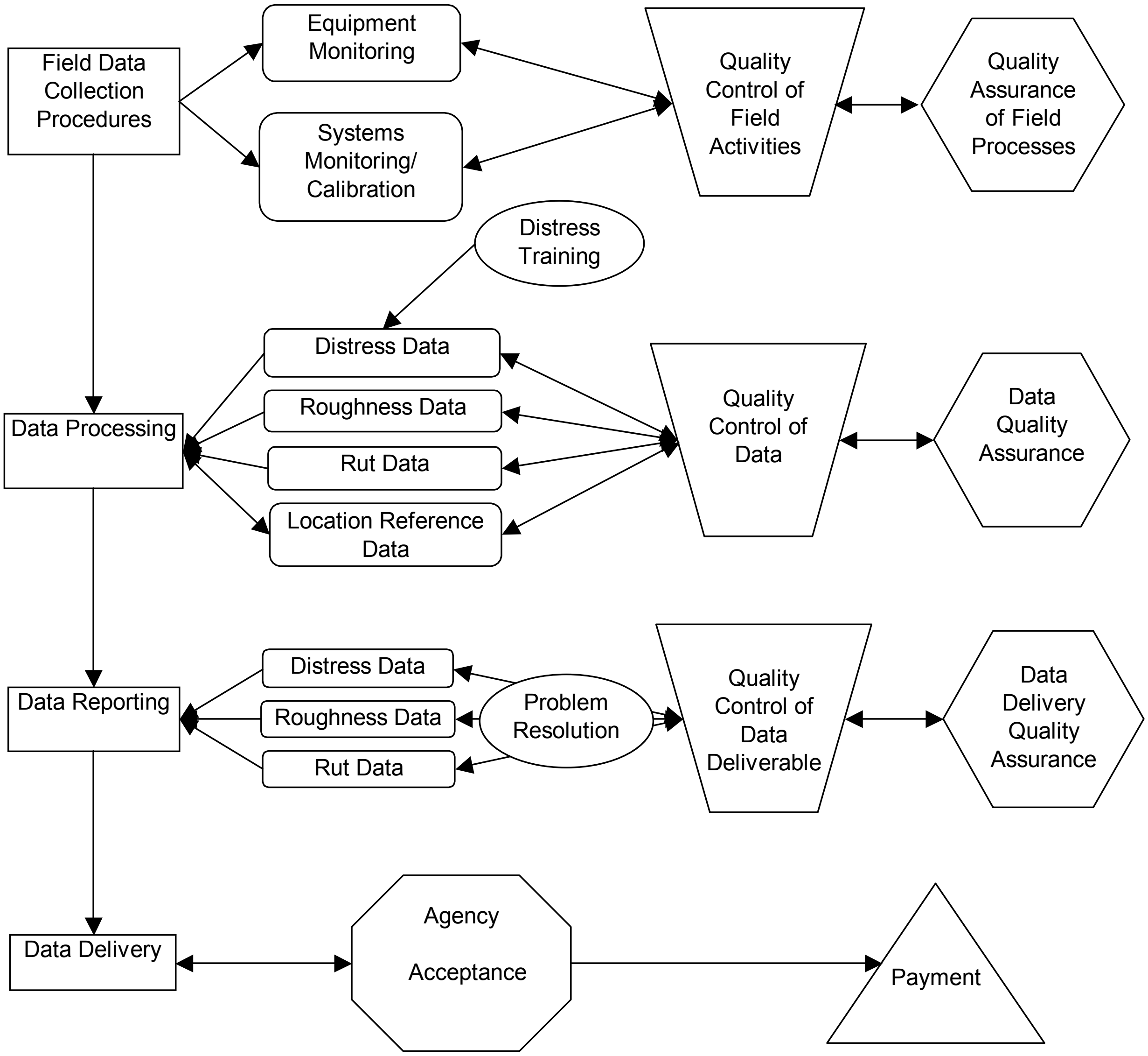

Figure 2 The quality control/quality assurance process for pavement management data.

For QA and/or agency acceptance review of PMS data those personnel must also be included in the processes of training, data management, and continuity of the entire operation. With all these elements in place, PMS data can be delivered which is truly meaningful. Those utilizing the data thoroughly understand the limits of the data, and how the application is affected.

CONCLUSIONS AND RECOMMENDATIONS

The experience gained in association with VDOT in achieving PMS quality data has highlighted the myriad sources of potentially inaccurate data. The consequences of inaccurate data to any specific pavement management system can, and should be assessed. Many lessons have been learned, leading to several conclusions and recommendations.

- Numerous sources of variability can exist for each type of data.
- The application of a comprehensive quality management process is vital to the delivery of quality PMS data.
- To achieve data including the accuracy necessary to accomplish preventive maintenance, very small cracks must be identified.
- Distress variation can, and must, be controlled. The application of the D2S process to VDOT's load-related (LDR) and non-load-related (NDR) distress indices provides an example of a statistically-based control system.
- In order to develop valid statistically-based sampling and control systems, sample sizes greater than one must be utilized at all steps.
- The consistency and uniformity of electronically collected data must be controlled.
- Computerized systems provide highly useful tools for collecting and managing PMS data, but all systems must be accompanied by data quality checks to insure the quality of the data delivered for pavement management applications.
- If systematic quality control, independent quality assurance, and acceptance procedures are not implemented for pavement management data, the recommended treatments may be compromised, and the effectiveness of and confidence in the pavement management process may be undermined.

In establishing the requirements for the ICAS project, VDOT set the goals necessary for providing reliable pavement management information. Major challenges were provided to the automated data collection industry. To date, virtually all of these challenges have been met. Distress images possessing the required, and necessary clarity have been collected. Quality control procedures for controlling and verifying the reliability of pavement management information have been developed and used on the ICAS project.

ACKNOWLEDGEMENTS

The authors wish to recognize, and thank, the numerous persons within the Virginia DOT, and their ICAS contractor, Parsons Facilities of Herndon, Virginia, for their respective roles in the development of the Pavement Management System process. While many individuals have been involved, principal figures include Mssrs. Richard Coullahan, Joseph Powers and Larry Anderson of Parsons Facilities, Mssrs. Charles Larson, Trenton Clark and Naveed Sami of VDOT, and Mr. Bill Swindle of Transportation Management Technologies.

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