Calibration Accuracy of Manual and Ground-Speed-Controlled Salters

Blackburn and Associates

CLEAR ROADS
research for winter highway maintenance

Project CR2005-02
February 2008

Pooled Fund #TPF-5(092)
www.clearroads.org

NOTICE

This research was funded by the Wisconsin Department of Transportation (WisDOT) and the United States Department of Transportation (USDOT) under pooled fund #TPF-5(092) and WisDOT Project #0092-06-21. The information reported is the result of research done under the auspices of the Department and the Clear Roads pooled funded research program. This Program is an ongoing, cooperative, and comprehensive research activity that focuses on field testing and evaluation of materials, methods, and equipment used in highway winter maintenance.

DISCLAIMER

Technical Report Documentation Page

1. Report No.	2. Government Accession No	3. Recipient's Catalog No
CR2005-02 / 0092-06-21		

4. Title and Subtitle Calibration Accuracy of Manual and Ground-Speed-Controlled Salters	5. Report Date February 2008 6. Performing Organization Code
7. Authors Robert R. Blackburn, Edward J. Fleege, and Duane E. Amsler	8. Performing Organization Report No.
9. Performing Organization Name and Address Blackburn and Associates 16545 East Fairfax Drive Fountain Hills, AZ 85268-2806	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 405857
12. Sponsoring Agency Name and Address Clear Roads Pooled Fund #TPF-5(092) Lead state: Wisconsin Department of Transportation 4802 Sheboygan Avenue Madison, WI 53707	13. Type of Report and Period Covered Final Report, 10/05 – 01/08 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Automatic control of material application rates is achieved with ground-speed-oriented controllers. This type of controller has been used in Europe since the 70's. Some state DOT's were using versions of ground-speed controllers on dry material spreaders as early as the 80's. However, it was not until the SHRP and FHWA anti-icing studies in the 90's that highway winter maintenance agencies became interested in ground-speed controllers and the controller/spreader manufacturers responded to the need. There are a wide variety of controllers manufactured as demonstrated by the spectrum used by the Clear Roads state DOT's.

In order for ground-speed controllers to optimally discharge salt and prewetted material, their calibration settings need to be accurate. The aim of this study was to determine if ground-speed-controller units accurately control the spreader discharge of salt and other material, and if they provide the savings expected when compared to manually controlled units.

The overall objective of the study was to document the accuracy of calibrated ground-speed-controller units along with the performance of these units as compared to manual spreader controls. Actual salt, abrasive, and prewetting liquid chemical dispensing rates from spreader trucks with various types of manual and ground-speed-controller units were investigated and documented from both a yard study and in simulated field settings that would be used during winter storm events. Testing of up to eight spreader/controller combinations was conducted. The actual discharge quantities (solid and liquid materials) were compared against theoretical discharges. Manufacturers' calibration procedures were reviewed and calibration verification tests were developed to ensure proper calibration.

17. Key Words	18. Distribution Statement
Ground-speed controller, closed-loop, open-loop, spreader/controller, calibration, prewetting, solid material discharge	No restriction. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield VA 22161

18. Security Classif.(of this report)	19. Security Classif. (of this page)	20. No. of Pages	21. Price
Unclassified	Unclassified	294	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The research reported herein was funded by the Wisconsin Department of Transportation (WisDOT) and the United States Department of Transportation (USDOT) under pooled fund project #TPF-5(092) and WisDOT Project #0092-06-21. The authors of this final report were Robert R. Blackburn, the Principal Investigator and Overall Project Manager; Edward J. Fleege, P.E.; and Duane E. Amsler, P.E. They were assisted in the statistical analysis of test data by Ronald G. Tolleson.

The authors thank all those state DOTs who responded to the Snow Belt States' stakeholder survey.

The authors would like to expresses their appreciation to all the maintenance personnel in the following state DOTs for their technical assistance and maintenance support in conducting the various yard testing and simulated field testing: Indiana, Iowa, Minnesota, Missouri, Ohio, and Wisconsin. The support of the NYSDOT is also acknowledged. The support provided by the various teams of state field maintenance personnel was invaluable and without their dedication, this study would not have been possible.

The authors would like to thank the following representatives of the controller equipment manufacturers who participated in the yard testing and simulated field testing. In addition, they took their valuable time to review the findings of the tests and made suggestions conceming this study:

- Mr. Mike van Meeteren of Cirus Controls
- Mr. Myles Hart of Component Technology
- Mr. Bruce Cox and Mark Lundeen of Dickey-john
- Mr. Steve Chlebeck of FORCE America
- Mr. Terry Crago of Muncie Power Products
- Mr. Jim Borowski of Pengwyn

The authors would also like to thank the Clear Roads Technical Advisory Committee members, including Tom Martinelli (past chair) (Wisconsin DOT), Dennis Burkheimer (present chair) (Iowa DOT), Dennis W. Belter (Indiana DOT), Diana Clonch (Ohio DOT), Linda K. Taylor (Minnesota DOT), Tim Jackson (Missouri DOT), Tim Croze (Michigan DOT), Adam Padilla (Colorado DOT), Shane Larson (Illinois DOT), Lynn Bernhard (Utah DOT), Cliff Spoonemore (Wyoming DOT), and Michael H. Lashmet II (New York DOT), who provided guidance in the direction and content of the study. Their interest in the calibration accuracy of spreader/controller systems, plus the funding they provided through the Clear Roads pooled fund process, made this study possible.

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EXECUTIVE SUMMARY

Automatic control of material application rates used in highway winter maintenance operations is achieved with ground-speed-oriented controllers. This type of controller has been used in Europe since the 70's. Some state DOT's were using versions of ground-speed controllers on dry material spreaders as early as the 80's. However, it was not until the SHRP and FHWA anti-icing studies in the 90's that highway winter maintenance agencies became interested in ground-speed controllers and the controller/spreader manufacturers responded to the need. Most ground-speed controllers used in the U.S. automatically adjust hydraulic fluid flow in proportion to ground speed. A truck operator with an automatic controller is able to maintain a constant application rate of material on the road without having to adjust the valve opening to conform to the changing speed of the truck. To spread a constant amount of material along a road segment, a truck operator needs only to select an application rate. There are a wide variety of controllers manufactured as demonstrated by the spectrum used by the Clear Roads state DOT's.

There are two types of automatic controllers: the open-loop and the closed-loop system. Both types require a speed sensor. The open-loop system monitors the truck speed and adjusts the control valve to a predetermined setting to provide the correct belt or auger speed for the desired spread rate. Any changes in the hydraulic system variables will result in an error in the belt or auger speed.

The closed-loop system monitors both truck speed and belt or auger speed and adjust the control valve until a predetermined ratio value of belt or auger speed and truck speed is obtained. The likelihood of a systematic error in delivery rate is greatly reduced by the closed-loop system.

Ground-speed controllers have the potential to dramatically reduce salt usage and liquid chemical dispensing rates, thus saving money and materials and helping to minimize the negative impact of these materials on the environment. The use of these controllers means that the operator can devote more of his/her attention to more important issues rather than manually adjusting the amount of material being spread.

In order for ground-speed controllers to optimally discharge salt and prewetting material, their calibration settings need to be accurate. The Clear Roads national pooled fund research program decided to address this calibration issue as part of its dedication to sponsoring real-world research in highway winter maintenance. The Clear Roads funded this research project with the goal of determining if ground-speed control units accurately manage the spreader discharge of salt and other material, and if they provide the savings expected when compared to manually controlled units. The hope for the outcome of the study was to provide state and local highway winter maintenance agencies with the ability to determine the calibration accuracy of ground-speed and manually controlled material spreaders.

The scope of the research was divided into three phases to meet the goal of the project: a literature search and survey of the Snow Belt States; a bench study of controller equipment; and a maintenance yard testing of controller/spreader combinations that simulated field operations.

The literature search and survey were conducted to access the types of manual and ground-speed-controller equipment in use and the calibration and operational experiences with the equipment. In addition, manufacturers of manual and ground-speed controllers in use by the Clear Roads members were surveyed to determine their recommended calibration procedures.

Very little information could be found in the literature that dealt with the calibration of ground-speed controllers used for highway winter maintenance operations. Several references were found and reviewed that relate to the calibration verification of spreader/controller combinations under both yard and controlled test track conditions.

About 94 percent of the highway agencies responding to the Snow Belt States' survey are currently using ground-speed controllers. Most of the ground-speed controllers in use are closed-loop systems.

Manual controllers are used currently by about 53 percent of the highway agencies responding to the survey. However, the number of manual controllers is much smaller than the number of ground-speed controllers in use. Only about 6 percent of the agencies are exclusively using manual controllers.

The calibration techniques most commonly used by the responding highway agencies for ground-speed controllers are those recommended by the manufacturers. Most often the controller calibrations are performed during maintenance yard tests. Very few agencies have developed their own calibration techniques; but those that have, generally modify the manufacturer's recommendations to serve the agencies needs.

A systems approach was used in the investigation of the ground-speed controllers. The installation of a controller in a spreader truck does not guarantee that the solid and liquid discharge goals will be achieved. An evaluation of the controller must not only include how well the controller functions, but also how well it interfaces with the truck-spreader system. Consequently, it was necessary to look at the truck's hydraulic system capacity, the hydraulic motor capacity for solid discharge, as well as the pumps used for liquid discharge in the evaluation of the spreader/controller combinations examined in the yard and simulated field studies.

Eight ground-speed controllers from six manufacturers were tested during the yard or bench portions of the study. The relatively new spreader/controller combinations were calibrated according to the controller manufacturers' recommendations. The units were then tested in accordance with a developed protocol in the maintenance yard to document the actual solid and liquid discharge amounts under a combination of operational variables.

Of the eight spreader/controller combinations tested, six controllers were operated in the closed-loop mode and two were operated in the open-loop mode. Four of the spreaders were of the hopper-box type of design and the other four were tailgate spreaders. Dry, solid salt was discharged by seven spreaders; and a 95% sand/5% salt mix was discharged by the eighth spreader. Salt brine was the primary prewetting liquid discharged by 6 units; liquid calcium chloride was discharged by one unit; and one system did not have prewetting capability.

The yard test results for each of the eight spreader/controller combinations are discussed in terms of summary data, plots of test results, and plots of theoretical and actual discharge amounts of both solids and liquids. The interpretations of the results are given in terms of the limitation of the spreader/controller systems to achieve desired discharge amounts. A statistical analysis of the yard test data produced estimates of the bias, accuracy, and precision of each spreader/controller system relative to its ability to control solid discharge amounts and, where appropriate, prewetting discharge amounts.

The tabulation and plots of the yard test data for each controller are given in separate appendices. Each spreader/controller system was analyzed independently of the other systems. No attempt was made to compare one system against another.

Simulated field tests were conducted in the maintenance yards with seven different controllers from six manufacturers. All seven controllers were tested under an open-loop mode of operation. Only five of the seven controllers could be tested under a closed-loop mode of operation because of design limitations.

The simulated field tests were conducted according to special procedures developed during the study. Solid material discharge was collected during the simulated field tests of each of the seven spreader/controller combinations, irregardless of the mode of operation. However, because of the system design, liquid discharge was collected from only five of the seven spreader/controller systems. Liquid discharge was collected from three of the five spreader/controller systems when tested under both closed-loop and open-loop modes of operation. Liquid discharge was collected from one system when only tested in a closed-loop mode of operation, and from one system when only tested in an open-loop mode of operation.

Special testing protocols were developed for conducting simulated freeway and highway operation tests. The freeway operation simulation used two levels of solid application – prewetting rate combinations for a range of truck speeds and discharge times. Each freeway operation simulation run took 42 minutes to complete.

The highway operation simulation used two levels of solid application – prewetting rate combinations for a range of truck speeds and discharge times. Each highway operation run contained two stops: one to simulate a stop sign controlled intersection and one to represent a signalized controlled intersection. The highway simulation test took 32 minutes to complete.

The tabulations of the results from the simulated field testing are given in the appendices for the seven systems tested. The test results showed that the simulated test method used is sound and has obvious benefits when compared with over-the-road testing in terms of control, observation opportunity, and scheduling. The simulated test results of each spreader/controller system were analyzed independently of the other systems. No attempt was made to compare the results of one system against another.

Comparison tests were conducted with two different spreader/controller combinations where each could be operated in both closed-loop and manual mode of operations. One spreader/controller was tested in an actual rural highway environment using a special test protocol. The other spreader/controller was tested in a maintenance yard using scenarios that simulated freeway and highway operations. Only dry salt was discharged during the comparison tests.

Considerable savings in dry salt usage can be achieved in a rural highway environment using a closed-loop spreader/controller combination compared to a manually controlled spreader. The savings can be as large as 47 percent for an application rate of 400 lbs/mile.

Greater savings in dry salt usage between closed-loop and manual modes of operation were noted for the highway scenario than for the freeway scenario. The savings found for the highway scenario were 2.2 and 1.6 times larger than the savings found for the freeway scenario for dry salt application rates of 200 lbs/mile and 400 lbs/mile, respectively.

A number of variables associated with the calibration and use of solid material spreaders and prewetting systems were identified during the study. When calibrating tailgate spreader/controller systems, it is imperative that the truck bed be in a raised position, comparable to that position used during normal snow and ice control operations. Finally, a satisfactory procedure was developed for the calibration of ground-speed spreader/controller combinations. The approach utilizes the controller manufacturer's recommended procedure in conjunction with standardized preparation procedures and with a special verification testing protocol.

A number of conclusions, recommendations, and areas suggested for further research were developed from the study findings and are presented for consideration at the end of the report.

SECTION 1
INTRODUCTION AND RESEARCH APPROACH

1.1 Research Problem Statement

Automatic control of material application rates is achieved with ground-speed-oriented controllers. This type of controller has been used in Europe since the 70's. Some state DOT's were using versions of ground-speed controllers on dry material spreaders as early as the 80's. However, it was not until the SHRP and FHWA anti-icing studies in the 90's that highway winter maintenance agencies became interested in ground-speed controllers and the controller/spreader manufacturers responded to the need (1,2). Most ground-speed controllers used in the U.S. automatically adjust hydraulic fluid flow in proportion to ground speed. A truck operator with an automatic controller is able to maintain a constant application rate of material on the road without having to adjust the valve opening to conform to the changing speed of the truck. To spread a constant amount of material along a road segment, a truck operator needs only to select an application rate. The spreading width can also be selected with some controllers. There is a wide variety of controllers manufactured as demonstrated by the spectrum used by the Clear Roads state DOT's. Some manufacturers have even incorporated GPS and GIS systems within the controllers for aid in material distribution and record keeping.

Automatic controllers use a truck-speed sensor for adjusting the opening of the hydraulic valve that in turn controls the operating speed of the feed mechanism. Various types of truck-speed sensors are available. Some are connected to the speedometer-cable while others measure the rotation of the drive shaft or a wheel.

There are two types of automatic controllers: the open-loop and the closed-loop system. Both types require a speed sensor. The open-loop system monitors the truck speed and adjusts the control valve to a predetermined setting to provide the correct belt or auger speed for the desired spread rate. Any changes in the hydraulic system variables will result in an error in the belt or auger speed.

The closed-loop system monitors both truck speed and belt or auger speed and adjust the control valve until a predetermined ratio value of belt or auger speed and truck speed is obtained. The likelihood of a systematic error in delivery rate is greatly reduced by the closed-loop system.

There is not a universal agreement among maintenance personnel on which types of automatic controllers are the best. The favorite, however, appears to be moving towards the closed-loop systems. There is a feeling that the second speed sensor is needed to correct changes that occur during snow and ice control operations such as wear of spreader equipment and variations in performance of the spreader's hydraulic fluid. Wear can change the calibration of the equipment. Also, the variable operating temperature and aging of the spreader's hydraulic capacity changes the operation of the belt, auger, and spinner motors.

Ground-speed controllers have the potential to dramatically reduce salt usage and liquid chemical dispensing rates, thus saving money and materials and helping to minimize the negative impact of these materials on the environment. The use of these controllers means that the operator can devote more of his/her attention to more important issues rather than manually adjusting the amount of material being spread.

In order for ground-speed controllers to optimally discharge salt and prewetted material, their calibration settings need to be accurate. The aim of this study was to determine if ground-speed control units accurately control the spreader discharge of salt and other material over time in the field and if they provide the savings expected when compared to manually controlled units. The outcome of the study will provide state and local highway winter maintenance agencies with the ability to determine the calibration accuracy of manual and ground-speed controlled material spreaders.

1.2 Research Objective and Scope

The overall objective of the research was to document the accuracy of calibrated ground-speed-controller units along with the performance of these units as compared to manual spreader controls. Actual salt, abrasive, and prewetting liquid chemical dispensing rates from spreader trucks with various types of manual and ground-speed-controller units were to be determined and documented from both a yard study and in the field during winter storm events. The recommended calibration procedure for determining the accuracy of manual and ground-speed-controlled spreaders was to be applicable to both state and local highway agencies.

The scope of the research was divided into three phases. The first phase was a literature search and survey of Snow Belt states to access the types of manual and ground-speed-controller equipment in use and their calibration and operational experiences with the equipment. Manufacturers of manual and ground speed controllers in use by the Clear Roads member states were surveyed to determine their recommended calibration procedures.

The second phase was a yard or bench study of new ground-speed-controllers that can also be operated in a manual mode. The relatively new equipment was calibrated according to the manufacturers' recommendations. It was then tested in accordance with a developed protocol in the maintenance yard to document the actual solid and liquid discharge amounts under a combination of operational variables.

The third phase of the study was originally envisioned to document actual material usage in the field during winter storm events for both manually controlled units and ground-speed-controlled units. That approach would have placed too much demand on the truck operators and maintenance support personnel during critical snow and ice control operations. Instead with the panel's concurrence, a different approach to the Phase 3 testing was taken. The Phase 3 tests of the controller/spreader combinations were conducted in the maintenance yard during wintertime conditions with the same controller/spreader used in the yard tests, but under extended run times and speeds that simulated field operations. The Phase 3 testing was conducted over a six month period of time, mainly during winter-time conditions..

1.3 Research Approach

The research approach described below was designed to document the accuracy of calibrated ground-speed-controller units along with the performance of these units as compared to manually controlled spreaders. Actual salt usage and prewetting liquid chemical dispensing rates from spreader trucks with various types of manual and ground-speed-controller units were documented in a maintenance yard study and in a study that simulates operational conditions that one would expect to experience during snow and ice control operations. The ultimate objective of the research was to determine if ground-speed controllers accurately discharge salt over time in the field and if they do provide the material savings expected when compared to manually controlled units.

The research plan consisted of three phases. A brief paragraph summarizing each phase is presented blow.

Phase 1 was a literature search/review and a survey. The objectives of this phase were to collect and review information on the types and capabilities of spreader controllers in use in the U.S. along with equipment calibration techniques employed and any spreader/controller test and evaluation protocols used. Snow Belt state DOT's were surveyed to determine the types of controllers in use (none, manual and automatic), types of materials spread and associated application rates, and spreader/controller calibration techniques used. The manufacturers of the manual and ground-speed controllers in use by the Clear Roads member states were contracted to obtain product descriptions/manuals and recommended calibration procedures. Near the end of this phase, the team met with the Clear Roads Technical Advisory Committee (TAC) to present the results of the literature search and survey together with a recommended preliminary calibration protocol to be used during the remainder of the study. The planned preliminary testing procedures for the Phase 2 and 3 work were also presented at this meeting. This phase was virtually completed during the first five months of the contract.

Phase 2 was a maintenance yard or bench study. In this phase, yard tests were to be conducted on selected new or nearly new manual and ground-speed-controllers in the maintenance yards of participating Clear Roads states. It was possible to conduct the yard tests with either new or nearly new ground-speed-controllers. However, it was not possible to locate nearly new manual controllers in the Clear Roads states participating in this phase of the project. Consequently, the yard tests were performed only with spreader/ground-speed-controller combinations.

The spreader/controller combinations tested were calibrated according to the manufacturers' recommendations. A member of the research team observed the controller calibration and then oversaw the testing of the spreader/controller combination to document actual discharge amounts of material. Materials used during the yard tests were straight salt, a 5/95 mixture of salt and sand, and a prewetting liquid. The yard tests followed an experimental design that incorporated the type of controller, type of material used, range of solid and liquid application rates, and simulated spreading speeds. The data analysis approach used was compatible with the experimental design. A systems approach was used to discuss the limitations of the spreader/controller combinations to achieve desired discharge amounts.

Representatives of each controller manufacturer were invited and were present during the calibration and testing of the respective units.

Phase 3 was a field study conducted mainly over one winter season. The team documented with the cooperation and assistance of selected Clear Roads member states, the actual material usage during simulated winter storm operations for both manually and ground-speed-controlled spreaders. The testing was conducted with representative models of calibrated maintenance truck/controllers, currently in use by the Clear Roads member states. A total of eight controllers operating in various modes of operation, including manual, open-loop and closed-loop, ground-speed controlled, were tested. The team documented, through use of specially designed equipment and data reporting forms, the controller settings; the amount of salt, sand, and prewetting liquid chemicals discharged during the simulation tests as determined from the materials collected and from the controller display; and the application rates used. Other data such as truck operating speed and salt moisture content (where available) at the time of testing were also recorded. Verification of the accuracy of the recording method used for miles traveled was also made. The analysis of the field data included among various items, a cost-performance comparison of manual versus ground-speed controllers. The respective equipment manufacturers were invited and were present during this final phase of the study.

A draft Implementation Plan and Final Report were submitted in this phase, three months prior to the end of the contract. The team took part in a face-to-face meeting with the Clear Roads TAC near the end of the contract to discuss the study findings and recommendations. The draft reports were revised in response to panel review comments and were submitted at the conclusion of the contract.

1.4 Organization of this Report

Following the Introduction, the report is divided into twelve sections plus appendixes.

- Section 2 presents the results obtained from the Phase 1 portion of the study. This section is subdivided into five major parts. The first presents the results of the literature search. The second part describes the results of the survey of the Snow-Belt States, including the survey questionnaire used during the interviews and the associated responses to the survey. The third part discusses the contacts made with manufacturers of spreader control equipment. The fourth part presents a review of spreader/controller calibration procedures. The fifth part describes the recommended approach to be taken in Phase 2 of the study.
- Section 3 provides a summary of the eight spreader/controller combinations tested during the Phase 2 – Yard Study. The summary information includes the corporate location of the controller manufacturer, the location of the spreader/controller tests, the yard test dates, a brief summary of the spreader/controller combination tested, and the types of materials used during the yard tests. The section ends with a discussion of the yard test preparations made and test protocol developed.
- Section 4 describes the methodology used in the analysis of the yard test data including the tabulation and plotting approach and statistical analysis approach.
- Section 5 provides a discussion of the analysis results for each of the eight spreader/controller combination tested.
- Section 6 presents a summary of the yard test findings, a discussion of the recommended direction of the Phase 3 – Field Study, and the preparations made for the field study.

- Section 7 describes the simulated field tests.
- Section 8 presents the results from the simulated field tests involving closed-loop and open-loop modes of operation.
- Section 9 describes the comparison testing of two spreader/controller combinations operated in both ground-speed-controlled and manual modes of operation. The potential material savings of ground-speed controlled salters over manually controlled salters are also discussed.
- Section 10 describes the variables that relate to the calibration and use of solid material spreaders and associated prewetting systems. The calibration verification procedures for ground-speed controllers are also discussed.
- Section 11 gives the recommendations for proper calibration of spreader/controller combinations operated in closed-loop, open-loop, and manual modes.
- Section 12 provides the conclusions, recommendations, and suggested research that were developed from the study.
- Fifteen appendixes provide information supplemental to the material presented in the main body of the report.

SECTION 2
RESULTS OBTAINED FROM PHASE 1–LITERATURE SEARCH AND SURVEY

2.1 Results of the Literature Search

An extensive literature search was conducted using the Transportation Research Board - Transportation Research Information Services (TRB-TRIS) to identify relevant information on spreader controllers and calibration procedures. Over ten different searches were conducted using various combinations of key words. The number of hits per key word combination ranged from 40 to 5,000. The number of potentially useful papers/reports was reduced to 76 by a review of the citation titles. The abstracts of the 76 citation were then reviewed and the final number of potentially useful documents was further reduced to 17, several of which were authored by one of the members of the research team.

In a search of other databases, the British Standard BS1622 entitled "Specifications for Spreaders for Winter Maintenance" was identified (3). A copy of the standard was obtained through the University of Minnesota Library via an inter-library loan arrangement.

Contacts were made with a number of groups in search of relevant information. Included in these contacts were the Salt Institute, various LTAP centers, APWA, and the Ministry of Transportation (MOT) – Ontario. As a result of these contacts, copies of calibration procedures were obtained from the Salt Institute, the University of New Hampshire Technology Transfer Center and the MOT – Ontario.

A notice was posted on Snow and Ice and WinOps List Servers that described the search for information on calibration procedures for manual and ground-speed controlled spreaders. A very limited response was obtained from these postings. One list server respondent observed that any inaccuracies in the spreading systems were probably related more to the spreader material supply rather than the controllers themselves. Tailgate an under-tailgate spreaders have to have the box raised periodically in order to keep a constant supply of material available to the auger. The respondent felt that the interruption in the supply of material to the distributor could be a primary reason for spreader inaccuracy.

On one of the FHWA sponsored scanning tours, France was identified as having an extensive training program for their maintenance operation people so that their snow and ice control operations are conducted with the minimum amount of chemicals. The training manual, written in French, was obtained during the tour. The Snow and Ice Cooperative Program (SICOP), a pooled fund administered by AASHTO, had the manual translated. Mr. Patrick Hughes of Mn/DOT who is a member of SICOP and a member of the scanning group, was contacted. Mr. Hughes indicated that the manual did not address the issue of calibration of spreaders. In addition, the scanning tour did not address calibration issues in its search for information.

A literature search was conducted using the Technical Library of the American Society of Agricultural Engineers. Potentially, 10 papers were identified that could provide some information. American Society of Agriculture Engineer Standard S341.3 entitled, "Procedure for

Measuring Distribution Uniformity and Calibration Granular Broadcast Spreaders" was also identified and a copy was obtained. Generally, the standard establishes a uniform method of determining and reporting performance data on broadcast spreaders designed to apply granular materials on top of the ground .The standard provides a means for measuring the distribution uniformity of the spreader and for comparing spreader distribution patters.

The review of the documents identified in the literature search revealed that only the information provided by the Salt Institute (4) and the University of New Hampshire Technology Transfer Center (5) address spreader calibration procedures. This information mainly discusses the calibration of manual spreaders, although a small portion of the procedure describes calibration of automatic controls.

Three other documents were found to be of some value. One pertains to the set of information provided by the Ministry of Transportation - Ontario that describes the calibration verification procedures for spreaders (6). The other two documents address the testing protocols for evaluating spreader performance characteristics ("Development of Anti-Icing Technology," Report SHRP-H-385, and BS1622:1989). The latter three documents were of the most value to the study of automatic controllers but all three require that the spreaders be calibrated first in accordance with the manufacturers specifications before verification testing is performed

Written contacts were attempted with foreign manufacturer of spreader controllers for information on their calibration procedures. No responses to our inquiries were received.

2.2 Survey of the Snow–Belt States

The research team developed a survey questionnaire that was used during telephone interviews of selected winter maintenance personnel in the 42 Snow-Belt States plus the District of Columbia. The survey questionnaire was submitted to the Clear Roads panel for review and approval before the interviews were conducted. The survey questionnaire plus a fax cover sheet used for interviewing are given in Appendix A of this report. The survey sought information on such items as: the number, types, and models of ground-speed and manual controllers in use for both dry and prewetted materials; the calibration techniques used for ground-speed and manual controllers; the spreader controller performance or calibration problems, especially those that are persistent; how often spreader controllers are calibrated; any preferences about the use of either open-loop or closed-loop ground-speed control systems; the material being spread such as salt, other dry chemicals, liquids, sand/abrasives, and mixes; and the range of application rates used for each material type. The interviewing began on November 17, 2005 and was terminated on February 14, 2006. Of the 43 interviews attempted, 36 interviews were completed for a return of 83.7%.

The results of the survey are tabulated in Appendix B and are summarized below.

- 34 of 36 (94.4%) agencies responding to the survey are currently using ground-speed controllers.
- Most of the ground-speed controllers in use are closed-loop systems.

- Manual controllers are used currently by 19 of 36 (52.8%) of the agencies responding to the survey. The number of manual controllers in service is much smaller than the number of ground-speed controllers in use.
- Only 2 of 36 (5.6%) agencies are exclusively using manual controllers.
- The most common manufacturers of ground-speed controllers currently being specified / purchased by the responding agencies are:
  - Dickey-john
  - FORCE America
  - Component Technology
  - Cirus Control
- The calibration techniques most commonly used by the responding agencies for ground-speed controllers are those recommended by the manufacturers. Most often the controller calibrations are performed during yard tests. Very few agencies have developed their own calibration techniques; but those that have generally modify the manufacturer's recommendations to serve the agencies needs.
- The calibration techniques used for the amount of liquid dispensed by ground-speed controllers of prewetted solid material are marginal, at best.
- The most common calibration technique used for manual controllers is the Salt Institute's procedure.
- The agencies responding to the survey either believe that closed-loop systems are better than open-loop systems or have no information on the performance comparison of the two types of systems.
- Most agencies use straight salt and/or a salt/sand or abrasive mix in their routine snow and ice control operations.
- The amount of salt in the salt/sand or salt/abrasive mixes varies from about 10% or less to 50%.
- Very few agencies use straight sand/abrasives in their routine snow and ice control operations.
- The range of application rates used for straight salt during snow and ice control operations appears to be in line with current guidance, with a few exceptions.
- The amount of liquid chemical used for prewetting solid material is quite varied, but generally is less than or equal to 10 gal/ton.

As a result of the survey, the research team obtained the calibration procedures used by a number of state agencies including Missouri DOT and Ohio DOT.

2.3 Contacts with Manufacturers of Spreader Control Equipment

The vendors of the spreader control equipment of primary interest to the Clear Roads states were contacted by phone and email. The vendors contacted included: Cirus Controls, Component Technology, Dickey-john, FORCE America, Muncie Power Products, and Pengwyn. The vendors were informed about the details of the study and their cooperation with the project was solicited. An invitation was extended for them to be present during the yard or bench study to show that every effort was being made to conduct the Phase 2 study in an objective and unbiased manner. They were also invited to participate in the field study portion of the project. Full cooperation for the study was extended by the vendors.

The vendors of the spreader control equipment were asked for copies of their recommended calibration procedures. The calibration procedures for Dickey-john and Cirus Control units were obtained from their web sites. Procedures from the other four vendors were obtained in either hard copy or electronic format. A through review was made of the operating manuals and calibration procedures received from each vendor.

2.4 Review of Spreader/Controller Calibration Procedures

A number of variables associated with the calibration and real world usage of solid material spreaders and equipment control measures were identified in the course of gathering information from highway agencies, equipment manufacturers, and other interested parties. The key variables are product delivery, product consistency, truck/spreader hydraulic system, amount of material discharged during calibration test method, speed/rate of discharge dynamics, flight bars on conveyor belts, calibration test method equipment, and various items associated with determining the speed and delivery constants for computer based material application controllers. Each of these variables is summarized in Appendix C together with an associated list of identified calibration/use control measures and the team's recommended approach to control the variables during calibration/use. Some of the variables are addressed in the manufacturers' recommended calibration procedures and calibration verification procedures found in the literature, but many are not.

2.5 Recommendations from Phase 1

Based on the findings from Phase 1, the recommended approach that was taken in Phase 2 was that the individual controller/spreader combinations would be calibrated first in accordance with the manufacturers' recommendation. The calibration verification process, that followed, would be conducted in accordance with a statistically – based experimental design that incorporated appropriate replication testing to evaluate the precision and accuracy of the equipment.

The development of a recommended final calibration procedure/protocol was postponed until after the yard tests of the controller/spreader combinations had been completed and much of the test results analyzed.

SECTION 3
DESCRIPTIONS OF SPREADER/CONTROLLER COMBINATIONS TESTED DURING PHASE 2-YARD OR BENCH STUDY

In Phase 2 of the project, yard tests were conducted on spreader/controller combinations in the maintenance yards of participating Clear Roads states. Tests were performed using selected new or nearly new spreader/controller combinations. All the controllers investigated were ground-speed-control units. No manual control units were investigated in this part of the project.

Section 3 describes the eight controllers tested from six manufacturers. The six manufacturers were Cirus Controls, Component Technology, Dickey-john, FORCE America, Muncie Power Products, and Pengwyn. Two controller models were tested from both Dickey-john and FORCE America. Single models were examined from the other four manufacturers.

Information is given below, for each manufacturer that includes the corporate location of the controller manufacturer and a brief description of the controller's capability. Also provide are the location of the spreader/controller tested, the dates of the tests, a description of the spreader used during the tests, and the snow and ice control materials used in the tests.

Section 3 concludes with a description of the preparations made for conducting the yard tests and the test protocol followed in the yard study.

3.1 Cirus Controls SpreadSmart RDS

The SpreadSmart Rx™ Spreader Control unit tested was manufactured by Cirus Controls. The corporate headquarters of Cirus Controls is at 9210 Wyoming Avenue North, Suite 200, Brooklyn Park, MN 55445. The vendor representative on the test site was Mike van Meeteren.

The controller has capability of controlling and monitoring of granular, liquid, or prewetted granular snow and ice control materials for highway winter maintenance operations. The unit can be operated in closed-loop, open-loop, and manual modes of operations. This unit can be used with either a hopper (V-bottom) or tailgate spreader.

The yard tests of the SpreadSmart RDS™ model were conducted at an Iowa DOT (IDOT) maintenance garage facility in Tipton, Iowa. The yard tests were conducted during the period of June 12- 13, 2006. The firmware installed in the controller was version 4.1.

The controller was mounted on a 2004 International truck (#A31768) and connected to a Monroe tailgate spreader. The prewetting pump, a hydraulic operated gear pump, was connected in series with the auger motor. The prewetting pump was rated at 4 gal/min and is manufactured by Oberdorpher Pump. The flow meter was rated at 5 gal/min with 12 pulses/revolution and is a Gems product. The hydraulic pump was made by Rexroth and was rated at 80cc or 4.88 cubic inch. The auger motor was a Parker TE series rated at 18 cubic inch.

The snow and ice material used during the yard test was straight salt and salt brine.

3.2 Component Technology Gl-400

The StormGuard GL-400 unit tested was manufactured by Component Technology which is a division of Certified Power Inc. The corporate headquarters of Certified Power is at 970 Campus Drive, Mundelein, IL 60060. The vendor representative on the test site was Myles Hart.

The controller has the capability of controlling and monitoring granular, liquid, or prewetted granular snow and ice control materials for highway winter maintenance operations. The unit can be operated in closed-loop, open-loop, and manual modes of operations. The controller has a feature that allows the user to set simulated ground-speed values along with granular, liquid, and prewettting application rates to visually check the performance of the conveyer or auger, spinner and the solid and liquid discharge (application) rates without moving the vehicle. The unit can be used with either a hopper (V-bottom) or tailgate spreader.

The yard tests of the 2005 GL-400 model were conducted at a Missouri DOT (MoDOT) maintenance garage facility in Bowling Green, Missouri. The yard tests were conducted during the period of June 28 to June 30, 2006. The firmware installed in the controller was version 5.6.

The controller was mounted on a 2005 International truck (No. 7450) and connected to a Swenson hopper spreader (No. S1004). A 4-inch gate opening was used during all the yard, and subsequent field tests.

The snow and ice control materials used during the yard tests were straight salt, salt brine (22% concentration), and liquid calcium chloride.

3.3 Dickey-john Models

Two controller models manufactured by Dickey-john were tested in the yard study. The two models were the ICS2000 and Control Point. The specifics of each model tested are given below. The Dickey-john Corporation has corporate offices at 5200 Dickey-john Road, Auburn, IL 62615. Bruce Cox was the representative who assisted in the calibrations and yard testing.

3.3.1 Model ICS2000

The Dickey-john model ICS2000 has the capability of controlling and monitoring granular or liquid snow and ice control materials for highway winter maintenance operations. The control of solid and liquid discharge rates is for direct application to the pavement. The unit was not designed to control or monitor the application of prewetted granular material. However, some highway agencies try to use the ICS2000 model to distribute prewetted granular material by connecting the unit to a liquid pump system that is purchased from off-the-shelf suppliers. These modifications are generally made in a local maintenance garage or in district maintenance shop.

The ICS2000 unit can be operated in closed-loop, open-loop, and manual modes of operations. The rear axel of the spreader needs to be raised off the ground during calibration tests and for checking the performance of the conveyer or auger, spinner, and the solid and liquid discharge (application) rates. In these cases, an operator is required to be in the truck cab to manually control the truck speed. The controller does not have the capability of simulating ground-speed values. The controller can be used with either a hopper-box or tailgate spreader.

The yard test of the relatively new ICS2000 model was conducted at a New York State DOT (NYSDOT) maintenance garage facility in Voorheesville, New York. The yard tests were conducted during the period of May 8 to 9, 2006.

The controller was mounted on a 2002 Monroe hopper-box spreader that was installed on 1998 International truck. Two gate openings of 1 ½- and 3-inches were used during the yard tests. A majority of the tests were conducted with a 3-inch gate opening. The spreader/controller combination tested contained a prewetting system that was manufactured by Monroe and installed by a local vendor in New York State.

The snow and ice control materials used during the yard tests were straight salt and salt brine at a 23% concentration. The testing of the prewetting capability was discontinued after only five tests when it became evident that the unit could not control the liquid during prewetting. Consequently, only test results for dry salt are presented in Section 5 and elsewhere.

3.3.2 Control Point

The Dickey-john Control Point has the capability of controlling and monitoring granular, liquid, or prewetted granular snow and ice control materials for highway winter maintenance operations. The unit can be operated in closed-loop, open-loop, and manual modes of operations. The Control Point has the ability to log a considerable amount of operational data for later evaluation.

The controller has a feature that allows the user to set simulated ground-speed values along with granular, liquid, and prewetting application rates to visually check the performance of the conveyer or auger, spinner, and the solid and liquid discharge rates without moving the vehicle. The unit can be used with either a hopper-box or tailgate spreader.

The yard tests of a new Control Point model was conducted at the same NYSDOT maintenance facility in Voorheesville as was the ICS2000 model. The yard tests were conducted during the period of September 20-21, 2006.

The controller was mounted on a Henderson uni-body spreader that was installed on 2006 Mack truck. A 2-inch gate opening was used during the yard tests. The spreader/controller combination tested contained a prewetting system that was manufactured by Henderson.

3.4 FORCE America Models

Two controller models manufactured by FORCE America were tested in the yard study. The two models were the 2100 and the 5100. The specifics of each model tested are given below. The corporate headquarters of FORCE America is at 501 East Cliff Road, Burnsville, MN 55337. Steve Chlebeck was the representative who assisted in the calibration, yard testing, and other test that followed.

3.4.1 FORCE America Model 2100

The FORCE America Model 2100 has the capability of controlling granular snow and ice control materials for highway winter maintenance operations. The unit can be operated, basically, in an open-loop mode of operation.

The yard test of the 2100 Spreader Control was conducted at St. Croix County maintenance garage facility in Hammond, Wisconsin. The yard tests were conducted on May 22, 2006. The firmware installed in the controller was version 2.3.

The Controller was mounted on a 2002 model truck (Truck #58) and connected to a Henderson tailgate spreader (#5058).

The snow and ice material used during the yard test was mixture of 95% sand and 5% salt. The truck did not have the capability of pre-wetting.

3.4.2 FORCE America Model 5100

The FORCE America Model 5100 has the capability of controlling and monitoring granular, liquid, or prewetted granular snow and ice control materials for highway winter maintenance operations. The unit can be operated in closed-loop and open-loop modes of operations. The unit can be used with either a hopper-box or tailgate spreader.

The yard tests of the 5100 Spreader Control were conducted at St. Croix County maintenance garage facility in Hammond, Wisconsin. The yard tests were conducted during the period of May 23 thru 25, 2006. The firmware installed in the controller was version 2.3.

The controller was mounted on a 2005 model truck (Truck #106) and connected to a Henderson tailgate spreader (#1058). The truck used an electronic speedometer sensor and the truck speed was matched with the speed displayed on the controller. The pre-wetting system used a 12VDC electric closed–loop pre-wet pump. The liquid pump, manufactured by Varitech Industries Inc., was a SHURflo positive displacement, 3 chamber, diaphragm pump, Model 2088-343-500. This pump was rated at 3.3 gal/min. The performance curve for this pump is a straight line from 10 psi @ 2.79 GPM to 50 psi @ 1.69 GPM.

The snow and ice material used during the yard test was straight salt and liquid calcium chloride.

3.5 Muncie Power Products MESP402D

The model MESP402D controller tested was manufactured by Muncie Power Products which has corporate offices at 201 East Jackson Street, Muncie, IN 47305. Terry Crago was the manufacturer's representation who assisted during the calibrations, yard tests, and other tests that followed.

The controller has the capability of controlling and monitoring granular and prewetted granular snow and ice control materials for highway winter maintenance operations. The unit can be operated in closed-loop, open-loop, and manual modes of operations. The controller has a feature that allows the user to set simulated ground-speed values along with granular and prewetting application rates without moving the vehicle.

The yard tests of the model MESP402D were conducted at an Indiana DOT maintenance facility in La Porte, IN during the period of June 12-14, 2006. The controller was mounted on a 2003 Sterling truck and connected to a Henderson hopper-box spreader with prewetting capability. A 2-inch gate opening was used during all the yard, and subsequent field tests.

The snow and ice control materials used during the yard tests were straight salt, and salt brine at a 23% concentration.

3.6 Pengwyn Model 485

The Pengwyn Model 485 controller tested was manufactured by Pengwyn Hydraulic Systems which has corporate offices at 2550 West Fifth Avenue, Columbus, OH 43204. Jim Borowske was the manufacturer's representative who assisted during the calibrations, yard tests, and other tests that followed.

The controller has the capability of controlling and monitoring granular and prewetted granular snow and ice control materials for highway winter maintenance operations. The unit can be operated in open-loop and manual modes of operations. The rear axel of the spreader needs to be raised off the ground during calibration tests and for checking the performance of the conveyer or auger and the solid and liquid discharge rates. In these cases, an operator is required in the truck cab to manually control the truck speed. The controller does not have the capability of simulating ground-speed values.

Two sets of yard tests were conducted with the Pengwyn controller. Both sets were conducted at an Ohio DOT maintenance facility in the Columbus, OH area. The first set of yard tests were conducted during the period of May 31- June 2, 2006. The data from the first testing period were discarded because of a computer board failure in the controller, plus problems with burst discharge quantities during short-time runs and problems with keeping the auger fully charged during the testing. A second set of yard (repeat) tests were conducted successfully during the period of October 10-11, 2006. The data from the second set of yard testing are the ones reported and analyzed in this report.

In both sets of tests, the controller was connected to a prewetting system that was associated with a tailgate spreader manufactured by a state agency. The spreader and controller were mounted on 2005 International truck.

The snow and ice control materials used during the yard tests were straight salt and salt brine at a 23% concentration.

3.7 Yard Study Preparations and Test Protocol

The yard or bench study was conducted over a six-month period starting about early May and continued until mid-September 2006. Initially, the Phase 2 work was to be done with new or recently purchased ground-speed and manual controllers. It was determined that it was not possible for new manual controllers to be available for testing. Therefore the yard tests were conducted only with ground-speed controllers that are operated in an open loop mode. The yard tests involved:

1. Calibrating the units according to the manufacturer's recommendations; and
2. Conducting multiple (verification) tests of the newly calibrated units to document the actual discharge rates at various settings.

3.7.1 Test Preparation/Assistance Needed from Clear Roads States

In preparation for the Yard Test, a document entitled "*Accuracy of Ground-Speed Controlled Snow and Ice Control Material Spreaders-Assistance Needed from Clear Roads States Involved in Yard/Field Studies*" was sent to the participating states. The purpose of the document was to provide some background on the Clear Roads project and to describe the assistance needed from the Clear Roads states involved in the maintenance yard and field studies of the project. What follows are excerpts from that document that deal with the state's assistance needed for the tests.

> "During the yard tests, it maybe necessary to jack up the rear axels and block the front wheels of the spreader truck. Multiple measurements of discharge rates at various speeds as indicated by the speedometer will be conducted. The discharged material to be collected includes: straight salt, a 95/5 sand/salt mix (in one location), and a prewetting liquid chemical(s) that is used by the highway agency. The maintenance yard equipment, facilities, and material needed for the yard testing include:
>
> - The same spreader truck that will be used in both the yard and field studies with the appropriate controller and necessary prewetting system mounted.
> - A known road distance near the maintenance yard where the spreader truck odometer and speedometer can be checked.
> - About 5 cu yd of each uniformly prepared granular material to be tested that is stored under cover and free of chunks with dimensions larger than the discharge gate opening.
> - A calibrated weighing device that will accommodate up to 200 pounds of discharged granular weight.
> - A device for catching the discharged granular material. (A plastic 2'x3'x1' deep or deeper mason tub used for mixing mortar might work.) .
> - Enough prewetting liquid chemical in the truck tanks to carry out a number of tests (tanks at least ½ full).
> - Adaptor hoses suited to capture the entire liquid chemical released from the spray nozzles during prewetting tests.
> - A 4 to 5-gallon graduated container for catching the discharged liquid chemical material plus several 1-gallon graduated containers.
> - A mechanism for storing the discharged liquid chemical for reuse.
> - A stop watch.
> - A way to mechanically keep a constant vehicle speed during each discharge test (such as with a throttle, if equipped). Perhaps a fan belt tensioner and a stick might work in the absence of a throttle.
> - A set of highway cones to warn people of rotating rear truck wheels.
> - Hard hats, if necessary.
> - A small tarp to help retain discharged granular material.
> - Shovels, brooms, wheelbarrows, etc. to help in collecting the discharged granular material."

It was anticipated the team would require the assistance of 3 to 4 agency people to conduct the tests which included at least one operator plus the use of one loader.

A member of the project team observed the calibration and oversaw the verification testing at a given work location. He worked closely with, and sought the advice of, the work location DOT maintenance personnel during the yard study. **The maintenance yard personnel performed all the tests.**

A representative of the controller manufacturer was encouraged to observe the yard tests. This activity was coordinated by the project team member overseeing the yard tests at a given location.

The team estimated that it would take up to 4 days to complete the yard testing of a given controller. The schedule for testing was somewhat at the discretion of the work location, but it was deemed highly beneficial for the project if the testing days were consecutive. Rainy days were okay as long as the work could be done in a salt storage building or other covered location.

3.7.2 Test Protocol

The approach taken in the yard test was that the individual controller/spreader combination was calibrated first in accordance with manufacturers' recommendation. A calibration verification process, described below, was conducted in accordance with a statistically – based experimental design that incorporated appropriate replication testing. This verification testing was performed to evaluate the precision and accuracy of the equipment. Separate designs were developed for spreader/controllers that distribute only dry solid material and those that distribute solid material prewetted with a liquid chemical. A full factorial experimental design was impractical considering the number of variables (solid material type, liquid material type, solid application rates, liquid application rates, and truck speeds) and test replications needed. Instead, a factional factorial design was developed for each of the two types of material distributors. A total of 126 tests were developed for each solid material spreader/controller combination. This total includes 21 combinations of truck speed-solid application rate and six replication tests for each combination of test variables. The 21 sets (combinations) of truck speed-solid application rates are given in Table 3-1. A total of 180 tests were developed for each spreader/controller combination used with prewetted solid material. This total is derived from 30 combinations of truck speed-solid application rate - liquid application rate and six replication tests for each combination of test variables. The 30 sets (combinations) of truck speed-solid application rate – liquid application rate combinations are given in Table 3-2.

Table 3-1. Values of Truck Speed-Solid Discharge for each Test Set Number

Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile
1	20	100	12	35	700
2	20	400	13	40	200
3	20	800	14	40	300
4	25	300	15	40	500
5	25	500	16	45	100
6	25	700	17	45	400
7	30	100	18	45	800
8	30	400	19	20	1000
9	30	800	20	30	1000
10	35	200	21	45	1000
11	35	600			

Table 3-2. Values of Truck Speed, Solid Discharge, and Prewetting for each Test Set Number

Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/mile	Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/mile
1	20	100	20	16	35	200	5
2	20	200	25	17	35	300	25
3	20	400	10	18	35	600	30
4	20	600	15	19	35	700	10
5	20	800	30	20	35	800	15
6	25	100	15	21	40	200	20
7	25	300	10	22	40	300	15
8	25	500	20	23	40	400	5
9	25	600	5	24	40	500	25
10	25	700	25	25	40	700	30
11	30	100	30	26	45	100	10
12	30	300	5	27	45	400	30
13	30	400	20	28	45	500	5
14	30	600	25	29	45	700	15
15	30	800	10	30	45	800	20

The procedures that were followed for conducting the yard study are itemized below in bullet fashion:

- Select late model spreader that has a new or late model controller that controls both solid and prewetting liquid material.
- Invite controller vendor to provide a "bench" demonstration of the calibration procedure for both solid and liquid materials.

- Invite controller vendor to supervise or perform the necessary calibrations of the test units.
- For those controllers that have a real time truck speed display, perform a check to see that the controller and speedometer give same speed reading over the range of testing.
- Identify any time lag from turning the controller on to the start of material delivery.
- For hopper spreaders, establish a constant gate opening that can be used without a problem over the speed – application rate range.
- Calibrate the scale for determining the test discharge weights.
- Conduct calibration verification testing of the controller/spreader for each material or material combination. (An analysis was conducted to determine discharge times that would produce solid and liquid discharge amounts convenient for capture and measurement. The discharge times of the tests generally ranged from 15 sec. to 60 sec., with most of the test discharge times closer to 15 sec. These run times generally produced solid discharge weights between 35 lbs. and 110 lbs.; and liquid discharge volumes of between 0.5 and 6 liters depending on the variable settings. The test data were recorded on special data forms.)
- Purge and clean the system prior to conducting calibration verification testing with different liquid chemicals.

SECTION 4
METHODOLOGY USED IN ANALYSIS OF YARD TEST DATA

The analysis of the yard study data was conducted along two lines. One approach taken was to tabulated and plot various test parameters to obtain an "engineering" feel for the functioning of the spreader/controller systems. The second approach was a more rigorous statistical analysis based upon the experimental design(s) established for the yard tests. The two main elements of interest in the analysis are the accuracy and precision of the spreader/controller systems. Each spreader/controller system was analyzed independently of the other systems. No attempt was made to compare one system against another. The two analysis approaches are summarized below.

4.1 Tabulation and Plotting (Quantitative Analysis) Approach

This approach starts with the computerized tabulation of the replicate yard tests conducted for each set of test parameters. The data recorded during the yard test of each spreader/controller system includes:

- Test set number
- Replicate test number
- Truck speed (mph)
- Test time (seconds)
- Set solid discharge rate (lbs/mile)
- Set prewetting application rate (gal/ton)
- Solid weight (lbs) discharged during test
- Shaft revolutions measured during discharge test
- Liquid volume (oz. or ml.) collected during test

Three additional items were computed for each test. These are:

- Test solid discharge rate (lbs/mile)
- Test liquid application rate (gals/ton)
- Test solid discharge weight (lbs) per shaft revolution (lbs/rev)

In addition, the arithmetic means of the last three items listed above were computed from the replicate test values for each set. An example of the format of the computerized tabulation of the replicate yard tests is shown in Figure 4-1.

Various types of two- and three- dimensional plots were generated during the analysis. These plots were produced to better understand the relationships between:

- the test (actual) solid and liquid discharge rates (lbs/mile and gals/ton) and the set (dial-in) application rates for a given truck speed (mph); and
- the test application rates and truck speed for various dial-in application rates.

Replicate Yard Testing Data Sheets
State of

Controller | **Solid Material:** | **Date:**
Controller (pre wet) : | **Liquid Material:**
Firmware Version: | **Serial Number:**
Location:
Spreader: | **Sheet 1 of 11**
Gate Opening: | **Truck # Year:**

Set #	Test	Truck Speed, Mph	Test Time, Seconds	Set Solid Discharge Rate Lbs./Mile	Set Prewetted Application Rate Gal/Ton	Solid Weight Lbs.	Test Solid Discharge Rate Lbs./Mile	Shaft Rev., No	Test Solid Discharge per Shaft Rev., lbs	Liquid Volumes (ml)	Test Liquid Rate, Gal/Ton	Comments
1	1	20		100	20							
	2	20										
	3	20										
	4	20										
	5	20										
	6	20										
	AVG.											
2	1	20		200	25							
	2	20										
	3	20										
	4	20										
	5	20										
	6	20										
	AVG.											

Figure 4-1. Computerized Tabulation of the Replicate Yard Tests

4.1.1 Summary Tabulations of Solid and Liquid Discharge Rates

Summary tabulations were made of the arithmetic means of the test (actual) solid and liquid application rates as a function of the set (dial-in) application rates (lbs/mile) and truck speed (mph). Samples of these data are given in Tables 4-1 and 4-2.

Table 4-1. Actual Solid Discharge Rates for Various Dial-In Application Rates and Truck Speeds

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**
20	103.7	207.3		423.8		645.2		865.2
25	106.0		321.6		546.6	667.7	769.0	
30	109.4		324.6	441.1		665.5		890.9
35		217.4	331.6			661.3	786.6	889.4
40		218.5	320.1	435.0	559.1		759.9	
45	107.8			435.0	543.7		762.3	857.8

Table 4-2. Actual Discharge Prewetting Rates for Various Dial-In Application Rates and Truck Speeds

Speed in mph	Dial-In Application Rate in gallons/ton					
	5	10	15	20	25	30
20		9.8	11.7	17.0	19.2	19.7
25	4.6	10.7	17.1	16.4	18.5	
30	5.5	9.7		15.4	20.7	30.1
35	7.8	10.1	14.9		23.6	25.0
40	4.9		14.0	19.6	20.7	28.6
45	5.0	11.7	17.0	25.8		23.0

An inspection of Tables 4-1 and 4-2 reveals cells with missing valves. The statistical approach to determine these missing valves is discussed in the next section.

4.1.2 Determination of Missing Summary Discharge Rates

One advantage of the design of experiments was that it was not necessary to test all possible combinations of the set discharge rate (both solid and liquid) and the ground speed of the vehicle in order to achieve valid test data across the full ranges of both variables.

For tests where the particular combination of set discharge rate and speed did exist, the arithmetic mean of those specific tests was the best estimate of the average discharge rate.

For those combinations that did not exist, it was possible to construct an estimate from a multiple linear regression model that incorporated all of the data for that particular controller. The estimate was constructed as a linear combination of model coefficients for both the set discharge rate and the speed plus the intercept coefficient. The model which generated the coefficients was a simple multiple linear regression model with actual discharge rate as the dependent variable and the set discharge rate and speed as the independent variables. Example:

$$Y = X1 * A1 + X2 * A2 + B$$

Where

Y is the estimated discharge (application) rate at a combination of set discharge (dial-in) application rate and speed
X1 is the nominal set (dial-in) application rate
A1 is the coefficient for the nominal set discharge rate from the regression model
X2 is the nominal speed
A2 is the coefficient for the nominal speed from the regression model
B is the coefficient for the intercept from the regression model

Table 4-3 demonstrates the application of a multiple linear regression model to construct an estimate of the missing discharge (application) rates in Table 4-1. The estimated missing discharge rates are displayed in bold type in Table 4-3. Similarly, the missing discharge rates in Table 4-2 are shown in bold type in Table 4-4 along with the test (actual) liquid application rates.

Table 4-3. Actual and Estimated Solid Discharge Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	103.7	207.3	**325.0**	423.8	**545.8**	645.2	**766.6**	865.2
25	106.0	**215.0**	321.6	**435.8**	546.6	667.7	769.0	**877.4**
30	109.4	**215.4**	324.6	441.1	**546.6**	665.5	**767.4**	890.9
35	**105.4**	217.4	331.6	**436.6**	**547.0**	661.3	786.6	889.4
40	**105.8**	218.5	320.1	435.0	559.1	**657.8**	759.9	**878.6**
45	107.8	**216.6**	**327.0**	435.0	543.7	**658.2**	762.3	857.8

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table 4-4. Actual and Estimated Prewetting Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial–In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**4.8**	9.8	11.7	17.0	19.2	19.7
25	4.6	10.7	17.1	16.4	18.5	**24.9**
30	5.5	9.7	**13.8**	15.4	20.7	30.1
35	7.8	10.1	14.9	**18.3**	23.6	25.0
40	4.9	**11.1**	14.0	19.6	20.7	28.6
45	5.0	11.7	17.0	25.8	**23.3**	23.0

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

4.1.3 Tabulations of Percent of Difference between Actual and Dial-In Solid and Liquid Application Rates

For each spreader/controller combination tested, summary tabulations were made of the percent of differences between the test (actual) solid discharge rates and the dial-in solid application rates. The percent of differences were calculated for each combination of dial-in application rate and truck speed. Similar calculations were made for the summary liquid discharge rates.

These calculations were made to obtain an insight into the variation of percent of difference over dial-in application rates for a given truck speed and the variation of percent of differences over truck speed for a given dial-in application rate.

The companion tabulations to those given in Tables 4-3 and 4-4 showing the percent of difference between actual discharge and dial-in application rate are given in Tables 4-5 and 4-6, respectively. Here, a positive percent number means that the spreader/controller discharged a larger amount of material than was specified by the controller. A negative percent number means that the spreader/controller discharged a lesser amount of material than was specified by the controller.

Table 4-5. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	3.7%	3.7%	**8.3%**	6.0%	**9.2%**	7.5%	**9.5%**	8.2%
25	6.0%	**7.5%**	7.2%	**9.0%**	9.3%	11.3%	9.9%	**9.7%**
30	9.4%	**7.7%**	8.2%	10.3%	**9.3%**	10.9%	**9.6%**	11.4%
35	**5.4%**	8.7%	10.5%	**9.2%**	**9.4%**	10.2%	12.4%	11.2%
40	**5.8%**	9.3%	6.7%	8.8%	11.8%	**9.6%**	8.6%	**9.8%**
45	7.8%	**8.3%**	**9.0%**	8.8%	8.7%	**9.7%**	8.9%	7.2%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table 4-6. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**-4.0%**	-2.0%	-22.0%	-15.0%	-23.2%	-34.3%
25	-8.0%	7.0%	14.0%	-18.0%	-26.0%	**-17.0%**
30	10.0%	-3.0%	**-8.0%**	-23.0%	-17.2%	0.3%
35	56.0%	1.0%	-0.7%	**-8.5%**	-5.6%	-16.7%
40	-2.0%	**11.0%**	-6.7%	-2.0%	-17.2%	-4.7%
45	0.0%	17.0%	13.3%	29.0%	**-6.8%**	-23.3%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

4.1.4 Various Types of Plots

Various types of two- and three- dimensional plots were generated during the analysis of the yard test data. These plots were produced to better understand the relationships that exit between tests, (actual) solid and liquid discharge rates, and the respective dial-in solid and liquid application rates, and truck speeds. A sample of the types of plots examined is described below.

Plots were generated of the test (actual) solid discharge amounts (lbs/mile) versus the set (dial-in) application rates (lbs/mile) for a given truck speed (mph). Sample plots are given in Figures 4-2 and 4-3 for truck speeds of 20 and 30 mph, respectively. Also shown on both plots is a line of equality to visualize the over or under amount of actual discharge compared to the set application rate.

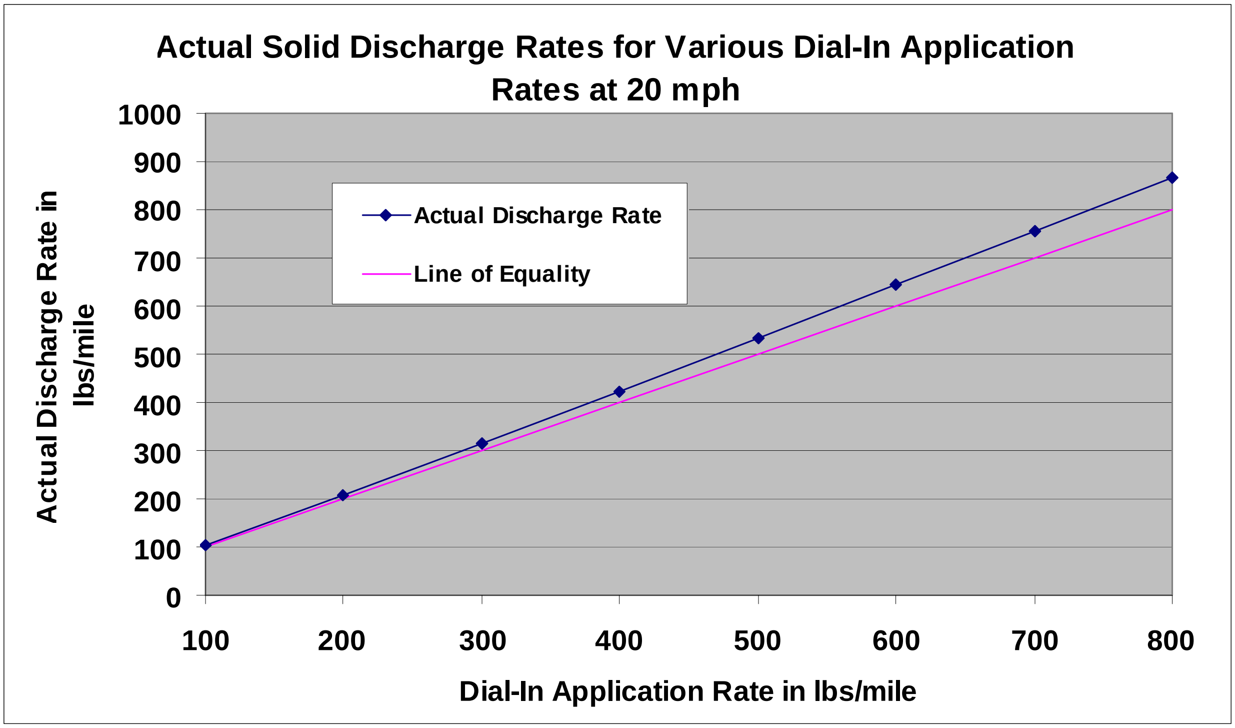

Figure 4-2. Actual Discharge Rates for Various Dial-In Application Rates at 20 mph

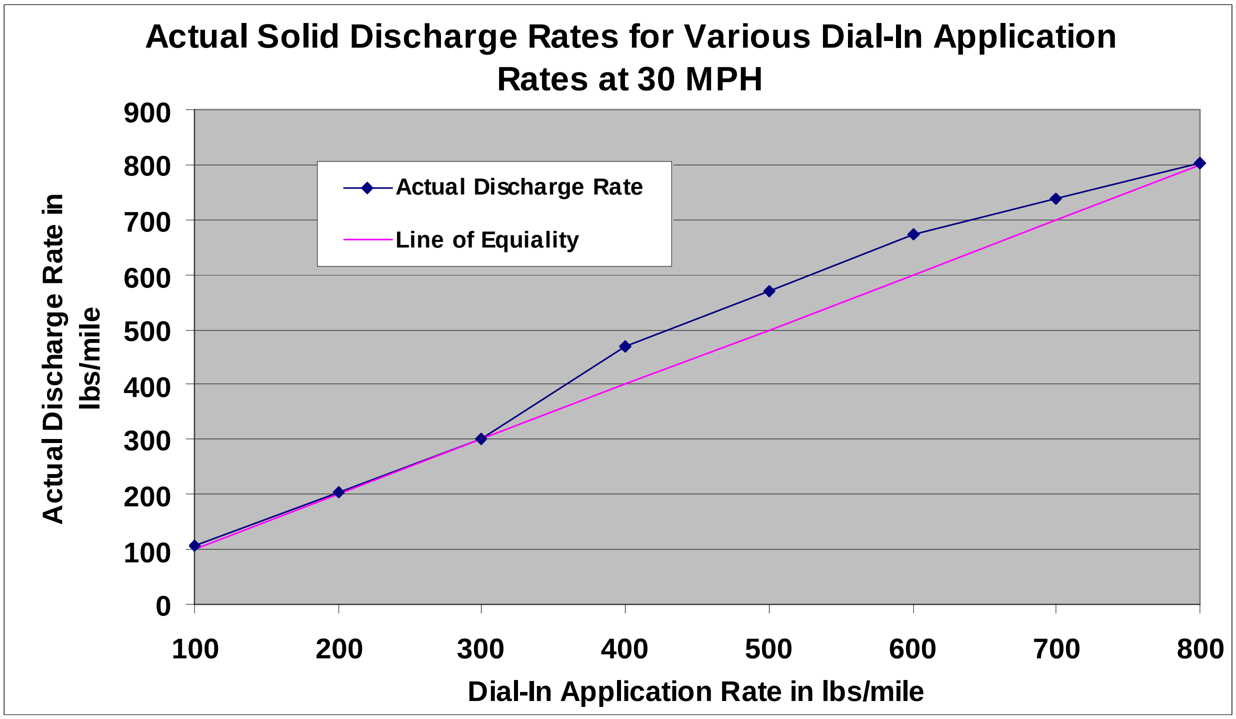

Figure 4-3. Actual Solid Discharge Rates for Various Dial-In Application Rates at 30 mph

Plots were also produced of the actual solid discharge amounts (lbs/mile) versus truck speed (mph) for fixed dial-in application rates. Sample plots of these curves for dial-in application rates of 100, 200, 300 lbs/mile are given in Figure 4-4; curves for dial-in application rates of 400, 500, and 600 lbs/mile are given in Figure 4-5. The curves in Figures 4-4 and 4-5 were obtained from the yard test data of the same spreader/controller combination.

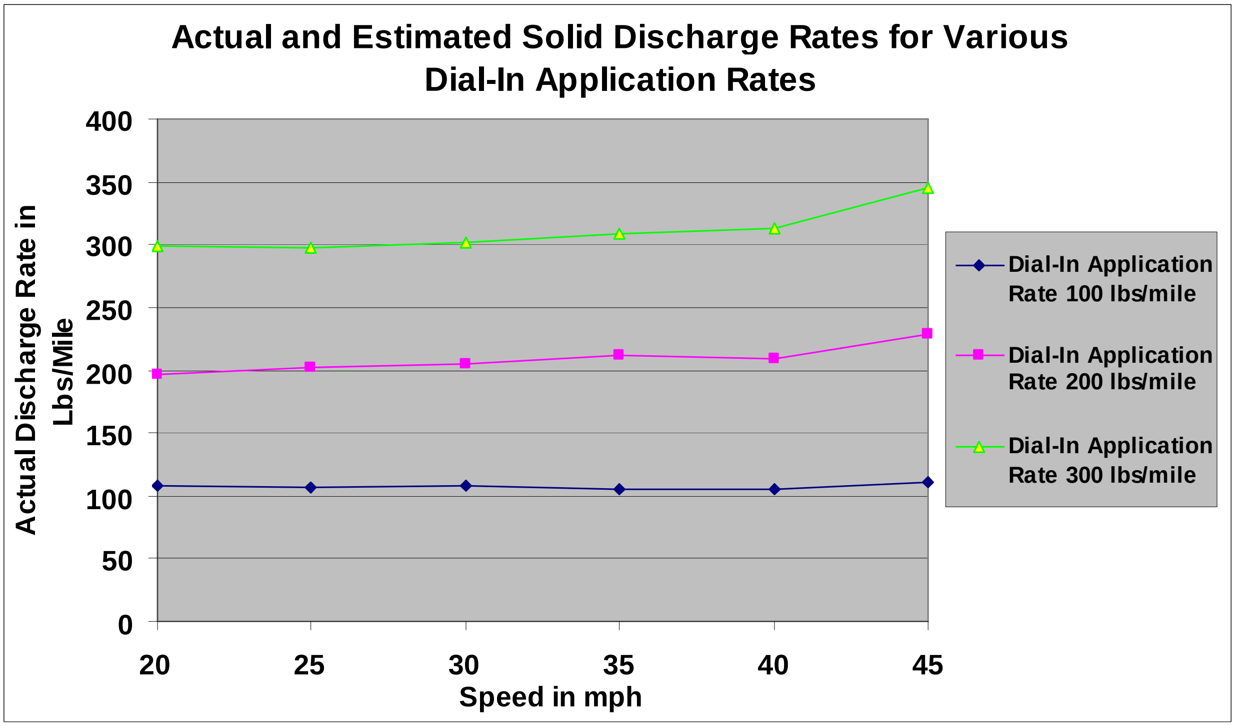

Figure 4-4. Actual and Estimated Solid Discharge Rate as a Function of Truck Speed for Dial-In Application Rates of 100, 200, and 300 lbs/mile.

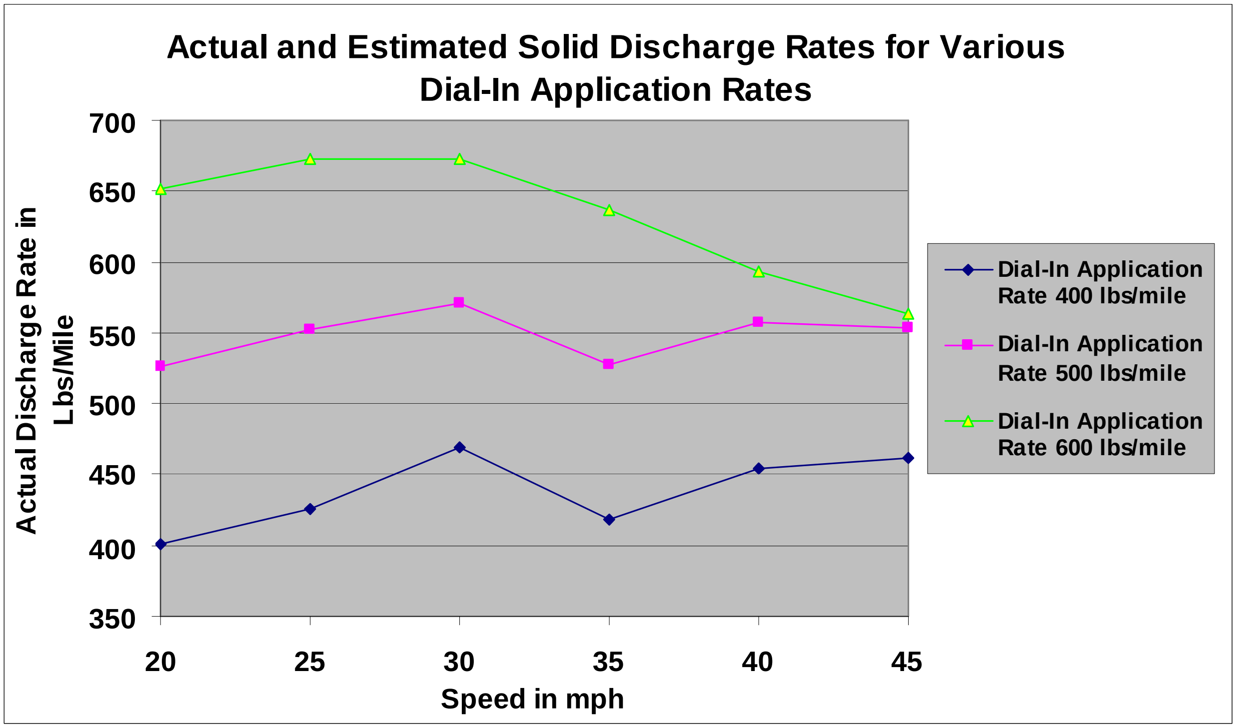

Figure 4-5. Actual and Estimated Solid Discharge Rates as a Function of Truck Speed for Dial-In Application Rates of 400, 500, and 600 lbs/mile.

Plots were generated of the differences between the actual discharge rates and the dial-in application rates versus truck speed for different dial-in application rates. The data given in Figures 4-4 and 4-5 are recast in percent of difference plots in Figures 4-6 and 4-7, respectively.

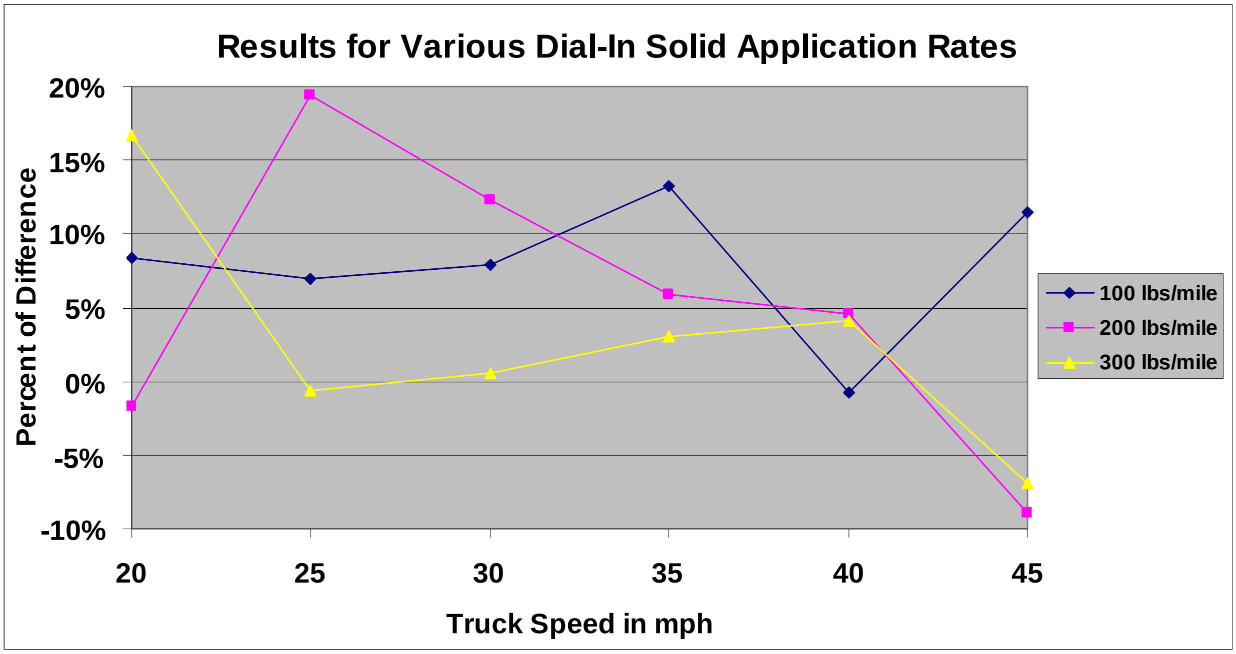

Figure 4-6. Percent of Difference between Actual and Estimated Solid Discharge Rate and Dial-In Application Rate as a Function of Truck Speed for Dial-In Application Rates of 100, 200, and 300 lbs/mile.

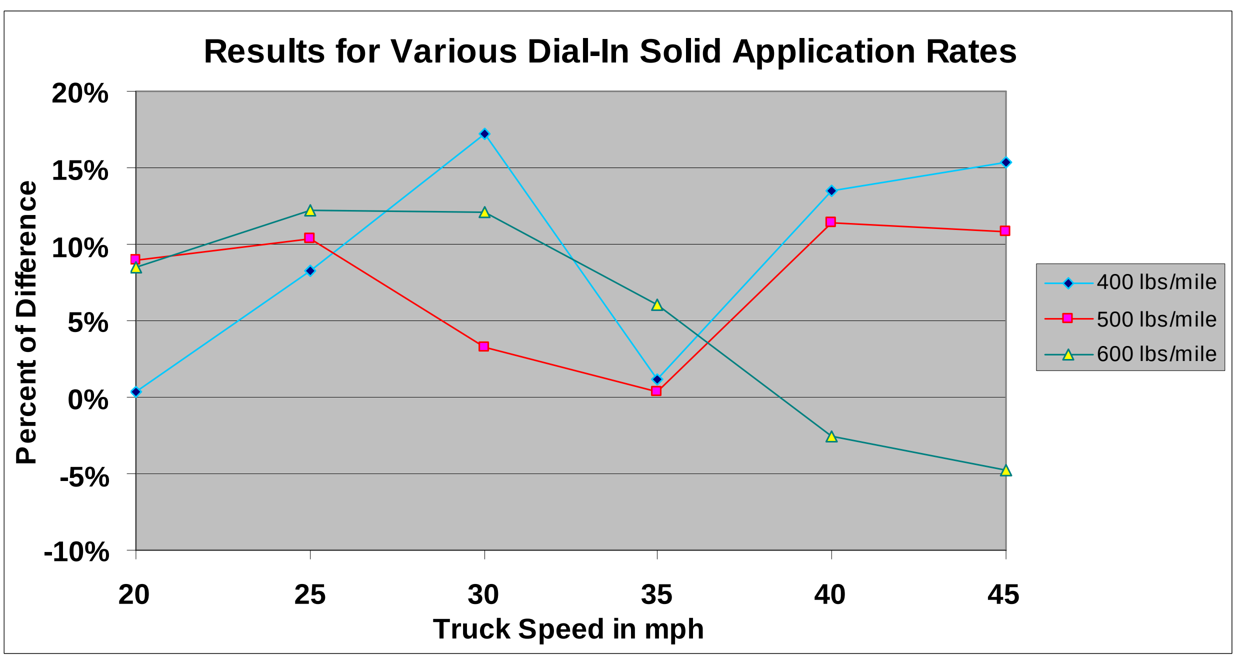

Figure 4-7. Percent of Difference between Actual and Estimated Solid Discharge Rate and Dial-In Application Rate as a Function of Truck Speed for Dial-in Application Rates of 400, 500, and 600 lbs/mile

The problem with the two-dimensional plot approach is that a number of plots are needed to identify trends and relationships between the primary variables of: actual discharge rates, dial-in application rates, percent of difference between actual discharge rates and dial-in application rates, and truck speeds. Three-dimensional plots of percent of difference between rates, dial-in application rates, and truck speed were generated in an attempt to reduce the number of plots for insight determination.

The three-dimensional plots provided a quick overview of the behavior of the variables, taken three at a time. However, the plots were very hard to use and need to be printed in color for visualization. The three-dimensional plots printed in black and while did not provide enough detail to distinguish the various levels of the variables. Thus, the three-dimensional plotting approach was abandoned.

The two-dimensional plots involving percent of difference between actual discharge and dial-in application rate versus either truck speed or dial-in application rates were selected as the preferred plots to use in Section 5.

4.1.5 Investigation into Theoretical vs. Actual Discharge Amounts

For solid material discharge, there are two primary variables: speed (mph) of the spreader vehicle and the dial-in application rate (lbs/mile) from the controller. For liquid material discharge, there are three primary variables: speed (mph) of the spreader vehicle, dial-in solid application rate (lbs/mile) from the controller, and dial-in prewetting application rate (gallons/ton) from the controller.

An approach was developed where the number of variables associated with solid material discharge was reduced from two to one: lbs/second. The number of variables associated with liquid discharge was also reduced to one: ounces/second. These variable combinations greatly assisted in the evaluations of the material discharge rates produced by the spreader/controller combinations.

Tables were developed to identify the theoretical values for solid and liquid discharges for application rates of 100 lbs/mile to 800 lbs/mile and truck speeds of 20 mph to 45 mph. Those tables along with sample calculations are contained in Appendix E of this report entitled: “Procedures for Computing Theoretical Solid and Liquid Discharge Amounts.”

Computations were made to determine the theoretical amount of solid material that could be dispensed (in lbs/second) from a spreader/controller system for a given application rate and truck speed combination. These theoretical results were then compared with the test results converted to actual solid discharge in lbs/second. A sample plot of the theoretical and actual solid discharge amounts versus test set number is given in Figure 4-8 for one of the spreader/controller tested. The two curves separate where the truck’s hydraulic system and other components are not capable of producing the proper discharge amount per second for the application rate – truck speed combination demanded by the controller. The set number of the test uniquely identifies those combinations of variables as shown in Table 3-2.

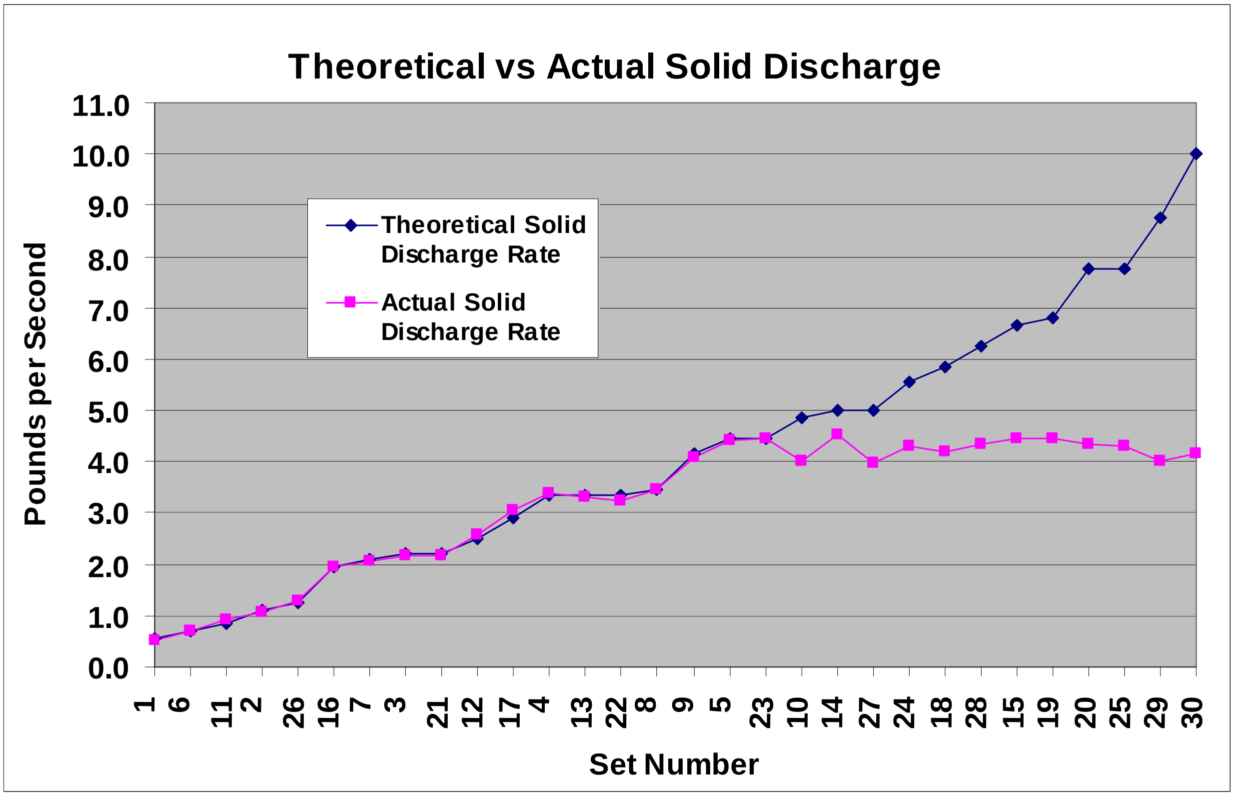

Figure 4-8. Theoretical and Actual Solid Discharge Rates in Pounds per Second versus Test Set Number

A sample plot of the theoretical and actual liquid discharge amounts versus test set number is given in Figure 4-9 for one of the spreader/controllers tested.

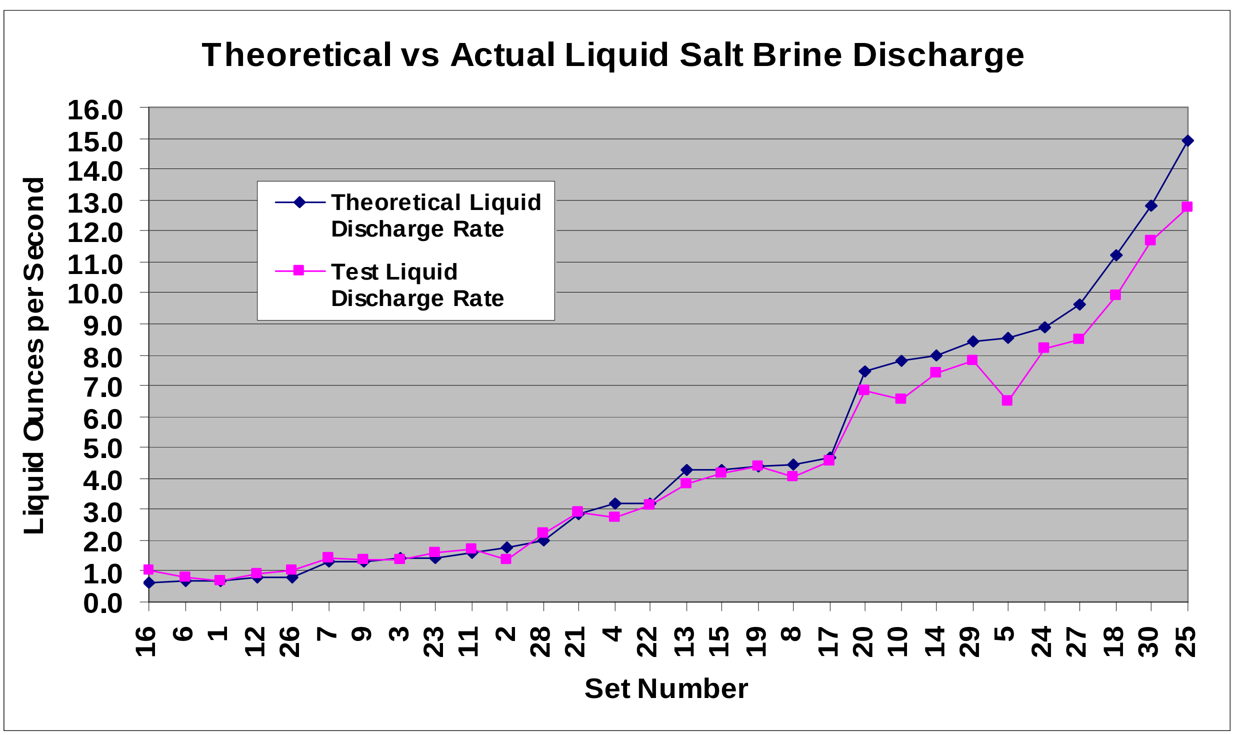

Figure 4-9. Theoretical and Actual Liquid Salt Brine Discharge Rates in Ounces per Second versus Test Set Number.

Tabulations were also made, for each spreader/controller tested, of the theoretical and test solid discharge amounts in lbs/second and the percent of error observed. Implicit in these tabulations is the test run time in seconds. The same tabulations were made for the liquid discharge amounts, where appropriate.

4.2 Statistical Analysis Approach

A statistical analysis was conducted using the yard test data from seven ground-speed controllers. Dry solid material data were collected for each of these seven spreader/controller systems and liquid prewetting data were recorded for five of the systems.

Understanding the performance of these systems was primarily assessed by the bias, accuracy, and precision calculations that follow. These assessments were augmented by the results of an Analysis of Variance (ANOVA).

Bias, accuracy, and precision of dry, solid material controllers

Bias, accuracy, and precision of each of the spreader/controller systems was calculated from the yard tests sets of data. Bias was simply calculated as the average difference between the collected test solid discharge rate and the nominal (set) solid discharge rate for each of the tests for a particular controller:

Bias = Average (TR – NR)

where
TR = collected test discharge rate,
and
NR = nominal discharge rate.

A bias close to zero would indicate the controller does a good job, on the average, of approximating the nominal, or set, solid discharge rate. A negative bias would indicate that the controller typically distributes less material than it should, where a positive bias would indicate that the controller typically distributes more than it should.

For each test, the difference between the collected test solid discharge rate and the nominal solid discharge rate was calculated (as in the bias calculation). As a proportion of the nominal solid discharge rate, this difference can be thought of as the percent “missed” in each test. One minus this percent is the “accuracy” percent for each test. Accuracy for a particular controller then was calculated as an average across all tests as follows:

Accuracy = Average (100*(1 – (TR – NR)/NR))

Accuracy is represented here as a percent. Accuracy close to 100% means that a controller would typically distribute material close to the nominal solid discharge rate.

In addition to the accuracy calculation, it is good to have a measure of how consistent measurements are with each other. In order to do this, the relative standard deviation of each of the differences was calculated in order to estimate precision. Like accuracy, precision was calculated as a percentage as follows:

Precision = 100* standard deviation (TR – NR)/accuracy

Precision close to 0% is desired. In other words, the more precise a controller is, the lower its standard deviation and the lower this precision calculation.

Bias, accuracy, and precision of liquid prewetting controllers

Bias, accuracy, and precision were calculated for each of the five spreader/controller systems that also controlled liquid prewetting. Calculations were exactly the same as for dry solid materials, except in units of liquid materials – specifically gal/ton.

ANOVA results for solid material controllers

An Analysis of Variance (ANOVA) was the statistical technique used to determine the effect that different spreader/controller system variables had, or did not have, on the accuracy of the test data. The three variables (covariates) examined were truck **speed** (mph), test **time** (seconds), and the nominal **solid** or **liquid** discharge rate.

Essentially, the ANOVA is a series of hypothesis tests that each of the covariates (and their combinations) has no effect on differences in the data. Where there is an effect, that covariate is marked as “significant” (S). If a controller worked perfectly (there is no such thing), then there would be no effect on any of the covariates – all differences would be the results of random chance. So, ideally it would be preferred that none of the covariates would be significant.

SECTION 5
DISCUSSION OF THE YARD STUDY DATA ANALYSIS RESULTS

This section of the report contains a discussion of the results from the analysis of the yard test data. The quantitative analysis results for each of the eight spreader/controller combinations tested are given, first, in Section 5.1. The results for each spreader/controller combination are discussed in terms of summary data, plots of test results, and plots of theoretical and actual discharge amounts of both solids and liquids. The interpretations of the results are given in terms of the limitations of the spreader/controller systems to achieve desired discharge amounts. Where appropriated, test observations, test limitations and problems encountered during the testing are also presented. Any vendor and/or maintenance DOT comments received on the test procedures/results are also given.

The results of a statistical analysis of the yard test data are given in Section 5.2. These analyses produced estimates of the bias, accuracy, and precision of each of the spreader/controller systems relative to their ability to control solid discharge amounts and, where appropriate, prewetting discharge amounts.

The tabulations and plots of the yard test data are given in the appendices for each controller tested. Each spreader/controller system was analyzed independently of the other systems. No attempt was made to compare one system against another.

5.1 Quantitative Analysis Results

Eight controllers from six manufacturers were tested during the yard study. The six manufactures were Cirus Controls, Component Technology, Dickey-john, FORCE America, Muncie Power Products, and Pengwyn. Two controller models were tested from both Dickey-john and FORCE America. Single models were examined from each of the other four manufacturers. Each controller was installed on a different spreader as described in Section 3. It was not possible to yard test the controllers using the same spreader. Consequently, the test results are given in terms of the spreader/controller combination examined.

5.1.1 Cirus Controls SpreadSmart RDS

The yard test results for the Cirus Controls SpreadSmart RDS are given in Appendix F. The yard tests followed the test protocol given in Section 3 for spreader/controller combinations used with prewetted solid material. The values of truck speed, set solid discharge rate, set prewetting application rate, and test run time for each test set number used in the yard tests are given in Table F-1. The test run times for the 30 sets of truck speed – solid application rate – liquid application rate ranged from 60 sec. down to 20 sec. Dry, solid salt and salt brine discharge amounts were collected during each of the 180 tests.

Summary tabulations of the actual solid and liquid discharge rates are given in Tables F-2 and F-4 respectively, for various dial-in application rates and truck speeds. The data from the 30 sets of test conditions yielded all but 18 solid and 7 liquid discharge rates in the two tables. Estimates of these missing discharge rates were determined using the multiple linear regression approach described in Section 4.1.2. The regression coefficients for estimating the missing cell values for the SpreadSmart RDS model are given in Table F-6.

The missing values determined using the multiple linear regression approach are given in bold type in Tables F-2 and F-4 and related Tables F-3 and F-5, respectively. In some instances the missing values appear to compliment the actual test data, and in other instances, they appear to be out of place, in spite of the moderately high R-squared values. Consequently, the missing values are used only as a convenience to generate plots of solid and liquid discharges as a function of truck speed and other test data. These plots are discussed at the end of this section. A majority of the discussion that follows concentrates on the actual test results.

A number of analysis approaches were undertaken to gain some insight into the overall performance of the spreader/controller system. The first approach involved computing the percent of difference between the actual (and estimated) solid and prewetting discharge application rates and the dial-in application rates for various truck speeds.

The percent of difference for the solid discharge amounts are given in Table 5-1 and also in Table F-3. The percent of difference for the solid discharge ranges from -60.2% (under application) to 11.0% (over application). The gray shaded cells in the Tables 5-1 and F-3 show approximately where the absolute percent of differences are greater than or equal to 8.5%. [The limit of 8.5% was arbitrarily selected for convenience. Any limit value less than or greater than 8.5% could have been selected.] The system had difficulty in achieving the dial-in application rates of 700 and 800 lbs/mile at speeds of 25 mph and higher. The difficulty in achieving even 500 lbs/mile is evident at 30, 35, 40, and 45 mph. Sizeable under application rates are noted at 35, 40, and 45 mph for the range of application rates of 500 to 800 lbs/mile. However, the system appears to operate best (low percent of differences) with dial-in application rates of 100 through 400 lbs/mile for truck speeds from 20 to 45 mph, with the exceptions of the dial-in application rate of 100 lbs/mile at 20 and 30 mph and the dial-in application rate of 400 lbs/mile at 45 mph.

Table 5-1. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	-8.5%	-5.5%	**16.9%**	-2.4%	**-6.3%**	1.5%	**-16.2%**	-0.4%
25	2.0%	**29.9%**	-0.9%	**-5.6%**	-0.7%	-1.9%	-17.6%	**-23.4%**
30	11.0%	**13.9%**	3.1%	-1.1%	**-19.1%**	-9.2%	**-25.4%**	-33.4%
35	**36.7%**	0.8%	4.7%	**-21.7%**	**-25.5%**	-28.1%	-34.6%	-44.2%
40	**4.6%**	-3.1%	4.7%	0.2%	-22.4%	**-33.5%**	-44.5%	**-35.4%**
45	2.9%	**-34.3%**	**-36.5%**	-20.8%	-30.5%	**-38.8%**	-54.0%	-60.2%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

The percent of difference for the prewetting discharge amount are given in Table 5-2 and also in Table F-5. The percent of difference for the prewetting discharge ranges from -43.0% (under application) to 50.0% (over application). The cells in Tables 5-2 and F-5, where the absolute percent of differences are greater than or equal to 8.5%, are sporadically distributed over speed and application rate combinations. The prewetting system appears to operate best with a dial-in prewetting application rate of 10 to 30 gallons/ton for a truck speed of 20 mph, and at application rates of 5, 10, and 20 gallons/ton for a truck speed of 25 mph. The control of prewetting application rates investigated at truck speeds of 30 mph and higher appears difficult, at best. The largest percent of differences, as well as a few small percent of differences, occur within the 30 to 45 mph truck speed range.

Table 5-2. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-in Prewetting Application Rates as a Function of Truck Speed

Speed in mph	Dial–In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**92.0%**	-2.0%	-4.0%	6.5%	0.8%	-38.3%
25	2.0%	1.0%	16.0%	-1.0%	-12.4%	**-22.7%**
30	12.0%	46.0%	**-2.7%**	-7.0%	-30.4%	**-23.7%**
35	34.0%	32.0%	16.7%	**-15.0%**	-4.8%	-38.3%
40	4.0%	**12.0%**	-2.7%	-6.0%	-30.8%	-43.0%
45	50.0%	13.0%	24.0%	-4.5%	**-23.2%**	-38.0%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

During the yard tests, there was some concern by the manufacturer that the test times were too short for some of the discharge amounts collected. The test times for the 30 sets ranged from 60 sec. down to 20 sec. The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates are given in Table F-7 for the test set numbers. The data in Table F-7 are arrayed in descending test run time in seconds. The data show that the percent of error values found for the longer test times (60 sec.) ranges from -8.63% to +11.04%. For the shorter test times of 30 sec, the percent of error values ranges from -44.50% to +0.20%, and for the shortest test time of 20 sec, the percent of error values ranges from -58.60% to -30.56%. Thus, it appears that the percent of error values for the solid discharge may have been influenced by the shorter test times, but there is not enough evidence to support that assumption. It appears, however, that the percent of error values for the liquid discharge were not greatly influenced by the shorter test run times. This fact is evident when looking at the percent of error values for the liquid discharges as a function of test run time in Table F-8.

The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates in Table F-7 are remarkably close to each other for a given set number. This means that the set solid discharge rate of the controller follows closely the theoretical solid discharge rate.

Such is not the case for the percent of error for prewetting discharge in Table F-8. The percent of error for the test prewetting discharge rate compared to the set prewetting application rate is much different, in many cases, than the corresponding percent of error for the test liquid discharge compared to the theoretical liquid discharge. This is because the test prewetting discharge rates in Table F-8 are based upon a test solid discharge amount which contains experimental error. The test prewetting discharge rate is considerably different than what would be expected from the set prewetting application rate displayed by the controller.

The data in Tables F-7 and F-8 were reordered in an attempt to better understand the limitations of the spreader/controller system to control both solid and liquid discharges. The data in Table F-7 are arrayed by increasing theoretical solid discharge values in Table F-9. Likewise, the data in Table F-8 are arrayed by increasing theoretical liquid discharge values in Table F-10.

The theoretical solid discharge and test (actual) solid discharge values in Table F-9 are plotted as a function of the test set numbers in Figure F-1. The two curves follow each other until they reach the conditions described by set number 23 (400 lbs/mile dial-in application rate and 40 mph truck speed). At this point the actual discharge curve separates from the theoretical discharge curve and remains essentially below the theoretical curve to set number 30. The vertical distance between the two curves for a given set number is a measure of the diminished output, or limitation of the spreader/controller system to produce the desired output. After set number 23 (conditions represented by set numbers 10, 14, 27, 24, 18, 28, 15, 19, 20, 25, 29, and 30), the system has reached its output capacity and is unable to produce the output specified by the controller. The truck speed – solid (dial-in) application rate combinations for the set numbers can be easily seen from Table F-9. For instance, the conditions described by set number 20, 25, 29, and 30 correspond to an application rate of 700 lbs/mile at speeds of 40 and 45 mph, and an application rate 800 lbs/mile at speeds of 35 and 45 mph.

The theoretical liquid discharge and test (actual) liquid discharge values in Table F-10 are plotted as a function of the test set numbers in Figure F-2. The two curves essentially separate vertically after set number 17 and remain so to the right edge of the figure. The greater the vertical separation between the theoretical liquid discharge curve and the actual liquid discharge curve for a given set number, the greater the percent of error. As before, the truck speed – liquid (dial-in) application rate combination for the set numbers can be seen from Table F-10.

Finally, a number of plots of solid and liquid discharge amounts were generated and reviewed for additional information on the capability of the spreader/controller system. These plots are presented in Figures F-3 through F-8. The ordinate values of all these plots are the percent of difference between the actual discharge and the dial-in application rate. Truck speeds and dial-in application rates are used as the abscissa in the plots.

The plots in Figures F-3 through F-8 exhibit extreme variations, possibly because of the multiple linear regression results, and possibly because of the nature of the system behavior. If the system were operating perfectly, all the curves in the figures would be collapsed along the zero percent of difference for all abscissa valves. Obviously, such is not the case and, if anything, the curves have a tendency to either increase or decrease towards the high end of the abscissa values. These results are somewhat surprising because of the moderately high R-squared valves for the regression analysis. The plots are given for information only.

After the yard tests were completed and the results of the theoretical discharges and test (actual) discharge values were plotted and shared with the highway agency, it was determined that the reason that the spreader/controller system performance drop-off at either high dial-in application rate and/or high truck speeds was because the agency designed their system to have a higher level of accuracy at low application rates and speeds.

5.1.2 Component Technology GL-400

The yard test results for the Component Technology model GL-400 are given in Appendix G. The yard tests followed the test protocol given in Section 3 for spreader/controller combinations used with prewetted solid material. The values of truck speed, set solid discharge rate, set prewetting application rate, and test run time for each test set number used in the yard tests are given in Table G-1. The test run times for the 30 sets of truck speed – solid application rate – liquid application rate ranged from 60 sec. down to 15 sec. Dry, solid salt and salt brine discharge amounts were collected during each of the 180 tests. Selective tests were also performed during the yard tests using liquid calcium chloride as the prewetting fluid, in place of salt brine. However, the primary yard test results are for solid salt and salt brine, which are discussed first.

Summary tabulations of the actual solid and liquid discharge rates are given in Tables G-2 and G-4 respectively, for various dial-in application rates and truck speeds. The data from the 30 sets of test conditions yielded all but 18 solid and 6 liquid discharge rate values in the two tables. Estimates of these missing discharge rate values were determined using the multiple linear regression approach described in Section 4.1.2. The regression coefficients for estimating the missing cell values for the GL-400 model are given in Table G-6.

The missing values determined using the multiple linear regression approach are given in bold type in Tables G-2 and G-4 and related Tables G-3 and G-5, respectively. In some instances the missing values appear to compliment the actual test data, and in other instances, they appear to be out of place, in spite of the relatively high R-squared values. Consequently, the missing values are used only as a convenience to generate plots of solid and liquid discharges as a function of truck speed and other test data. These plots are discussed at the end of this section. A majority of the discussion which follows concentrates on the actual test results.

A number of analysis approaches were undertaken to gain some insight into the overall performance of the spreader/controller system. The first approach involved computing the percent of difference between the actual (and estimated) solid and prewetting discharge application rates and the dial-in application rates for various truck speeds.

The percent of difference for the solid discharge amounts are given in Table 5-3 and also in Table G-3. The percent of difference for the solid discharge ranges from -29.2% (under application) to 17.2% (over application). The gray shaded cells in Table 5-3 and Table G-3 show where the absolute percent of differences are greater than or equal to 8.5%. With the exception of the cells corresponding to 800 lbs/mile at 30 mph and the entire range of application rates at 35 mph, the system had difficulty in achieving the dial-in application rates of 500 lbs/mile and higher for the range of truck speeds investigated. The difficulty in achieving even 400 lbs/mile is evident at 30, 40, and 45 mph. Sizeable over and under application rates are noted at 45 mph for the range of application rates investigated. The ability to control the dial-in application rate of 100 lbs/mile appears marginal for the range of truck speeds investigated. However, the system appears to operate best (low percent of differences) with dial-in application rates of 200 and 300 lbs/mile for the range of truck speeds investigated below 45 mph.

Table 5-3. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	8.4%	-1.7%	**16.7%**	0.3%	**8.9%**	8.5%	**5.6%**	16.0%
25	6.9%	**19.4%**	-0.6%	**8.3%**	10.4%	12.2%	12.5%	**2.7%**
30	7.9%	**12.3%**	0.5%	17.2%	**3.2%**	12.1%	**1.5%**	0.4%
35	**13.3%**	5.9%	3.1%	**1.2%**	**0.4%**	6.1%	-0.2%	-7.9%
40	**-0.8%**	4.6%	4.1%	13.5%	11.4%	**-2.5%**	-10.2%	**-2.6%**
45	11.5%	**-8.9%**	**-6.9%**	15.4%	10.8%	**-4.8%**	-18.1%	-29.2%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

The percent of difference for the prewetting discharge amounts are given in Table 5-4 and also in Table G-5. The percent of difference for the prewetting discharge ranges from -34.3% (under application) to +56.0% (over application). The cells in the two tables, where the absolute percent of differences are greater than or equal to 8.5%, are sporadically distributed over speed and application rate combinations. The prewetting system appears to operate best with a dial-in prewetting application rate of 10 gallons/ton, except at the 45 mph truck speed. The control of prewetting application rates below and above 10 gallons/ton appears difficult, at best. Large percent of differences occur at the 5 gallons/ton rate at 30 and 35 mph, as well as at the 15 gallons/ton rate and higher at speeds of 20, 25, and 30 mph. Large percent of differences occur at 45 mph for prewetting application rates greater than 5 gallons/ton.

Table 5-4. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed

Speed in mph	Dial–In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**-4.0%**	-2.0%	-22.0%	-15.0%	-23.2%	-34.3%
25	-8.0%	7.0%	14.0%	-18.0%	-26.0%	**-17.0%**
30	10.0%	-3.0%	**-8.0%**	-23.0%	-17.2%	0.3%
35	56.0%	1.0%	-0.7%	**-8.5%**	-5.6%	-16.7%
40	-2.0%	**11.0%**	-6.7%	-2.0%	-17.2%	-4.7%
45	0.0%	17.0%	13.3%	29.0%	**-6.8%**	-23.3%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

During the yard tests, there was some concern by the manufacturer that the test run times were too short for some of the discharge amounts collected. The test run times for the 30 sets ranged from 60 sec. down to 15 sec. The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates are given in Table G-7 for the test set numbers. The data in Table G-7 are arrayed in descending test run time in seconds. The data in Table G-7 demonstrates that high percent of error values are found for the longer test run times, as for the shorter test run times. Also, some low percent of error values are found for the shorter test run times. Thus, it appears that the percent of error values were not greatly influenced by the shorter test run times. This fact is more evident when looking at the percent of error values for the liquid discharges as a function of test run time in Table G-8. Some speed and feed/liquid rate limiting conditions were experienced during the testing. These conditions are noted at the bottom of Tables G-7 and G-8.

The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates in Table G-7 are remarkably close to each other for a given set number. This means that the set solid discharge rate of the controller follows closely the theoretical solid discharge rate.

Such is not the case for the percent of error for prewetting discharges in Table G-8. The percent of error for the test prewetting discharge rate compared to the set prewetting application rate is much different, in many cases, than the corresponding percent of error for the test liquid discharge compared to the theoretical liquid discharge. This is because the test prewetting discharge rates in Table G-8 are based upon a test solid discharge amount which contains experimental error. The test prewetting discharge rate is considerably different than what would be expected from the set prewetting application rate displayed by the controller.

The data in Tables G-7 and G-8 were reordered in an attempt to better understand the limitations of the spreader/controller system to control both solid and liquid discharges. The data in Table G-7 are arrayed by increasing theoretical solid discharge values in Table G-9. Likewise, the data in Table G-8 are arrayed by increasing theoretical liquid discharge values in Table G-10.

The theoretical solid discharge and test (actual) solid discharge values in Table G-9 are plotted as a function of the test set numbers in Figure G-1. The plot of the actual discharge contains some surprising and unexplained behavior. The two curves in Figure G-1 follow each other until they reach the conditions described by set number 17 (300 lbs/mile dial-in application rate and 35 mph truck speed). At this point, the actual discharge curve separates from the theoretical discharge curve and remains above the theoretical curve to set numbers 15 and 19. The position of the actual discharge curve above the theoretical discharge curve suggests experimental error and/or artificially enhanced actual discharge. Never-the-less, the trends of the two curves generally follow each other until they reach the conditions described by set number 15 (800 lbs/mile dial-in application rate and 30 mph truck speed). After set number 19 (conditions represented by set numbers 20, 25, 29, and 30), the system has reached its output capacity and is unable to produce the output specified by the controller. The vertical distance between the two curves for a given set number in this area is a measure of the diminished output, or limitations of the spreader/controller system to produce the desired output. The truck speed – solid (dial-in) application rate combination conditions corresponding to set numbers 20, 25, 29, and 30 can be easily seen from Table G-9. These conditions correspond to the application rate of 700 lbs/mile at speeds of 40 and 45 mph and an application rate of 800 lbs/mile at speeds of 35 and 45 mph.

The theoretical liquid discharge and test (actual) liquid discharge values in Table G-10 are plotted as a function of the test set numbers in Figure G-2. The two curves essentially separate vertically after set number 17 and remain so to the right edge of the figure. The greater the vertical separation between the theoretical liquid discharge curve and the actual liquid discharge curve for a given set number, the greater the percent of error. As before, the truck speed – liquid (dial-in) application rate combination for the set numbers can be seen from Table G-10.

As stated earlier, some limited tests were performed with liquid $CaCl_2$ as a prewetting chemical. The purpose of these tests was to determine any difference between the actual liquid discharge amounts using salt brine and liquid $CaCl_2$. The results of these limited tests are plotted in Figure G-3. Very little, if any, differences are noted between the actual liquid discharge using salt brine and liquid $CaCl_2$.

Finally, a number of plots of solid and liquid discharge amounts were generated and reviewed for additional information on the capability of the spreader/controller system. These plots are presented in Figures G-4 through G-9. The ordinate values of all these plots are the percent of difference between the actual discharge and the dial-in application rate. Truck speed and dial-in application rates are used as the abscissa in the plots.

The plots in Figures G-4 through G-9 exhibit extreme variations, possibly because of the multiple linear regression results, and possibly because of the nature of the system behavior. If the system were operating perfectly, all the curves in the figures would be collapsed along the zero percent of difference for all abscissa valves. Obviously, such is not the case and, if anything, the curves have a tendency to either increase or decrease towards the high end of the abscissa values. These results are somewhat surprising because of the high R-squared values for the regression analysis. The plots are given for information only.

5.1.3 Dickey-john Models

Two controller models manufactured by Dickey-john were tested in the yard study. The yard test results for the ICS2000 model are discussed in Section 5.1.3.1; and the yard test results for the Control Point model are discussed in Section 5.1.3.2.

5.1.3.1 Dickey-john ICS2000

The yard test results for the Dickey-john ICS200 are given in Appendix H. Initially, the yard tests attempted to follow the test protocol given in Section 3 for spreader/controller combinations used with prewetted solid material. Shortly after the beginning of the yard tests of the ICS2000 unit, it was discovered that it could not control the liquid during prewetting. Consequently, the use of liquids during the yard test was abandoned in favor of testing the system with only dry salt. This decision resulted in a modification of the test protocol given in Section 3 from the 30 sets of conditions down to 28 sets. The values of truck speed, set solid discharge rate, and test run time for each set number used in the yard tests are given in Table H-1. The set solid discharge rates in Table H-1 are also modified from the values given in Section 3 because of controller/calibration constraints. The test run times for the 28 sets of truck speed – solid (dial-in) application rate combinations ranged from 60 sec. down to 10 sec. Dry, solid salt discharge amounts were collected during each of the 168 tests.

Summary tabulations of the actual solid discharge rates are given in Table H-2 for various dial-in application rates and truck speeds. The data from the 28 sets of test conditions yielded all but 21 solid discharge rates in Table H-2. Estimates of these missing discharge rates were determined using the multiple linear regression approach described in Section 4.1.2. The regression coefficients for estimating the missing cell values for the ICS2000 model are given in Table H-4.

The missing values determined using the multiple linear regression approach are given in bold type in Table H-2 and related Table H-3. In some instances the missing values appear to compliment the actual test data, and in other instances, they appear to be out of place, in spite of the relatively high R-squared value. Consequently, the missing values are used only as a convenience to generate plots of the solid discharges as a function of truck speed and other test data. These plots are discussed at the end of this section. A majority of the discussion that follows, concentrates on the actual test results.

A number of analysis approaches were undertaken to gain some insight into the overall performance of the spreader/controller system. The first approach involved computing the percent of difference between the actual (and estimated) solid discharge application rates and the dial-in application rates for various truck speeds.

The percent difference for the solid discharge amounts are given in Table 5-5 and also in Table H-3. The percent of difference for the solid discharge ranges from -30.4% (under application) to +11.9% (over application). The grey shaded cells in Tables 5-5 and H-3 show where the absolute percent of differences are greater than or equal to 8.5%. In general, these cells are sporadically distributed over speed and application rate combinations. However, the system appears to operate best (low percent of differences) with dial-in application rate of 107 lbs/mile for the range of truck speeds investigated. The system also appears to operate well, except for a very few cells, at truck speeds of 20, 25, and 30 mph for the range of dial-in solid application rates investigated.

Table 5-5. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	107	215	322	429	537	644	751	858
20	0.7%	8.6%	1.5%	7.1%	**6.3%**	2.6%	**3.4%**	8.0%
25	3.0%	**12.9%**	1.0%	**4.5%**	9.7%	2.2%	5.6%	**0.2%**
30	-4.9%	**4.0%**	-1.9%	-0.8%	**-0.8%**	-1.4%	**-1.7%**	-2.2%
35	**-5.8%**	11.6%	11.9%	**-4.5%**	**-4.4%**	7.0%	11.6%	4.3%
40	**-23.7%**	**-13.8%**	**-10.6%**	**-8.9%**	**-7.9%**	**-7.3%**	**-6.8%**	**-6.5%**
45	-6.4%	**-22.7%**	-4.0%	-2.5%	-3.7%	**-10.2%**	-27.8%	-30.4%

Note: Red entries are for 1.5 inch gate opening
Black entries are for 3.0 inch gate opening
The numbers in bold type are computed from the actual test data using a multiple linear regression model.

During the yard tests, there was some concern by the manufacturer that the test run times were too short for some of the discharge amounts collected. The test run times for the 28 sets ranged from 60 sec. down to 10 sec. The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates are given in Table H-5 for the test set numbers. The data in Table H-5 are arrayed in descending test run time in seconds. The data show that the percent of error values found for the longest test run times (60 sec.) ranges from -6.43% to +8.63%. For the shorter test run times of 30 sec., the percent of error values ranges from -4.02% to +11.88%; and for the test run times of 15 sec., the percent of error values ranges from -27.78% to +7.01%. For the shortest test run time of 10 sec., the percent of error values ranges from -30.35% to +11.63%. Thus, it appears that the percent of error values for the solid discharge may have seen influenced by the shorter test run times, but there is not enough evidence to support that assumption.

The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates in Table H-5 are remarkably close to each other for a given set number. This means that the set solid discharge rate of the controller follows closely the theoretical solid discharge rate.

The data in Table H-5 were reordered in an attempt to better understand the limitations of the spreader/controller system to control solid material discharges. The data in Table H-5 are arrayed by increasing theoretical solid discharge values in Table H-6.

The theoretical solid discharge and test (actual) solid discharge values in Table H-6 are plotted as a function of set numbers in Figure H-1. The two curves basically follow each other fairly closely until they reach the conditions described by set numbers 27 and 28 (751 lbs/mile and 858 lbs/mile dial-in application rate, respectively, at 35 mph truck speed). At these two points, the actual discharge curve separates from the theoretical discharge curve and remains above the theoretical curve. The conditions of the actual discharge curve at these two points suggest experimental error and/or artificially enhanced actual discharge. The conditions at set numbers 17 and 18 (751 lbs/mile and 858 lbs/mile solid application rate, respectively, at 45 mph speed) indicate the system has reached its output capacity and is unable to produce the output specified by the controller.

Finally, a number of plots of solid discharge amounts were generated and reviewed for additional information on the capability of the spreader/controller system. These plots are presented in Figures H-3 through H-5. The ordinate values of all these plots are the percent of difference between the actual discharge and dial-in application rate. Truck speed and dial-in application rate are used as the abscissa in the plots.

The plots in Figures H-3 through H-5 exhibit extreme variations, possibly because of the multiple linear regression results, and possibly because of the nature of the system behavior. If the system were operating perfectly, all the curves in the figures would be collapsed along the zero percent of difference for all abscissa valves. Obviously, such is not the case and, if anything, the curves have a tendency to either increase or decrease towards the high end of the abscissa values. The results in Figures H-3 through H-5 are somewhat surprising because of the relatively high R-squared value for the regression analysis of the solid discharge values. The plots are given for information only.

5.1.3.2 Dickey-john Control Point

The yard test results for the Dickey-john Control Point are given in Appendix H following the results of the ICS2000 model. The yard tests of the Control Point model followed the test protocol given in Section 3 for spreader/controller combinations used with prewetted solid material. The values of truck speed, set (dial-in) solid discharge rate, set (dial-in) prewetting application rate, and test run time for each test set number used in the yard tests are given in Table H-8. The test run times for the 30 sets of truck speed - solid application rate – liquid application rate ranged from 90 sec. down to 12 sec. Dry, solid salt and liquid carbohydrate enhanced calcium chloride discharge amounts were collected during each of the 180 tests.

Summary tabulation of the actual solid and liquid discharge rates are given in Tables H-9 and H-11 respectively, for various dial-in application rates and truck speeds. The data from the 30 sets of the test conditions yielded all but 18 solid and 6 liquid discharge rates in the two tables. Estimates of the missing solid discharge rates were determined using the multiple linear regression approach described in Section 4.1.2. The regression coefficients for estimating the missing cell values of the solid discharge of the Dickey-john Control Point model are given in Table H-13.

An attempt was made to also estimate the missing liquid discharge rates in Table H-11 using the procedure described in Section 4.1.2. The results of the multiple linear regression analysis of the liquid discharge rates produced an extremely low R-squared value of 7.5%. This means that the regression model that worked so well with other liquid discharge rates was not suitable for the liquid discharge rates from the Control Point. (We could get a similarly low R-squared value by just guessing at a model to estimate the missing liquid discharge rates.) Consequently, no further work was done to estimate the missing liquid discharge rates in Table H-11 and the related Table H-12. The impact of this decision will be seen later in this section.

The missing values of the solid discharge rates using the multiple linear regression approach are given in bold type in Table H-9 and related Table H-10. In some instances, the missing values appear to compliment the actual test data, and in other instances, they appear to be out of place, in spite of the high R-squared value. Consequently, the missing values are used only as a convenience to generate plots of solid discharges as a function of truck speed and other test data. These plots are discussed at the end of this section. A majority of the discussion that follows, concentrates on the actual test results.

A number of analysis approaches, similar to those used with the ICS2000 model, were undertaken to gain some insight into the overall performance of the spreader/Control Point controller system. The approach involved computing the percent of difference between the actual (and estimated) solid and the actual prewetting discharge application rates and the dial-in application rates for the various truck speeds.

The percent of difference for the solid discharge amounts are given in Table 5-6 and also in Table H-10. The percent of difference for the solid discharge ranges from -2.7% (under application) to +12.7% (over application). The gray shaded cells in Table 5-6 and H-10 show approximately where the absolute percent of differences are greater than or equal to 8.5%. The system had difficulty in achieving the full range of dial-in application rates investigated at truck speeds of 40 and 45 mph. However, the system appears to operate best (low percent of difference) with the full range of dial-in application rates investigated at truck speeds of 20, 25, 30, and 35 mph.

Table 5-6. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	-1.0%	0.8%	**1.3%**	1.9%	**4.1%**	4.2%	**5.3%**	6.4%
25	-2.7%	**1.3%**	5.3%	**4.8%**	6.2%	6.3%	7.0%	**6.6%**
30	-2.5%	**4.8%**	5.0%	6.7%	**6 .9%**	8.5%	**7.3%**	4.5%
35	**8.4%**	6.3%	7.9%	**8.3%**	**8.3%**	7.2%	7.2%	6.8%
40	**15.4%**	11.3%	10.7%	10.5%	9.1%	**9.5%**	12.7%	**9.2%**
45	10.3%	**15.4%**	**13.0%**	10.9%	11.2%	**10.7%**	11.6%	11.8%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

The percent of difference for the prewetting discharge amounts are given in Tables 5-7 and H-12. Except for the one condition of 5 gallons/ton dial-in application rate at 35 mph, the prewetting system consistently under applied liquid to the solid material for the full range of dial-in application rates and truck speeds investigated. The percent of difference of under application for the prewetting discharge ranges from -89.5%, at its worst, to - 5.0% at its best.

Table 5-7. Percent of Difference between Actual Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	NE	-5.0%	-40.0%	-89.5%	-58.0%	-76.7%
25	-8.0%	-11.0%	-29.3%	-59.0%	-72.4%	NE
30	-18.0%	-42.0%	NE	-55.5%	-74.0%	-63.0%
35	2.0%	-44.0%	-64.0%	NE	-59.6%	-79.7%
40	-12.0%	NE	-41.3%	-52.0%	-75.6%	-83.3%
45	-12.0%	-67.0%	-66.0%	-74.5%	NE	-77.7%

Note: NE = Not estimated

During the yard tests, there was some concern by the manufacturer that the test run times were too short for some of the discharge amounts collected. The test run times for the 30 sets ranged from 90 sec. down to 12 sec. The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates are given in Table H-14 for the test set numbers. The data in Table H-14 are arrayed in descending test run time in seconds. The data show that the percent of error value found for the longest test run time (90 sec.) is -1.08%. For the shorter test run time of 60 sec., the percent of error value is -2.40%; and for the test run time of 40 sec., the percent of error values ranges from 1.85% to 10.40%. For the test run time of 15 sec., the percent of error values ranges from 4.20% to 12.72%. For the shortest test run time of 12 sec., the percent of error value is 11.83%. Thus, it appears that the percent of error values for the solid discharge may have been influenced by the shorter test run times, but there is not enough evidence to support that assumption. It appears, however, that the percent of error values for the liquid discharge were not greatly influenced by the shorter test run times. This fact is evident when looking at the percent of error values for the liquid discharges as a function of test run time in Table H-15. The large percent of error values in Table H-15 is a reflection of the inaccuracy of the prewetting component of the system.

The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates in Table H-14 are remarkably close to each other for a given set number. This means that the set solid discharge rate of the controller follows closely the theoretical solid discharge rate.

Such is not the case for the percent of error for prewetting discharge in Table H-15. The percent of error for the test prewetting discharge rate compared to the set prewetting application rate is much different, in many cases, than the corresponding percent of error for the test liquid discharge compared to the theoretical liquid discharge. This is because the test prewetting discharge rates in Table H-15 are based upon a test solid discharge amount which contains experimental error. The test prewetting discharge rate is considerably different than what would be expected from the set prewetting application rate displayed by the controller.

The data in Tables H-14 and H-15 were reordered in an attempt to better understand the limitations of the spreader/controller system to control both solid and liquid discharges. The data in Table H-14 are arrayed by increasing theoretical solid discharge values in Table H-16. Likewise, the data in Table H-15 are arrayed by increasing theoretical liquid discharge values in Table H-17.

The theoretical solid discharge and test (actual) solid discharge values in Table H-16 are plotted as a function of test set numbers in Figure H-6. The plot of the actual solid discharge contains some surprising and unexplained behavior. The two curves in Figure H-6 follow each other until they reach the conditions described by set number 26 (100 lbs/mile dial-in application rate and 45 mph truck speed). At this point, the actual discharge curve separates from the theoretical discharge curve and remains above the theoretical curve to set number 30 (right edge of Figure H-6). The position of the actual discharge curve above the theoretical discharge curve suggests this may be the result of experimental error and/or artificially enhanced actual discharge. Never-the-less, the trends of the two curves generally follow each other to set number 30 (800 lbs/mile dial-in application rate and 45 mph truck speed). The truck speed – solid (dial-in) application rate combinations for the set numbers can be easily seen in Table H-16.

The theoretical liquid discharge and test (actual) liquid discharge values are plotted as a function of the test set numbers in Figure H-7. The two curves finally separate vertically after set number 28 and remain so to the right edge of the figure. The vertical distance between the two curves for a given set number is a measure of the diminished output, or limitation of the spreader/controller system to produce the desired prewetting output. The greater the vertical separation between the theoretical liquid discharge curve and the actual liquid discharge curve for a given set number, the greater the percent of error. As before, the truck speed – liquid (dial-in) application rate combination for the set numbers can be seen from Table H-17.

Finally, a number of plots of solid and liquid discharge amounts were generated and reviewed for additional information on the capability of the spreader/controller system. These plots are presented in Figures H-8 through H-13. The ordinate values of all these plots are the percent of difference between the actual discharge and the dial-in application rate. Truck speed and dial-in application rates are used as the abscissa in the plots.

The plots in Figures H-8 through H-10 exhibit extreme variations, possibly because of the multiple linear regression results, and possibly because of the nature of the system behavior. If the system were operating perfectly, all the curves in the figures would be collapsed along the zero percent of difference for all abscissa valves. Obviously, such is not the case and, if anything, the curves have a tendency to either increase or decrease towards the high end of the abscissa values. The results in Figures H-8 through H-10 are somewhat surprising because of the high R-squared value for the regression analysis of the solid discharge values. The plots of liquid discharge amounts in Figure H-11 through H-13 show discontinuities because of difficulty in estimating the missing discharge amounts. The plots are given for information only.

5.1.4 FORCE America Models

Two controller models manufactured by FORCE America were tested in the yard study. The yard test results for the 2100 model are discussed in Section 5.1.4.1; and the yard test results for the 5100 model are discussed in Section 5.1.4.2.

5.1.4.1 FORCE America Model 2100

The yard test results for the FORCE America Model 2100 are given in Appendix I. The yard tests followed a modified form of the test protocol given in Section 3 for spreader/controller combinations used with solid material. The values of truck speed, set solid discharge rate, and test run time for each test set number used in the yard tests are given in Table I-1. The set solid discharge rates in Table I-1 are modified from the values given in Section 3 because of the controller/calibration constraints. In addition, five extra test sets were run to make up for those five test set numbers that could not be run because of system constraints, including conditions where the discharge auger would not turn. The test run times for the 21 sets of truck speed – solid application rate combinations ranged from 45 sec. down to 5 sec. Mixture of sand and salt discharge amounts were collected during each of the 126 tests.

Summary tabulation of the actual solid discharge rates are given in Tables I-2 and I-3, respectively, for various dial-in application rates and truck speeds. The data from the 21 sets of the test conditions yielded all but 28 solid discharge rate values in the two tables. Estimates of these missing discharge rate values were determined using the multiple linear regression approach described in Section 4.1.2. The regression coefficients for estimating the missing cell values are given in Table I-4.

The missing values determined using the multiple linear regression approach are given in bold type in Tables I-2 and I-3, respectively. In some instances, the missing values appear to compliment the actual test data, and in other instances, they appear to be out of place. Consequently, the missing values are used only as a convenience to generate plots of solid discharges as a function of truck speed and other test data. These plots are discussed at the end of this section. A majority of the discussion that follows concentrates on the actual test results.

A number of analysis approaches were undertaken to gain insight into the overall performance of the spreader/controller system. The first approach involved computing the percent of difference between the actual (and estimated) solid discharge application rates and the dial-in application rates for various truck speeds.

The percent of difference for the solid discharge amounts are given in Table 5-8 and also in Table I-3. The percent of difference for the solid discharge ranges from -44.4% (under application) to +43.9% (over application). The cells in the two tables, where the absolute percent of differences are greater than or equal to 8.5%, are sporadically distributed over speed and application rate combinations. The system had difficulty in achieving some of the dial-in application rates at each of the truck speeds investigated.

Table 5-8. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile								
	117.5	205.8	268.8	340.2	420.0	525.0	798.0	966.0	1008.0
20	ANT	**NE**	**-69.0%**	**-45.9%**	-28.5%	**-33.9%**	-44.4%	**-30.3%**	-32.1%
25	**NE**	**-77.6%**	-18.8%	-4.0%	**-23.3%**	-13.0%	**-30.2%**	**-23.0%**	**-6.2%**
30	ANT	0.7%	**-16.3%**	0.2%	-11.7%	-5.0%	-23.4%	**-15.7%**	12.1%
35	**NE**	-27.5%	**10.0%**	**16.5%**	**10.4%**	**6.5%**	**-12.5%**	**-8.3%**	**7.8%**
40	**NE**	-17.7%	-1.6%	-9.6%	**27.2%**	30.1%	**-3.6%**	**-1.0%**	**14.8%**
45	-15.6%	**60.0%**	**60.0%**	**58.1%**	43.9%	**33.5%**	26.5%	**6.3%**	20.0%

Note: ANT = Auger would not turn
NE = Not estimated
The numbers in bold type are computed from the actual test data using a multiple linear regression model.

During the yard tests, there was some concern by the manufacturer that the test run times were too short for some of the discharge amounts collected. The test run times for the 21 sets ranged from 45 sec. down to 5 sec. The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates are given in Table I-5 for the test set numbers. The data in Table I-5 are arrayed in descending test run time in seconds. The data show that the percent of error values found for the longest test run time of about 45 - 40 sec., ranges from -28.46% to -15.59%. For the shorter test run time of about 30 -20 sec., the percent of error values ranges from -44.44% to +0.18%; and for test run time of about 15 - 10 sec., the percent of error values ranges from -23.41% to +43.81%. For the shortest test run time of 5 sec., the percent of error was +20.00%. Thus, it appears that the percent of error values were not greatly influenced by the shorter test run times.

The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates in Table I-5 are remarkably close to each other for a given set number. This means that the set solid discharge rate of the controller follows closely the theoretical solid discharge rate.

The data in Tables I-5 were reordered in an attempt to better understand the limitations of the spreader/controller system to control solid discharges. The data in Table I-5 are arrayed by increasing theoretical solid discharge values in Table I-6.

The theoretical solid discharge and test (actual) solid discharge values in Table I-6 are plotted as function of test set numbers in Figure I-1. The two curves generally follow each other until they reach the conditions described by set number 24 (525.0 lbs/mile dial-in application rate and 30 mph truck speed). At this point, the actual discharge curve separates from the theoretical discharge curve and becomes unstable. The actual discharge curve bottoms and peaks on both side of the theoretical discharge until set number 20 (1008 lbs/mile dial-in application rate and 30 mph truck speed). At this point, the actual discharge curve stays above the theoretical discharge curve.

Finally, a number of plots of solid discharge amounts were generated and reviewed for additional information on the capability of the spreader/controller system. These plots are presented in Figures I-2 through I-4. The ordinate values of all these plots are the percent of difference between the actual discharge and the dial-in application rate. Truck speed and dial-in application rates are used as the abscissa in the plots.

The plots in Figures I-2 and I-3 exhibit a general trend from minus percent of difference values to plus percent of difference values as truck speeds increases. If the system were operating perfectly, all the curves in the figures would be collapsed along the zero percent of difference for all abscissa valves. Obviously, such is not the case and, if anything, the curves have a tendency to increase towards the high end of the abscissa values. The results in Figures I-2 and I-3 are somewhat surprising because of the relatively good R-squared value for the regression analysis of the solid discharge values. The plots are given for information only.

The data collected during the yard tests were forwarded to vendor for his information and comments. The following were the comments received:

> "It was noted that there were variations between the SSC2100 open loop controller setting and actual output. The reasons for these variations were discussed in a conference call between Ed Fleege, Steve Chlebeck, and Mike Helbig on 9/8/06. After reviewing the data, two major factors were noted. A summary of the discussion follows:
>
> Item #1: The spreader did not spread material at setting #1 at the lower ground speeds:
>
> It is likely that the auger valve MINIMUM setting was adjusted too low, creating a situation where the auger valve did not open until a sufficient driving signal was present, in this case a higher speed. This condition can be corrected by increasing the setting to a point where the auger motor will begin to turn immediately upon the output going active.
>
> Item #2: The higher set rates resulted in too much material spread:

In general, there was a trend in the data showing that the spreader applied too much material at the higher set rates and ground speeds. This was likely caused by the GSPEED adjustment being set too high. This resulted in the 2100 spreader control assuming that the vehicle was traveling faster than it actually was, and over-applied the material. By reducing this adjustment, a proper correlation between actual speed and the spreader output can be synchronized.

FORCE America is interested in seeing how accurately the open loop spreader can be calibrated. Steve Chlebeck has committed to going back to this spreader control and re-calibrating prior to the next round of testing and the vehicle going back into service. In addition, we have offered to send an engineer along during this calibration as an additional technical resource.

Open loop controllers in general:

In addition, it can be noted that there are several factors that can affect an open loop controller's accuracy. These include: Oil temperature/viscosity, Hydraulic valve spool friction, Hydraulic motor efficiency, mechanical auger efficiency, mechanical binding/worn components, and material consistency.

Some of these factors do gradually change with age, while some can occur at random or unexpectedly. Therefore, It would be difficult to determine what a typical window of accuracy would be expected for an open loop controller. With an accurate calibration of the open loop spreader at the beginning of each season, the affects of some of these factors can be minimized."

5.1.4.2 FORCE America Model 5100

The yard test results for the FORCE America Model 5100 are given in Appendix J. The yard tests followed the test protocol given in Section 3 for spreader/controller combinations used with prewetted solid material. The values of truck speed, set solid discharge rate, set prewetting application rate, and test run time for each test set number used in the yard tests are given in Table J-1. The test run times for the 30 sets of truck speed – solid application rate – liquid application rate ranged from 60 sec. down to 5 sec. Dry, solid salt and liquid calcium chloride discharge amounts were collected during each of the 180 tests.

Summary tabulations of the actual solid and liquid discharge rates are given in Tables J-2 and J-4 respectively, for various dial-in application rates and truck speeds. The data from the 30 sets of test conditions yielded all but 18 solid and 6 liquid discharge rate values in the two tables. Estimates of these missing discharge rate values were determined using the multiple linear regression approach described in Section 4.1.2. The regression coefficients for estimating the missing cell values for the FORCE America Model 5100 are given in Table J-6.

The missing values determined using the multiple linear regression approach are given in bold type in Tables J-2 and J-4 and related Tables J-3 and J-5, respectively. In some instances the missing values appear to compliment the actual test data, and in other instances, they appear to be out of place, in spite of the high to moderately high R-squared values. Consequently, the missing values are used only as a convenience to generate plots of solid and liquid discharges as a function of truck speed and other test data. These plots are discussed at the end of this section. A majority of the discussion which follows concentrates on the actual test results.

A number of analysis approaches were undertaken to gain some insight into the overall performance of the spreader/controller system. The first approach involved computing the percent of difference between the actual (and estimated) solid and prewetting discharge application rates and the dial-in application rates for various truck speeds.

The percent of difference for the solid discharge amounts are given in Table 5-9 and also in Table J-3. The solid discharge system consistently over applied material for the full range of dial-in application rates and truck speeds investigated. The percent of difference of over application for the solid discharge ranges from 3.7% to 12.4%. The gray shaded cells in Tables 5-9 and J-3 show approximately where the absolute percent of differences are greater than or equal to 8.5%. The system generally had difficulty in achieving the dial-in application rates of 400 lbs/mile and higher at speeds of 25 mph and higher. The difficulty in achieving even 200 lbs/mile is evident at 35 and 40 mph. However, the system appears to operate best (low percent of difference) with dial-in application rates of 100 through 800 lbs/mile at 20 mph, and at a dial-in application rate of 100 lbs/mile for the full range of truck speeds investigated. The system also operates well at dial-in application rates of 200 and 300 lbs/mile at truck speeds of 25 and 30 mph.

Table 5-9. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	3.7%	3.7%	**8.3%**	6.0%	**9.2%**	7.5%	**9.5%**	8.2%
25	6.0%	**7.5%**	7.2%	**9.0%**	9.3%	11.3%	9.9%	**9.7%**
30	9.4%	**7.7%**	8.2%	10.3%	**9.3%**	10.9%	**9.6%**	11.4%
35	**5.4%**	8.7%.	10.5%	**9.2%**	**9.4%**	10.2%	12.4%	11.2%
40	**5.8%**	9.3%	6.7%	8.8%	11.8%	**9.6%**	8.6%	**9.8%**
45	7.8%	**8.3%**	**9.0%**	8.8%	8.7%	**9.7%**	8.9%	7.2%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

The percent of difference for the prewetting discharge amounts are given in Tables 5-10 and J-5. The percent of difference for the prewetting discharge ranges from -61.3% (under application) to +8.0% (over application). The cells in Table 5-10 and J-5, where the absolute percent of differences are greater than or equal to 8.5%, are sporadically distributed over speed and application rate combinations. The prewetting system appears to operate best with a dial-in prewetting application rate of 5 gallons/ton at all the truck speeds investigated. The prewetting system also operates well at dial-in prewetting application rates of 10 through 25 gallons/ton at 20 mph, and at rates of 5 through 20 gallons/ton at 25, 30, and 40 mph.

Table 5-10. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial–In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**90.0%**	1.0%	-3.3%	4.0%	1.6%	-31.7%
25	-2.0%	-4.0%	-0.7%	-7.5%	-25.2%	**-23.0%**
30	-8.0%	-6.0%	**-12.7%**	-6.5%	-28.4%	0.3%
35	8.0%	-6.0%	-24.0%	**-25.5%**	-6.8%	-47.3%
40	-2.0%	**-22.0%**	-4.7%	-3.0%	-38.0%	-61.3%
45	-2.0%	-12.0%	-34.0%	-54.5%	**-38.0%**	-41.3%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

During the yard tests, there was some concern by the manufacturer that the test run times were too short for some of the discharge amounts collected. The test run times for the 30 sets ranged from 60 sec. down to 5 sec. The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates are given in Table J-7 for the test set numbers. The data in Table J-7 are arrayed in descending test run time in seconds. The data show that the percent of error values for the 30 sets of test conditions range from 3.60% to 12.30%, again indicating a tendency to consistently over apply solid material for the full range of test run times.

The data in Table J-7 show that the percent of error values found for the longest test run time (60 sec.) ranges from 3.78% to 6.34%. For shorter run times of 25 sec., the percent of error values ranges from 6.21% to 9.05%; and for the test run times of 10 sec., the percent of error values ranges from 7.34% to 11.59%. For the shortest test run time of 5 sec., the percent of error values ranges from 6.00% to 11.08%. Thus, it appears that the percent of error values for the solid discharge amounts may have been marginally influenced by the shorter test run times, but there is not enough evidence to support that assumption.

It appears, however, that the percent of error values for the liquid discharge were not greatly influenced by the shorter test run times. This fact is evident when looking at the percent of error values for the liquid discharge as a function of test run time in Table J-8.

The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates in Table J-7 are remarkably close to each other for a given set number. This means that the set solid discharge rate of the controller follows closely the theoretical solid discharge rate.

Such is not the case for the percent of error for prewetting discharges in Table J-8. The percent of error for the test prewetting discharge rate compared to the set prewetting application rate is much different, in many cases, than the corresponding percent of error for the test liquid discharge compared to the theoretical liquid discharge. This is because the test prewetting discharge rates in Table J-8 are based upon a test solid discharge amount which contains experimental error. The test prewetting discharge rate is considerably different than what would be expected from the set prewetting application rate displayed by the controller.

The data in Tables J-7 and J-8 were reordered in an attempt to better understand the limitations of the spreader/controller system to control both solid and liquid discharges. The data in Table J-7 are arrayed by increasing theoretical solid discharge values in Table J-9. Likewise, the data in Table J-8 are arrayed by increasing theoretical liquid discharge values in Table J-10.

The theoretical solid discharge and test (actual) solid discharge values in Table J-9 are plotted as a function of the test set numbers in Figure J-1. The plot of the actual discharge contains some surprising and unexplained behavior. The two curves in Figure J-1 follow each other until they reach the conditions described by set number 2 (200 lbs/mile dial-in application rate and 20 mph truck speed). At this point, the actual discharge curve separates from the theoretical discharge curve and remains above the theoretical curve to set number 30 (right edge of Figure J-1). The position of the actual discharge curve above the theoretical discharge curve suggests experimental error and/or artificially enhanced actual discharge. Never-the-less, the trends of the two curves generally follow each other to set number 30 (800 lbs/mile dial-in application rate and 45 mph truck speed). The truck speed – solid (dial-in) application rate combinations for the set numbers can be easily seen in Table J-9.

The theoretical liquid discharge and test (actual) liquid discharge values in Table J-10 are plotted as a function of the test set numbers in Figure J-2. The two curves essentially separate vertically after set number 17 and remain so to the right edge of the figure. The vertical distance between the two curves for a given set number is a measure of the diminished output, or limitation of the spreader/controller system to produce the desired prewetting output. The greater the vertical separation between the theoretical liquid discharge curve and the actual liquid discharge curve for a given set number, the greater the percent of error. As before, the truck speed – liquid (dial-in) application rate combinations for the set numbers can be seen from Table J-10.

Finally, a number of plots of solid and liquid discharge amounts were generated and reviewed for additional information on the capability of the spreader/controller system. These plots are presented in Figures J-3 through J-8. The ordinate values of all these plots are the percent of difference between the actual discharge and the dial-in application rate. Truck speed and dial-in application rates are used as the abscissa in the plots.

The plots in Figures J-3 through J-8 exhibit extreme variations, possibly because of the multiple linear regression results, and possibly because of the nature of the system behavior. If the system were operating perfectly, all the curves in the figures would be collapsed along the zero percent of difference for all abscissa valves. Obviously, such is not the case and, if anything, the curves have a tendency to either increase or decrease towards the high end of the abscissa values. These results are somewhat surprising because of the high to moderately high R-squared values for the regression analysis. The plots are given for information only.

5.1.5 Muncie Power Products MESP402D

The yard test results for the Muncie Power MESP402D are given in Appendix K. The yard tests followed the test protocol given in Section 3 for spreader/controller combinations used with prewetted solid material. The values of truck speed, set solid discharge rate, set prewetting application rate, and test run time for each test set number used in the yard tests are given in

Table K-1. The set solid discharge rates in Table K-1 are modified from the values given in Section 3 because of the controller/calibration constraints. The test run times for the 30 sets of truck speed – solid application rate – liquid application rate combinations ranged from 105 sec. down to 12.09 sec. Dry, solid salt and salt brine discharge amounts were collected during each of the 180 tests.

Summary tabulations of the actual solid and liquid discharge rates are given in Tables K-2 and K-4, respectively, for various dial-in application rates and truck speeds. The data from the 30 sets of test conditions yielded all but 18 solid and 6 liquid discharge rate values in the two tables. Estimates of these missing discharge rate values were determined using the multiple linear regression approach described in Section 4.1.2. The regression coefficients for estimating the missing cell values for the MESP402D model are given in Table K-6.

The missing values determined using the multiple linear regression approach are given in bold type in Tables K-2 and K-4 and related Tables K-3 and K-5, respectively. In some instances the missing values appear to compliment the actual test data, and in other instances, they appear to be out of place, in spite of the moderately high R-squared values. Consequently, the missing values are used only as a convenience to generate plots of solid and liquid discharges as a function of truck speed and other test data. These plots are discussed at the end of this section. A majority of the discussion that follows concentrates on the actual test results.

A number of analysis approaches were undertaken to gain some insight into the overall performance of the spreader/controller system. The first approach involved computing the percent of difference between the actual (and estimated) solid and prewetting discharge application rates and the dial-in application rates for various truck speeds.

The percent of difference for the solid discharge amounts are given in Table 5-11 and also in Table K-3. The percent of difference for the solid discharge ranges from -31.5% (under application) to +54.6% (over application). The gray shaded cells in Tables 5-11 and K-3 show approximately where the absolute percent of differences are greater than or equal to 8.5%. The system generally had difficulty in achieving the full range of dial-in solid application rates investigated at truck speeds of 30 mph and higher. The system also had difficulty in achieving the dial-in solid application rates of 107 and 215 lbs/miles at 20 mph. However, the system appears to operate best (low percent of differences) with dial-in solid application rates greater than 215 lbs/mile at 20 mph and the full range of solid application rates investigated at 25 mph.

Table 5-11. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	107	215	322	429	537	644	751	858
20	-23.1%	-13.2%	**1.8%**	-4.7%	**-8.8%**	-1.6%	**-13.4%**	-6.8%
25	-3.5%	**17.9%**	-5.9%	**-3.4%**	-4.2%	-6.3%	-6.6%	**-14.1%**
30	-24.1%	**20.7%**	-11.5%	-8.9%	**-6.6%**	-13.2%	**-11.8%**	-15.3%
35	**72.3%**	-9.1%	54.6%	**-0.6%**	**-5.4%**	10.0%	-12.0%	-14.2%
40	**78.0%**	53.8%	48.0%	47.9%	2.5%	**-7.7%**	-14.2%	**-12.0%**
45	46.5%	29.2%	11.2%	30.8%	-6.9%	**-6.8%**	-31.5%	**-37.9%**

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

The percent of difference for the prewetting discharge amounts are given in Tables 5-12 and K-5. The prewetting system consistently under applied liquid to the solid material for the full range of dial-in liquid application rates and truck speeds investigated. The percent of difference of under application for the prewetting discharge ranges from -65.0%, at its worst to -32.0%, at its best.

Table 5-12. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed

Speed in mph	Dial–In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**8.0%**	-38.0%	-38.0%	-38.5%	-36.4%	-41.7%
25	-38.0%	-35.0%	-36.7%	-36.5%	-38.8%	**-44.7%**
30	-36.0%	-38.0%	**-40.0%**	-35.0%	-38.4%	-32.0%
35	-42.0%	-37.0%	-40.7%	**-46.0%**	-41.2%	-63.3%
40	-38.0%	**-44.0%**	-41.3%	-39.0%	-50.0%	-65.0%
45	-36.0%	-37.0%	-40.7%	-46.0%	**-51.6%**	-62.3%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

During the yard tests, there was some concern by the manufacturer that the test run times were too short for some of the discharge amounts collected. The test run times for the 30 sets ranged from 105 sec. down to about 12 sec. The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates are given in Table K-7 for the test set numbers. The data in Table K-7 are arrayed in descending test run time in seconds. The data show hat the percent of error value found for the longest test run time (105 sec.) is -22.56%. For the shorter test run time of about 30 sec., the percent of error values range from -11.48% to -4.18%; and for test run times of about 15 sec., the percent of error values range from -15.30% to 53.83%. For the shortest test run time of about 12 sec., the percent of error value is -38.0%. Thus, it appears that the percent of error values were not greatly influenced by the shorter test run times. This fact is more evident when looking at the percent of error values for the liquid discharges as a function of test run time in Table K-8.

The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates in Table K-7 are remarkably close to each other for a given set number. This means that the set solid discharge rate of the controller follows closely the theoretical solid discharge rate.

Such is not the case for the percent of error for prewetting discharges in Table K-8. The percent of error for the test prewetting discharge rate compared to the set prewetting application rate is much different, in many cases, than the corresponding percent of error for the test liquid discharge compared to the theoretical liquid discharge. This is because the test prewetting discharge rates in Table K-8 are based upon a test solid discharge amount which contains experimental error. The test prewetting discharge rate is considerably different than what would be expected from the set prewetting application rate displayed by the controller.

The data in Tables K-7 and K-8 were reordered in an attempt to better understand the limitations of the spreader/controller system to control both solid and liquid discharges. The data in Table K-7 are arrayed by increasing theoretical solid discharge values in Table K-9. Likewise, the data in Table K-8 are arrayed by increasing theoretical liquid discharge values in Table K-10.

The theoretical solid discharge and test (actual) solid discharge values in Table K-9 are plotted as a function of test set numbers in Figure K-1. The plot of actual solid discharge contains some surprising and unexplained oscillations. The peaks of the oscillations rise above the theoretical solid discharge curve which suggests experimental error. Never-the-less, the trend of the two curves generally follow each other until they reach the conditions described by set number 28 (537 lbs/mile dial-in application rate and 45mph truck speed). Just before this point, the actual discharge curve separates from the theoretical discharge curve and remains below the theoretical curve to set number 30. The vertical distance between the two curves for a given set number is a measure of the diminished output, or limitation of the spreader/controller system to produce the desired output. The conditions represented by set number 28, 15, 19, 20, 25, 29, and 30 describe where the system has reached it's output capacity and is unable to produce the output specified by the controller. The truck speed – solid (dial-in) application rate combinations for these set numbers can be easily seen from Table K-9. These conditions are the higher dial-in application rates from the various truck speeds.

The theoretical liquid discharge and test (actual) liquid discharge values are plotted as a function of the test set numbers in Figure K-2. The two curves essentially separate vertically after set number 17 and remain so to the right edge of the figure. The greater the vertical separation between the theoretical liquid discharge curve and the actual liquid discharge curve for a given set number, the greater the percent of error. As before the truck speed – liquid (dial-in) application rate combination for the set numbers can be seen from Table K-10.

Finally, a number of plots of solid and liquid discharge amounts were generated and reviewed for additional information on the capability of the spreader/controller system. These plots are presented in Figures K-3 through K-8. The ordinate values of all these plots are the percent of difference between the actual discharge and the dial-in application rate. Truck speed and dial-in application rates are used as the abscissa in the plots.

The plots in Figures K-3 through K-8 exhibit extreme variations, possibly because of the multiple linear regression results, and possibly because of the nature of the system behavior. If the system were operating perfectly, all the curves in the figures would be collapsed along the zero percent of difference for all abscissa valves. Obviously, such is not the case and, if anything, the curves have a tendency to either increase or decrease towards the high end of the abscissa values. These results are somewhat surprising because of the moderately high R-squared values for the regression analysis. The plots are given for information only.

5.1.6 Pengwyn Model 485

The yard test results for the Pengwyn Model 485 are given in Appendix L. The yard tests followed the test protocol given in Section 3 for spreader/controller combinations used with prewetted solid material. The values of truck speed, set solid discharge rate, set prewetting application rate, and test run time for each test set number used in the yard tests are given in Table L-1. The test run times for the 30 sets of truck speed – solid application rate – liquid application rate combinations ranged from 90.3 sec. down to 12.1 sec.. Dry, solid salt and salt brine discharge amounts were collected during each of the 180 tests.

Summary tabulation of the actual solid and liquid discharge rates are given in Tables L-2 and L-4, respectively, for various dial-in application rates and truck speeds. The data from the 30 sets of the test conditions yielded all but 18 solid and 6 liquid discharge rate values in the two tables. Estimates of these missing discharge rate values were determined using the multiple linear regression approach described in Section 4.1.2. The regression coefficients for estimating the missing cell values for the Pengwyn Model 485 are given in Table L-6.

The missing values determined using the multiple linear regression approach are given in bold type in Tables L-2 and L-4 and related Tables L-3 and L-5, respectively. In some instances, the missing values appear to compliment the actual test data, and in other instances, they appear to be out of place. Consequently, the missing values are used only as a convenience to generate plots of solid and liquid discharges as a function of truck speed and other test data. These plots are discussed at the end of this section. A majority of the discussion that follows concentrates on the actual test results.

A number of analysis approaches were undertaken to gain insight into the overall performance of the spreader/controller system. The first approach involved computing the percent of difference between the actual (and estimated) solid and prewetting discharge application rates and the dial-in application rates for various truck speeds.

The percent of difference for the solid discharge amounts are given in Table 5-13 and also in Table L-3. The percent of difference for the solid discharge ranges from -38.0% (under application) to 12.2% (over application). The cells in the two tables, where the absolute percent of differences are greater than or equal to 8.5%, are sporadically distributed over speed and application rate combinations. The system had difficulty in achieving some of the dial-in application rates at each of the truck speeds investigated, However, the system appears to operate best (low percent of differences) with dial-in application rates of 200 lbs/mile and higher at truck speeds of 30 and 35 mph.

Table 5-13. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	-7.0%	-3.2%	**-13.0%**	-22.9%	**-8.9%**	-18.0%	**-7.2%**	-14.7%
25	-25.0%	**-12.8%**	-15.9%	**-7.8%**	-5.3%	0.5%	9.6%	**-5.3%**
30	-38.0%	**-7.5%**	-5.4%	-6.3%	**-4.7%**	-6.7%	**-4.1%**	-6.6%
35	**-1.5%**	-6.9%	3.4%	**-2.5%**	**-2.5%**	8.5%	6.9%	-2.8%
40	**9.1%**	-13.1%	-5.3%	-3.4%	8.9%	**-0.8%**	-0.4%	**-1.3%**
45	-4.3%	**8.5%**	**4.7%**	12.2%	8.1%	**1.0%**	-1.8%	-12.6%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

The percent of difference for the prewetting discharge amounts are given in Tables 5-14 and L-5. The percent of difference for the prewetting discharge ranges from – 50.3% (under application) to 202.0% (over application). Only one cell in the two tables could be found where the absolute percent of difference is as low as 8.5%. All other cells had larger absolute percent of difference values, meaning that the prewetting system had extreme difficulty in accurately controlling the prewetting application rate in the range investigated.

Table 5-14. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**236.0%**	82.0%	9.3%	202.0%	15.2%	-33.0%
25	46.0%	78.0%	106.7%	-15.5%	-43.2%	**0.3%**
30	34.0%	-12.0%	**16.7%**	-8.5%	-39.2%	102.0%
35	76.0%	-22.0%	-38.7%	**-11.0%**	-27.6%	-42.7%
40	44.0%	**-16.0%**	-9.3%	19.5%	-47.6%	-50.3%
45	-10.0%	33.0%	-40.0%	-39.0%	**-39.2%**	-47.3%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

During the yard tests, there was some concern by the manufacturer that the test run times were too short for some of the discharge amounts collected. The test run times for the 30 sets range from 90.3 sec. down to 12.1 sec. The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates are given in Table L-7 for the test set numbers. The data in Table L-7 are arrayed in descending test run time in seconds. The data show that the percent of error values found for the longest test run time of about 90 sec. range from -24.93% to +7.01%. For the shorter test run time of about 30 sec., the percent of error values range from -15.79% to -5.32%; and for test run time of about 15 sec., the percent of error values range from -7.02% to +12.06%. For the shortest test run time of about 12 sec., the percent of error ranges from -12.98% to -2.24%. Thus, it appears that the percent of error values were not greatly influenced by the shorter test run times. This fact is more evident when looking at the percent of error values for the liquid discharges as a function of test run time in Table L-8.

The percent of error for the test solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates in Table L-7 are remarkably close to each other for a given set number. This means that the set solid discharge rate of the controller follows closely the theoretical solid discharge rate.

Such is not the case for the percent of error for prewetting discharges in Table L-8. The percent of error for the test prewetting discharge rate compared to the set prewetting application rate is much different, in almost all cases, than the corresponding percent of error for the test liquid discharge compared to the theoretical liquid discharge. This is because the test prewetting discharge rates in Table L-8 are based upon a test solid discharge amount which contains experimental error. The test prewetting discharge rate is considerably different than what would be expected from the set prewetting application rate displayed by the controller.

The data in Tables L-7 and L-8 were reordered in an attempt to better understand the limitations of the spreader/controller system to control both solid and liquid discharges. The data in Table L-7 are arrayed by increasing theoretical solid discharge values in Table L-9. Likewise, the data in Table L-8 are arrayed by increasing theoretical liquid discharge values in Table L-10.

The theoretical solid discharge and test (actual) solid discharge values in Table L-9 are plotted as a function of test set numbers in Figure L-1. The two curves generally follow each other until they reach the conditions described by set number 29 (700 lbs/mile dial-in application rate and 45 mph truck speed). At this point, the actual discharge curve separates from the theoretical discharge curve and remains below the theoretical curve to set number 30 (800 lbs/mile dial-in application rate and 45 mph). After set number 29, the system has reached its output capacity and is unable to produce the output specified by the controller.

The theoretical liquid discharge and test (actual) liquid discharge values in Table L-10 are plotted as a function of the test set numbers in Figure L-2. The two curves essentially separate vertically after set number 21 and remain so to the right edge of the figure. The greater the vertical separation between the theoretical liquid discharge curve and the actual liquid discharge curve for a given set number, the greater the percent of error. As before, the truck speed – liquid (dial-in) application rate combination for the set numbers can be seen from Table L-10.

Finally, a number of plots of solid and liquid discharge amounts were generated and reviewed for additional information on the capability of the spreader/controller system. These plots are presented in Figures L-3 through L-8. The ordinate values of all these plots are the percent of difference between the actual discharge and the dial-in application rate. Truck speed and dial-in application rates are used as the abscissa in the plots.

The plots in Figures L-3 through L-8 exhibit extreme variations, possibly because of the multiple linear regression results, and possibly because of the nature of the system behavior. If the system were operating perfectly, all the curves in the figures would be collapsed along the zero percent of difference for all abscissa valves. Obviously, such is not the case and, if anything, the curves have a tendency to either increase or decrease towards the high end of the abscissa values. The results in Figures L-3 through L-5 are somewhat surprising because of the high R-squared value for the regression analysis of the solid discharge values. The plots are given for information only.

5.2 Statistical Analysis Results for Spreader/Controllers Tested

Eight ground-speed controllers were evaluated during the yard study. Dry, solid materials were collected from all eight spreader/controller systems during the yard tests. Prewetting discharge data were collected from seven of the eight spreader/controller systems during the tests. However, prewetting discharge data from only five of the seven spreader/controllers systems were suitable for statistical analysis. Understanding the performance of these systems was primarily assessed by the bias, accuracy, and precision calculations that follow. These assessments were augmented by the results of an Analysis of Variance (ANOVA).

5.2.1. Bias, Accuracy, and Precision of Dry, Solid Material Controllers

Bias, accuracy, and precision of each of the eight solid material spreader/controller systems was calculated from the yard tests sets of data. Bias was simply calculated as the average difference between the collected test solid discharge rate and the nominal (set) solid discharge rate for each of the tests for a particular controller:

$$\text{Bias} = \text{Average}\ (TR - NR)$$

where

TR = collected test discharge rate,

and

NR = nominal discharge rate.

A bias close to zero would indicate the controller does a good job, on the average, of approximating the nominal, or set, solid discharge rate. A negative bias would indicate that the controller typically distributes less material than it should, where a positive bias would indicate that the controller typically distributes more than it should.

For each test, the difference between the collected test solid discharge rate and the nominal solid discharge rate was calculated (as in the bias calculation). As a proportion of the nominal solid discharge rate, this difference can be thought of as the percent “missed” in each test. One minus this percent is the “accuracy” percent for each test. Accuracy for a particular controller then was calculated as an average across all tests as follows:

$$\text{Accuracy} = \text{Average}\ (100*(1 - (TR - NR)/NR))$$

Accuracy is represented here as a percent. Accuracy close to 100% means that a controller would typically distribute material close to the nominal solid discharge rate.

In addition to the accuracy calculation, it is good to have a measure of how consistent measurements are with each other. In order to do this, the relative standard deviation of each of the differences was calculated in order to estimate precision. Like accuracy, precision was calculated as a percentage as follows:

Precision = 100* standard deviation (TR – NR)/accuracy

Precision close to 0% is desired. In other words, the more precise a controller is, the lower its standard deviation and the lower this precision calculation.

A summary is given in Table 5-15 of the bias, accuracy, and precision of each of the eight spreader/controller systems when it comes to distribution solid material.

Table 5-15. Summary of Bias, Accuracy, and Precision of Eight Spreader/Controller Systems in Distributing Solid Material

Controller Manufacturer and Model	Bias (lbs/mile)	Accuracy	Precision
Cirus SpreadSmart RDS	-92.9	84.2%	20.8%
Component Technology GL-400	11.9	90.7%	7.6%
Dickey-john ICS2000	-3.5	93.0%	8.0%
Dickey-john Control Point	34.3	92.9%	4.1%
FORCE America 2100	121.4	64.7%	44.5%
FORCE America 5100	42.5	91.2%	3.6%
Muncie Power MESP402D	-20.7	80.7%	20.8%
Pengwyn 485	-16.7	90.0%	9.0%

It can be seen from Table 5-15, that five of the spreader/controller systems distributing dry solid material have at least 90% accuracy, with excellent precision. Another two spreader/controller systems have at least 80% accuracy, and one spreader/controller has less than 70% accuracy.

5.2.2 Bias, Accuracy, and Precision of Prewetting Controllers

As stated earlier in this section, one of the eight spreader/controller systems evaluated during the yard tests did not have prewetting capability. In addition, it was not possible to perform a statistical analysis of the prewetting discharge data from two of the other seven systems because of either insufficient liquid discharge data or the liquid discharge data was too erratic to make a performance assessment.

The bias, accuracy, and precision estimations of the eight spreader/controller systems in distributing prewetted material are given in Table 5-16. Calculations were exactly the same as for dry solid materials, except in units of liquid materials - specifically gals/ton.

Table 5-16. Summary of Bias, Accuracy, and Precision of Eight Spreader/Controller Systems in Distributing Prewetting Material

Controller Manufacturer and Model	Bias (gallons/ton)	Accuracy	Precision
Cirus SpreadSmart RDS	-2.6	77.8%	29.4%
Component Technology GL-400	-1.6	85.3%	17.3%
Dickey-john ICS2000	*	*	*
Dickey-john Control Point	**	**	**
FORCE America 2100	N/A	N/A	N/A
FORCE America 5100	-3.6	82.2%	22.0%
Muncie Power MESP402D	-7.6	58.9%	15.5%
Pengwyn 485	0.1	54.2%	72.1%

Note: N/A = Prewetting not available with this controller

*** =** Insufficient data to made determination

****** = Data too erratic to made determination

It can be seen from Table 5-16, that of the five spreader/controller systems whose liquid discharge data could be analyzed, only two units have at least 80% accuracy. One other spreader/controller system has at least 70% accuracy, and two other systems have less than 60% accuracy. These figures demonstrate the difficulty the spreader/controller systems tested in the yard study had in controlling the prewetting discharge amounts.

5.2.3 ANOVA Results for Solid and Prewetting Material Controllers

An Analysis of Variance (ANOVA) was the statistical technique used to determine the effect that different spreader/controller system variables had, or did not have, on the accuracy of the test data. Three variables (covariates) were examined for spreader/controller systems that distribute solid material. These were truck **speed** (mph), test run **time** (seconds), and nominal **solid** discharge rate (lbs/mile). Four covariates were examined for spreader/controller systems that distribute prewetted material. These were truck **speed** (mph), test run **time** (seconds), nominal **solid** discharge rate (lbs/mile), and nominal prewetting **liquid** discharge rate (gallons/ton).

Essentially, the ANOVA is a series of hypothesis tests that each of the covariates (and their combinations) has no effect on differences between the actual discharge rate and the set discharge rate. If a variable is significant, it has an effect on the difference more than just chance. So suppose speed is significant and the magnitude of the differences increase as speed increases. Then one would expect that as speed increases, the controller does a poorer job at actually hitting the set discharge rate.

If a controller worked perfectly, then there would be no effect on any of the covariates. All the differences found would be the results of random chance. Consequently, it would be preferred that none of the covariates, or their combinations, would be significant.

The variables and interactions (combinations) found significant for the spreader/controller systems distributing solid material are identified with a "S" in Table 5-17. Likewise, the variables and interactions found significant for the spreader/controller systems distributing prewetted material are marked with a "S" in Table 5-18. It can be seen from Table 5-17 that only one of the eight spreader/controller systems had none of the three variables as significant when it came to distributing solid material. When it came to distributing prewetted material, all of the five systems had at least two variables that were significant.

Table 5-17. Variables and Interactions Found Significant of Eight Spreader Systems in Distributing Solid Material

Controller Manufacturer and Model	Significant Effects			
	Speed	Time	Solid	Interactions
Cirus SpreadSmart RDS	**S**		**S**	Speed - Solid
Component Technology GL-400	**S**		**S**	Speed - Solid
Dickey-john ICS2000	**S**		**S**	
Dickey-john Control Point	**S**		**S**	
FORCE America 2100	**S**		**S**	
FORCE America 5100				
Muncie Power MESP402D	**S**		**S**	Speed – Time & Time - Solid
Pengwyn 485	**S**		**S**	Speed – Solid & Time - Solid

Note: **S** = Significant

Table 5-18. Variables Found Significant for Eight Spreader/Controller Systems in Distributing Prewetted Material

Controller Manufacturer and Model	Significant Effects			
	Speed	Time	Solid	Liquid
Cirus SpreadSmart RDS	**S**		**S**	**S**
Component Technology GL-400	**S**	**S**	**S**	**S**
Dickey-john ICS2000	**N/E**	**N/E**	**N/E**	**N/E**
Dickey-john Control Point	**N/E**	**N/E**	**N/E**	**N/E**
FORCE America 2100	**N/A**	**N/A**	**N/A**	**N/A**
FORCE America 5100	**S**		**S**	**S**
Muncie Power MESP402D	**S**			**S**
Pengwyn 485		**S**		**S**

Note: **S** = Significant
N/E = Not evaluated
N/A = Prewetting not available with this controller

SECTION 6
SUMMARY OF YARD TEST FINDINGS AND RECOMMENDED DIRECTION OF PHASE 3-FIELD STUDY

A summary is given below in Section 6.1 of all the yard test findings discussed in the pervious section. No attempt is made to compare the advantages or disadvantages of one system to those of other systems. The recommended direction of Phase 3 – Field Study is given in Section 6.2.

6.1 Summary of Yard Test Findings

Yard tests were conducted on spreader/controller combinations in the maintenance yards of participating Clear Roads states. These tests were performed using selected new or nearly new spreader/controller combinations. All of the eight controllers investigated were ground-speed-control units. No manual control units were investigated during the yard study.

Experimental designs for the yard tests were developed to efficiently and effectively conduct the tests of the spreader/controller combinations. These designs also aided in the analysis of the test data. Separate designs were developed for spreader/controller systems that distribute only dry solid material and for those that distribute solid material prewetted with a liquid chemical.

A full factorial experimental design was considered impractical considering the number of variables (solid material type, liquid material type, solid application rates, liquid application rates, and truck speeds) to be considered, as well as the number of test replications needed. Two types of solid materials were investigated: dry solid salt and a 5/95 mixture of salt and sand. Two types of liquid materials were investigated: salt brine and liquid calcium chloride. The dry solid salt application rates ranged from about 100 lbs/mile to about 800 lbs/mile: the 5/95 mixture application rates ranged from about 100 lbs/mile to about 1000 lbs/mile. The liquid application rates investigated ranged from 5 gals/ton to 30 gals/ton. The range of truck speeds investigated was 20 to 45 mph.

To simplify the amount of testing required, a fractional factorial design was developed for each of the two material type distributors. A total of 126 tests were developed for each solid material controller/spreader combination. This total included 21 combinations of truck speed – solid application rate and six replication tests for each combination of test variables. A total of 180 tests were developed for each controller/spreader combination used with prewetted solid material. This total included 30 combinations of truck speed – solid application rate – liquid application rate and six replication tests for each combination.

Prior to the yard tests, simple procedures were developed to estimate the solid and liquid theoretical discharge amounts expected from the spreader/controller combinations. These theoretical discharge estimates proved highly useful in assessing the discharge capability of the spreader/controller combinations.

None of the eight spreader/controller systems tested were able to distribute solid material with 100% accuracy over the application rate – truck speed range investigated. However, five of the eight units could distribute solid material with at least 90% accuracy, with excellent precision. Several of the systems in the 90% accuracy range were able to control the material distribution over a wide range of application rates, but for a limit value or range of truck speeds. Other systems in the 90% accuracy range were able only to satisfactorily control the material distribution over the lower range of application rates (100 to 400 lbs/mile), but for a wide range of truck speeds (20 to 40 mph).

Two spreader/controller systems could distribute solid material with at least 80% accuracy, but with much less precision than the five just referenced. Here, the accuracy was confined to either a wide range of application rates at a single truck speed or over the lower range of application rates (100 to 400 lbs/mile) for a wide range of truck speeds (20 to 40 mph).

Finally, one spreader/controller system distributed solid material with less than 70% accuracy and less than desirable precision. This system appeared to work well at only a few discrete combinations at application rate and truck speed.

An investigation was made to determine if the test run times were too short for some of the solid discharge amounts collected during the yard tests. The minimum test run times ranged from 20 sec. down to 5 sec. The percent of error values for the solid discharge compared to both the theoretical solid discharge and dial-in solid discharge rates for four of the eight spreader/controller systems were not greatly influenced by the shorter test run times. The percent of error values for the other four systems may have been influenced by the shorter test run times, but there is not enough evidence to support that assumption.

Comparisons were made of the test (actual) solid discharge with the theoretical solid discharge for a given application rate – truck speed condition. These comparisons revealed insight into the limitations of the output capacity of the spreader/controller systems. Some systems did not reach their output capacity until the high end of the application rate – truck speed combination conditions. Other systems reached their output capacity at much lower application rate – truck speed conditions. It appears that, for some systems, the controller's capacity to manage the solid discharge is limited by the capacity of the truck-spreader system.

Liquid discharge data was collected from seven of the eight spreader/controller systems tested. Liquid discharge data from two of the seven systems was either insufficient or too erratic for analysis. Of the five spreader/controller systems whose prewetting data could be analyzed, only two units were able to discharge liquid material with at least 80% accuracy. One other spreader/controller system discharged liquid material with at least 70% accuracy; and two other systems discharged liquid material with less than 60% accuracy. These figures demonstrate the difficulty the spreader/controller systems had in accurately controlling the prewetting discharge amounts.

No consistent areas of liquid application rate – truck speed combinations were found where the prewetting performance was satisfactory. Some systems exhibited very erratic liquid discharge behavior over the entire range of variables investigated. Other systems were able to control the prewetting rate satisfactorily, but over a limited range of conditions. Generally, better control was found at 5 and 10 gals/ton application rates for truck speeds, that sometimes spanned the full range of speeds investigated, and sometimes for limited values of truck speed.

The percent of error values for the test liquid discharge compared to the theoretical liquid discharge was not greatly influenced by the shorter test run times. The actual (test) prewetting discharge rates were found to be considerably different than what would be expected from the set prewetting application rate of the controller.

Finally, very little difference, if any, was found between the actual liquid discharge using salt brine and liquid calcium chloride. This finding came from limited yard tests of a single spreader/controller combination.

The yard tests gave the research team an opportunity to learn about the capabilities and limitations of the spreader/controller units and what was possible and not possible to do with the equipment during winter-time conditions. The local field maintenance personnel involved with the yards were also helpful in identifying concerns about the material handling aspects of the spreader/controller units during winter maintenance operations. These equipment capabilities, limitations, and material handling aspects guided the recommend direction of the field study described in the next section.

6.2 Recommended Direction of Phase 3-Field Study

The objectives of Phase 3 were to develop and to evaluate testing procedures that can be used by highway agencies to validate actual material usages in the field during winter-time conditions. In the development of the approach to be used for Phase 3, two methods were proposed for documenting actual material usage during winter storm events. These two methods were: 1) weighing the spreader truck both before and after spreading operations, and 2) measuring the number of spreader motor drive shaft revolutions experienced during spreading operations and combining this information with data collected during the yard test study. A third method emerged as the Phase 2 study drew to completion. The third method for determining material usage was based on weighing the spreader truck both before and after simulated spreading operations in the maintenance yard. A brief summary of each method is presented below along with the extra equipment needed to conduct the tests and the advantages and disadvantages of the methods.

Field Test Method No. 1:

Weigh spreader truck both and before and after spreading operations.

Brief Description of Test Protocol:

A designated calibrated spreader truck would be fully loaded with snow and ice control material. The fully loaded truck would then be weighed. The operator would be asked to record specific information on a specially designed truck operator form. The truck would then be dispatched on a specified maintenance operation run. Upon completion of the run(s), the truck would return to the reloading station where it would be hosed down to remove the slush, snow, and ice that accumulated on the side, back, and underbody of the truck.

Maine Department of Transportation (MDOT) reported (7) that 1,275 pounds of slush, snow, and ice accumulated on a truck during snow and ice control operations. It is likely that this extra weight is not a constant but depends on many uncontrollable factors, such ambient temperature, moisture contents of precipitation, roadway conditions, and maintenance operations.

The "cleaned" truck would then be weighed and additional data recorded by the operator. The truck could then be reloaded with material to start another cycle of operations and data collection, after reweighing. These cycles would continue for selected winter weather storm events during the winter.

Special Equipment Needed:

The only special equipment needed would be a truck scale. Access to the scale would be needed during winter maintenance operations throughout the winter.

Advantages:

- Relatively simple test method.
- Only special equipment needed is a truck scale.

Disadvantages

- Truck operator would need to record data on special forms during winter maintenance operations.
- Cleaning of truck to remove accumulated slush, snow, and ice increases the treatment cycle time.
- Uncertainly as to the completeness of the removal of accumulated slush, snow, and ice.
- Spreader truck would need to be weighed both after loading and cleaning which also increases the treatment cycle time.
- Truck weigh scales would need to be available throughout winter and particularly, throughout winter storm events.
- Difficult to explain material discharge differences because of non-repeatable experimental conditions.
- The quality of hand recorded winter maintenance field date is always a problem because of competing demands placed on truck operator's time.
- There are no opportunities to observe when and for how long "tunneling" of material occurs during field operations.
- It was noted there are some field supervisors that indicated a refusal to participate in the field study during winter storm events due to shortage of personal.

Field Test Method No. 2:

Use measurements of spreader motor drive shaft revolutions plus spreading distance traveled and data collected during the yard test study.

Brief Description of Test Protocol:

An alternative to the above field test Method No. 1 was considered. The alternative method was predicated on using strikers affixed to the spreader motor drive shafts along with appropriately mounted mechanical counters in weatherproofing enclosures. This special equipment would be used to record the number of spreader motor drive shaft revolutions experienced during spreading operations. These data would be combined with the spreading distance traveled and data collected during the yard test study. The operator would be required to record specific operational information on a specially designed truck operator form before and after spreader operations along with the spreading distance traveled. The length of the route (s) would need to be verified by measuring the distance with a suitable procedure.

During the yard study, it was discovered that four of the eight truck-controller combinations did not have an exposed drive shaft end that could be used for revolution measurements. However, most, if not all the closed-loop controllers, keep track of the number of revolutions experienced during spreading operations. Thus, the specialized striker/mechanical counters are not necessary to capture the revolution data.

The controllers compute the amount of material discharged during maintenance operations by using a calibration constant and a revolutions count recorded to the nearest whole number. The accuracy of the controller to keep track of the amount of material dispensed during a prolonged run was not verified during the yard test study. There is no evidence to suspect any controller inaccuracies when it comes to keeping track of the number of revolutions made during maintenance operations. However the actual amount of material discharged still needed to be verified following the before and after weighing procedure identified for Method No. 1.

Special Equipment Needed:

The main special equipment needed would be a truck scale. Access to the scale would be needed during winter maintenance operations for selected storm events until the accuracy of the controller to determine total material weight distributed was determined. The length of the route (s) would also need to be verified by measuring the distance with a suitable procedure.

Advantages:

- Relatively simple test method.
- A truck scale would be needed for part of the winter.

Disadvantages:

- The same disadvantages exist for Method No. 2 as for Method No. 1 with the exception that truck weighing possibly would not have to be done for the entire winter testing. However, there is the chance that truck weighing would need to continue throughout the winter if the controller could not accurately record the true material weight distributed.

- There are a number of spreaders that were yard tested where it was not possible to affix counters to the spreader shafts.

Field Test Method No. 3:

Weigh spreader truck both before and after simulated spreading operations conducted in a stationary mode in the maintenance yard.

Brief Description of Test Protocol:

The tests for Method No.3 would be conducted at a time when there would be no winter maintenance operations in progress. Thus, the tests could be “worked in” during a down-time and concentrated in two test periods during the winter-time.

A designated, calibrated spreader truck would be fully loaded with solid and liquid snow and ice control material. The fully loaded truck would then be weighed. The truck would be backed into a maintenance material storage shed and the drive wheels jacked up and blocks placed in front of the other wheels. The drive wheels would not need to be jacked up if a speed simulator could be used to control the truck speed. The operator would be asked to record specific information on a specially designed truck operator form.

The truck would then be “driven” through simulated maintenance operations following a set of prescribed truck speed-application rate combinations over a defined test time period.

At the end of a simulated maintenance run, the truck would be re-weighed and the amount of prewetting liquid discharge noted. The weight loss and volume decrease would be compared with the calculated weight and volume loss and the amount of solid and liquid discharged according to the controller information.

Two simulated spreading operations would be conducted for each mode of controller operation considered [open-loop (OL), closed-loop (CL), or manual (M)]. One spreading operation would represent freeway conditions; the other would represent highway conditions with both a stop sign controlled and a signalized controlled intersection. The simulator scenarios for each operation are given in Table 6-1.

Table 6-1. Simulation Scenarios

1. Freeway Operations

- Application rate of 200 lbs/mile and prewetting of 10 gal/ton
- Set speed at 20 MPH and travel for 8 minutes (Theoretical Discharge of 533.3 lbs. and 341.3 ounces)
- Set speed at 35 MPH and travel for 5 minutes (Theoretical Discharge of 583.2 lbs and 373.2 ounces)
- Set speed at 15 MPH and travel for 8 minutes (Theoretical Discharge of 399.8 lbs and 256.0 ounces) (*Simulate travel congestion)*
- Change Application rate to 500 lbs/mile and prewetting of 15 gal/ton
- Set speed at 20 MPH and travel for 8 minutes (Theoretical Discharge of 1333.4 lbs. and 1280.2 ounces)
- Set speed at 30 MPH and travel for 5 minutes (Theoretical Discharge of 1250.1 lbs and 1200.0 ounces)
- Set speed at 15 MPH and travel for 8 minutes (Theoretical Discharge of 999.8 lbs and 959.9 ounces (*Simulate travel congestion)*

Resources required: 42 minutes per simulation, 5,099.6 pounds of solid material, and 4,410.6 ounces or 34.46 gallons of liquid

2. Highway Operations with both a stop sign and a signalized intersection

- Application rate of 300 lbs/mile and prewetting of 10 gal/ton
- Set speed at 20 MPH and travel for 10 minutes (Theoretical Discharge of 1000.2 lbs and 640.2 ounces)
- Stop for a duration of 1.5 minutes *(Simulate a stop sign intersection)*
- Set speed at 30 MPH and travel for 5 minutes (Theoretical Discharge of 750 lbs and 480.0 ounces)
- Stop for a duration of 3 minute *(Simulate a signalized intersection)*
- Change Application rate to 600 lbs/mile and prewetting of 15 gal/ton
- Set speed at 15 MPH and travel for 5 minutes (Theoretical Discharge of 750 lbs. and 720.0 ounces)
- Set speed at 25 MPH and travel for 5 minutes (Theoretical Discharge 1250.1 lbs and 1200 ounces)

Resources required: 29.5 minutes per simulation, 3,750.3 pounds of solid material, and 3,040.2 ounces or 23.75 gallons of liquid.

The freeway operation simulation would use two levels of solid application-prewetting rate combinations of 200 lbs/mile – 10 gal/ton and 500 lbs/mile – 15 gal/ton. Each solid-liquid application rate combination would be used for a range of truck speeds and discharge times.

Each freeway operations simulation run would take 42 minutes to complete and would require about 5100 lbs of salt and about 34 ½ gallons of liquid being discharged.

The highway operations simulation would use two levels of solid application – prewetting rate combinations of 300 lbs/mile – 10 gal/ton and 600 lbs/mile – 15 gal/ton. Each solid-liquid application rate combination would be used for a range of truck speeds and discharge times. Both a 1 ½ minute idle stop and a three minute idle stop would be incorporated during the highway operation run to simulate a stop sign control intersection and a signalized controlled intersection, respectively. Each highway operations simulation run would take about 30 minutes to complete and would require 3,750 lbs of salt and 23 ¾ gallons of liquid being discharged.

It was anticipated that each simulated run would be replicated. The number of replicate tests to be conducted was based upon the quality of the test data required balanced against the funds budgeted for the Phase 3 site visits and number of controller-mode of operation combinations investigated.

Special Equipment Needed:

The main special equipment needed would be a truck scale. Access to the scale would be at a convenient time the simulated test runs were made.

Advantages:

- Very simple test method.
- Tests can be performed during non-winter maintenance activities.
- Test procedures eases demands on truck operator's time during critical winter maintenance activities.
- Full control over operating test conditions.
- Repeatable test results can be obtained within experimental error.
- Tests do not depend on the number of snow and ice events.
- Tests can be completed within time allocated for Phase 3 and with team member and manufacturer's representatives present during the tests.
- Simplified data collection and quality control of the test results.

Disadvantages:

- Needed to overcome stigma of not conducting Phase 3 tests of procedures during actual winter-time events.
- Need agreement on ingredients of winter simulation test protocol.

The three above methods were submitted to the project panel for review along with a recommendation that the Phase 3 tests be conducted using the simulated field test method (Method No. 3). The third method solves many of the uncertainties and disadvantages of the other two methods that were originally proposed. The recommended method also found favor from a number of field maintenance personnel that would be involved with the field tests. An almost unanimous approval to use the recommended method was received.

SECTION 7
SIMULATED FIELD STUDY

The field study was conducted with the cooperation and assistance of six Clear Roads member states with actual material usage during winter-time conditions for both manually and ground-speed-controlled spreaders that were calibrated according to the manufacturers' specifications. The six states were Indiana, Iowa, Minnesota, Missouri, Ohio, and Wisconsin. The simulated field testing was conducted at the same work locations where the yard tests were conducted, with one exception. The field work in Minnesota was conducted at a metro garage location, because the yard tests of the Dickey-john controllers were conducted in New York State.

7.1 Preparation for Simulated Field Study

In preparation for the Field Tests, a document entitled *"Background information and Procedures for Conducting Phase 3 Tests"* was sent to the participating states. The purpose of the document was to provide some background on the Clear Roads project and to describe the assistance needed from the Clear Roads states involved in the field studies of the project. This document, besides providing the background and assistance needed, also went into details on procedures (testing protocols) for conducting simulated freeway and highway operations tests and the special forms that were to be used to collect data during the tests. For convenience, the simulated freeway and highway operation scenarios are given in Tables 7-1 and 7-2, respectively. What follows are excerpts from that document that deal with the procedures. The whole document is contained in Appendix M of this report. The procedures that follow are for conducting simulated testing with closed-loop, ground-speed controllers that control and monitor both solid and liquid discharges. The procedure can be used with open-loop, ground-speed controllers by substituting the term open-loop for closed-loop. The procedure can also be used with controllers that do not control liquid discharges by simply disregarding the steps dealing with liquid discharges.

Table 7-1. Simulated Freeway Operation Scenario

Task No.	Truck Speed (mph)	Application Rate (Solid) (lbs/mile)	Prewetting Rate (gals/ton)	Duration (minutes)	Elapsed Time (minutes)
1	20	200	10	8	8
2	35	200	10	5	13
3	15	200	10	8	21
4	20	500	15	8	29
5	30	500	15	5	34
6	15	500	15	8	42

Table 7-2. Simulated Highway Operation Scenario

Task No.	Truck Speed (mph)	Application Rate (Solid) (lbs/mile)	Prewetting Rate (gals/ton)	Duration (minutes)	Elapsed Time (minutes)
1	20	300	10	3	3
2	15	300	10	3	6
3	25	300	10	3	9
4	**Stop**			1	10
5	30	300	10	3	13
6	25	300	10	3	16
7	35	300	10	3	19
8	**Stop**			1	20
9	15	600	15	3	23
10	20	600	15	3	26
11	25	600	15	3	29
12	30	600	15	3	32

> "Before the simulation tests are conducted, the controller/spreader combination will need to be calibrated in the closed-loop, ground-speed-controlled mode. The calibration will then need to be checked by running four sets of verification discharge tests. If possible, these tests should be conducted using the controller speed simulator. Each scenario run will be replicated as many times as possible, using the controller speed simulator.

The steps for conducting the simulated operations tests follow.

1. Calibrate eight, 5-gallon plastic buckets to be used in measuring the liquid discharge. This step includes making a wooden dip stick for measuring the amount of liquid accumulated in a plastic bucket when the amount is less than 5 gal. The procedure for this step is described in Attachment A of Appendix M.

2. Attach hoses to the spray nozzles so that the liquid discharge can be channeled to the 5-gallon plastic collection buckets.

3. Measure the specific gravity of the salt brine with a hydrometer and record the results.

4. Load the truck and spreader with the appropriate amounts of salt and salt brine.

5. Calibrate the controller/spreader combination in the closed-loop, ground-speed-controlled mode using the manufacturer's recommended procedure. Record the calibration factors and other appropriate controller data.

6. Recheck the calibration by running verification tests using the following combinations of variables as shown in Table 7-3, Calibration Verification Test Variables.

Table 7-3. Calibration Verification Test Variables

Solid Application Rate (lbs/mile)	Liquid Application Rate (gal/ton)	Test Speed (mph)	Test Discharge Time (sec.)
200	10	25	73
300	10	25	49
500	15	20	36
600	15	20	30

7. Run three discharge tests for each combination of variables. Weigh and measure the solid and liquid discharge amounts and record the results. The discharge time should produce about 100 lbs of solid material and about ½ and ¾ gallons of liquid.

8. Prepare the truck and spreader for the first simulation test of the **FREEWAY SCENARIO** using the closed-loop, ground-speed-controlled mode by adding solid and liquid material. Top off the fuel tank to a point that can be seen and marked.

9. Weigh and record the weight of the fully loaded truck.

10. Conduct the first simulation run of the closed-loop, ground-speed-controlled mode using the test conditions identified for the **FREEWAY SCENARIO.** The tests conditions, including elapsed time, solid and liquid application rates, and truck speeds are given in Attachment B of Appendix M. Use a stop watch to monitor the elapsed time for each task. If more convenient, use the Task duration times on the recording forms in Attachment C of Appendix M.

11. During the simulation run, collect the liquid discharge in the 5-gallon plastic buckets and record the total amount discharged at the end of the simulation run using the recording forms in Attachment C of Appendix M.

12. During the simulation run, collect the solid material by discharging into a loader bucket to minimize hand work. If this does not work, we may have to use a multi-wheel barrow shuttle to keep the discharge reasonably orderly. Place the discharged material in a pile where it can be retrieved after the test. Do not attempt to weigh the solid discharge at this point.

13. At the end of the simulation run, turn the engine off after recording on the attached forms the following information from the CONTROLLER: the weight (lbs) of solid discharged, the solid application rate discharged (lbs/mile), the distance traveled (miles), the liquid volume (gallons) discharged, and the liquid application rate (gal/ton).

14. Pump the liquid collected in the plastic buckets back into the prewetting tank(s) on the truck. A small utility pump and a small garden hose can be used to get the liquid back into the tank(s).

15. Top off the truck fuel tank to the mark indicated.

16. Weigh the truck and record the weight (lbs) of solid material discharged by differencing the after-test truck weight with the before-test truck weight.

17. Review the data reported to determine any inconsistencies and resolve.

18. Reload the truck with solid material that was set aside.

19. Repeat Steps 9 through 18 to conduct replicate tests with the closed-loop, ground-speed controlled mode and the **FREEWAY SCENARIO**.

This completes the tests with the controller/spreader combination operated in the closed-loop, ground-speed-controlled mode and following the **FREEWAY SCENARIO.**

20. Prepare the truck and spreader for the first simulation test of the **HIGHWAY SCENARIO** using the closed-loop, ground-speed-controlled mode by checking to see that solid and liquid have been added to the unit. Make sure that the fuel tank has been toped off to the mark indicated.

21. Weigh and record the weight of the fully loaded truck.

22. Prepare to conduct the first simulation run of the closed-loop, ground-speed-controlled mode using the test conditions identified in the **HIGHWAY SCENARIO.** The test conditions are given in Attachment B of Appendix M. Continue to use a stop watch to monitor the elapsed time for each task of the simulation run.

23. Repeat Steps 11 through 18 to run the first simulation run of the **HIGHWAY SCENARIO.**

24. Repeat Steps 9 through 18 to conduct replicate tests with the closed-loop, ground-speed controlled mode and the **HIGHWAY SCENARIO.**

After Step 24, prepare to run both simulation scenarios using the manual mode of operation. Start with Step 4 and then jack up the rear axels and block the front wheels of the spreader truck.

25. Calibrate the controller/spreader in the manual mode using the manufacturer's recommended procedure, or if none, use that of the Salt Institute. Record the calibration factors and other appropriate data.

26. Recheck the calibration by conducting the verification tests described in Steps 6 and 7 using the manual mode of operation.

27. Repeat Steps 8 through 24 to conduct first and replicate tests with the manual mode of operation for both the FREEWAY and **HIGHWAY SCENARIOS**. These tests will require repeated jacking up the rear axels and blocking the front wheels of the spreader truck during the tests and then removing these items for weighing the truck.

This completes the tests with the controller/spreader combination operated in the manual mode of operation. If for some reason, the simulation runs using the manual mode of operation can not be conducted at this time, use the following procedure.

28 Repeat Steps 8 through 24 using the open-loop, ground-speed-controlled mode of operation for both the **FREEWAY** and **HIGHWAY SCENARIOS."**

A representative of the controller manufacturer was encouraged to observe the yard tests. This activity was coordinated by a project team member overseeing the simulated field testing at a given location.

During the field tests, data were collected through the use of specially designed data reporting forms. The data included: the controller settings; the solid and liquid chemical application rates used; the truck spreading speed; and the amount of salt, sand, and prewetting liquid chemicals used during the tests. Other data such as salt moisture content (where available) and weather conditions at the time of tests were also recorded. Verification of the accuracy of the recording method for miles traveled was also made.

7.2 Simulated Field Tests

Seven different controllers from six manufacturers were field tested. Because of the nature of the controllers' design, many units were able to be operate in different modes, including closed-loop, open-loop, and manual. The distribution of state DOTs, controller manufacturer/model, and controller mode of operation involved in the field testing are given in Table 7-4. The definitions of terms used for mode of controller operation in the table are, CL stands for closed-loop, OL stands for Open-loop, and M stands for Manual.

Table 7-4. Combination of State DOTs, Controller Manufacturers, and Mode of Controller Operation Involved in Field Testing

State DOT	Controller Manufacturer/Model	Mode of Controller Operation
Indiana	Muncie Power Products MESP402D	CL, OL
Iowa	Cirus Controls SpreadSmart RX	CL, OL, M
Minnesota	Dickey-john Control Point	CL, OL
Missouri	Component Technology GL-400	CL, OL, M
Ohio	Pengwyn 485	OL, M
Wisconsin	FORCE America Model 2100 Model 5100	 OL CL, OL

7.2.1 Testing Involving Closed-loop and Open-loop Modes of Operation

The field tests of the spreader/controller equipment in the six states were conducted basically during the winter of 2006 – 2007. Circumstances required retesting of the units in two states during early summer of 2007. The respective equipment manufacturer's representatives were in attendance during the valid field tests. The dates of the field tests of each controller are given in Table 7-5 along with number of tests conducted for each combination of mode of operation and scenario type.

Table 7-5. Controllers Tested During Comparison of Closed-loop and Open-loop Modes of Operation during Simulated Field Tests

State	Controller Model	Date of Testing	Number of Tests			
			Closed-Loop Mode		Open-Loop Mode	
			Freeway Scenario	Highway Scenario	Freeway Scenario	Highway Scenario
Indiana	MESP402D	Dec. 4-5, 2006	0	0	2	2
		June 18-20,2007*	2	2	2	2
Iowa	SpreadSmart RDS	Nov. 13-15, 2006	3	1	0	1
Minnesota	Control Point	Jan. 10-11, 2007	3	3	1	1
Missouri	GL-400	Dec. 12-14, 2006	2	2	2	2
Ohio	Pengwin 485	Dec. 7-8, 2006	0	0	2	2
		June 12-14,2007*	0	0	2	2
Wisconsin	Model 2100	April 25-26, 2007	0	0	3	2
	Model 5100	Feb. 5-7, 2007	3	2	1	1

Noted: * indicates a retest

It was planned to conduct at least two replicate tests with each combination of mode of operation and scenario type. This replicate testing was not possible in all cases because of various reasons. The main limiting factor was the time it took to conduct each test. No closed-loop tests were conducted in Ohio with the Pengwyn 485 model or in Wisconsin with the FORCE America Model 2100 because these units do not operate in that mode.

The field testing in Wisconsin of the spreader with the FORCE America Model 2100 was completed in late April 2007. These tests were originally scheduled for early February 2007 but could not be conducted at that time because it was too cold to perform the tests. (The truck containing the 2100 Model controller could not be jacked up during the extreme cold.)

The retesting in Ohio was necessary because of previous problems with keeping the tailgate spreader's auger fully charged during the tests and weight scale inaccuracies. Also, it was not possible for the manufacturer's representative to be present to calibrate the spreader/controller on the first day of testing because of scheduling conflicts. All of these problems were resolved during the retesting in early June 2007.

The retesting in Indiana was necessary because of two problems experienced during the first round of testing in early December 2006. At that time, the rear sensor on the truck was physically removed. This modification meant that the control system was capable of only operating in the open-loop mode. Also, the manufacturer's representative could not be present during the field tests because of scheduling conflicts. The absence of the vendor's participation meant that the spreader/controller combination could not be calibrated before the first round of field tests was conducted. All of these problems were resolved during the retesting in mid-to-late June 2007.

The data collected during the field tests were entered into spreadsheets for analysis along with field notes recorded during the tests. The computer generated files for each controller tested were shared with the respective state maintenance personnel and controller manufacturer involved with the testing.

7.2.2 Comparison Testing Between Ground-Speed-Controlled and Manual Modes of Operations

Comparison testing was conducted in Iowa and Missouri where the spreader/controller combinations could be operated in both closed-loop and manual modes of operation. Similar comparison tests were conducted in Ohio where the spreader/controller combination could be operated in both an open-loop and manual modes of operation. Only solid material (dry salt) was dispensed during the comparison testing. Liquid materials were not used.

The comparison testing in Iowa was conducted during the week of April 19, 2007 by driving the spreader truck over a course on a rural, 2-lane highway site specially selected for the tests. The test site (Johnson County F 12) was selected by the IDOT in conjunction with Johnson County personnel. The test loop was 4 miles long and allowed for test speed of 20 and 30 mph. IDOT mounted a manual revolution counter on the auger shaft so that the number of revolutions of the auger could be tracked during each mode of operation. Figure 7-1 shows a picture of the manual revolution counter that was mounted on the shaft of the auger. The recording of shaft revolutions were made during the tests to see if the revolution counts could be used later in the analysis of the test data to determine the reliability of estimating the weight of material discharged by two methods. One method involved knowing the number of shaft revolutions experienced

Figure 7-1. Revolution Counter

during a test and the pounds of material discharged for each revolution as determined from calibration testing. The second method involved weighing the truck before and after the test.

Special testing protocols were developed for the comparison testing in Iowa. The parameter values of the special testing protocols (solid application rate and truck speed) were somewhat different from those values used in the simulated field test discussed earlier in this section. The parameter values used in the comparison testing were based on the constraints of the highway test site and on the need to accommodate the limitations of the spreader/controller system that were identified during the yard tests. These limitations are discussed in Section 5.1.1. The upper limit of solid application rate was reduced to 400 lbs/mile with a maximum speed of 30 mph. The protocols called for the truck to travel at 20 and 30 mph and discharge salt at application rates of 200 and 400 lbs/mile in both closed-loop and manual modes of operations. The special testing protocols and data collection form that were used in the Iowa testing are described in Appendix N.

The comparison testing in Missouri was conducted during the week of June 4, 2007 at the MoDOT maintenance garage located in Bowling Green, MO. The tests were performed with the truck in a stationary position and discharging solid material (dry salt) into the salt shed. Two testing scenarios, one simulating a freeway environment and the other simulating a highway environment, were developed and used during the tests. The local Missouri DOT personnel mounted a manual revolution counter on the conveyor shaft so that the total number of revolutions of the auger could be tracked during each scenario test. Figure 7-2 shows a picture of the manual revolution counter that was mounted on the shaft of the conveyor.

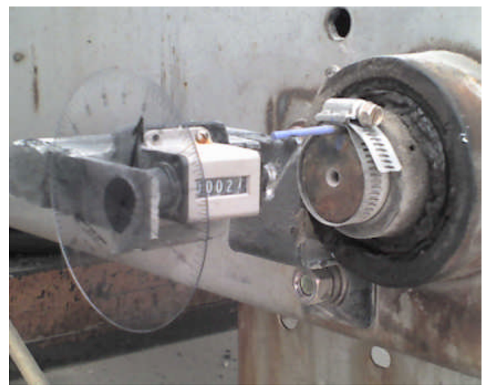

Figure 7-2. Revolution Counter

The comparison testing in Missouri used scenarios that were similar to the ones used in that state during the testing of the closed-loop and open-loop modes of operation. The freeway scenario for both the closed-loop and manual modes of operation consisted of two truck speeds (20 and 30 mph) with one intermediate stop. Separate freeway scenario runs were made for each mode of operation using a fixed salt application rate of 200 lbs/mile. The freeway scenario runs were repeated for each mode of operation using a fixed salt application rate of 400 lbs/mile. The duration of each freeway test was 31 minutes.

The highway scenario for both the closed-loop and manual modes of operation consisted of three truck speeds (20, 25, and 30 mph) and three intermediate stops. As with the freeway scenario tests, separate highway scenario runs were made for each mode of operation using fixed salt application rates of 200 and 400 lbs/mile. The duration of each highway test was 28 minutes. The special scenario testing protocols and data collection forms used in the Missouri comparison testing are given in Appendix N.

The comparison testing in Ohio was conducted during the week of June 11, 2007 in connection with the retesting of the open-loop mode of operation. The tests were performed with the truck in a stationary position. The freeway and highway scenarios used with the open-loop mode of operation were the same as were used during the December 2006 simulation tests with the exception that only dry, solid salt was discharged. The freeway and highway scenarios used with the manual mode of operation were the same as were used during the Missouri comparison testing just described.

The results of the comparison testing of spreader/controller combination operated in both ground-speed controlled and manual modes of operation are discussed in Section 9.

SECTION 8

RESULTS FROM SIMULATED FIELD TESTS INVOLVING CLOSED-LOOP AND OPEN-LOOP MODES OF OPERATION

Simulated field tests were conducted with seven different controllers from six manufacturers. All seven controllers were tested under an open-loop mode of operation. However, because of design limitations, only five of the seven controllers were tested under a closed-loop mode of operation.

The simulated field tests were conducted according to the procedures described in the previous section. Solid material discharge was collected during the simulated field tests of each of the seven spreader/controller combinations, irregardless of the mode of operation. However, because of the system design or limitation of the controller software, liquid discharge was collected from only five of the seven spreader/controller systems. Liquid discharge was collected from three of the five spreader/controller systems when tested under both closed-loop and open-loop modes of operation. Liquid discharge was collected from one system when only tested in a closed-loop mode of operation, and from one system where only tested in an open-loop mode of operation.

The data collected during the simulated field tests were manually recorded on specially designed reporting forms. The field data were then entered into spreadsheets for analysis along with field notes recorded during the tests. Summaries of simulation run results plus derived comparison results were entered into additional spreadsheets from evaluation purposes. These additional spreadsheets contained such items as:

- Scenario/mode of operation description
- Test set number
- Theoretical discharge amount
- Actual discharge amount
- Discharge amount registered by the controller
- Percent of difference of actual (discharge) compared to the theoretical discharge
- Percent of difference of controller (discharge display) compared to the theoretical discharge
- Percent of difference of controller (discharge display) compared to the actual discharge
- Percent of difference of actual discharge for open-loop operation compared to closed-loop operation

Separate summary tabulations were made for solid discharge – related quantities and for liquid discharge – related quantities, where appropriate. Arithmetic means of some of the quantities were generated to produce tables of:

- Solid discharge comparison for freeway and highway scenarios in both closed-loop and open-loop operations.
- Solid discharge comparison of open-loop to closed-loop operations for freeway and highway scenarios using actual discharge and controller display discharge amounts.
- Prewetting discharge comparison for freeway and highway scenarios in both closed-loop and open-loop operations.

- Prewetting discharge comparison of open-loop to closed-loop operations for freeway and highway scenarios using actual discharge and controller displayed discharge amounts.

The tabulations of the results from the simulated scenario testing are given in Appendixes F through L for the seven systems tested. The test results showed that the simulated test method is sound and has obvious benefits when compared with over-the-road testing in terms of control, observation opportunity, and scheduling.

The simulated field tests were conducted, generally, with the same spreader/controller combinations used during the yard tests. Consequently, the test results are given in terms of the spreader/controller combination examined. The simulated test results of each spreader/controller system were analyzed independently of the other systems. No attempt was made to compare one system against another.

8.1 Cirus Controls SpreadSmart RDS

The summary results from the simulated scenario testing of a tailgate spreader with the Cirus Controls SpreadSmart RDS controller are given in Tables F-12 through F-17. Data are presented for both solid and liquid discharges under closed-loop and open-loop modes of operation.

The actual solid discharge amount was consistently larger by about 4 to 5 percent than the theoretical solid discharge amount for both the freeway and highway scenarios, as well as both modes of operation. The amount of solid discharge indicated by the controller was very close to the theoretical discharge amount for the closed-loop mode of operation during both the freeway and highway scenarios. However, the controller under-reported the amount of solid material discharge (by about -8 percent) compared to the theoretical solid discharge amount expected for the open-loop mode of operation and the highway simulation conditions. The controller also under-reported the actual amount of solid material discharged (by about -5 percent) for the closed-loop mode of operation and both freeway and highway scenarios. In addition, the controller under-reported the actual amount of solid material discharged (by about -12 percent) for the open-loop mode of operation and the highway scenario.

Finally, the controller reported about 8 percent less solid material discharged in the open-loop compared to the closed-loop mode of operation for the highway scenario. The actual solid material discharged was about the same for both modes of operation and the highway scenario, which is suspicious.

The actual prewetting discharge amount was larger by about 1 and 4 percent than the theoretical prewetting discharge amount for the highway and freeway scenarios, respectively, and the closed-loop mode of operation. However, the actual prewetting discharge for the highway scenario and the open-loop mode of operation was between 8 and 9 percent less than the estimated theoretical prewetting discharge amount for those conditions. The amount of prewetting discharge indicated by the controller was considerably less than the theoretical prewetting discharge amount for both modes of operation and scenarios. The greatest difference between the controller display of prewetting discharge amount and the theoretical prewetting discharge amount (-26.8 percent) was found for the highway scenario and open-loop mode of operation.

The controller under-reported the actual amount of liquid material discharged (by about -15 percent and -23 percent) for the closed-loop mode of operation and the freeway and highway scenarios, respectively. The controller also under-reported the actual amount of liquid material discharged (by -20 percent) for the open-loop mode of operation and the highway scenario.

Finally, the actual amount of liquid material discharged was about 10 percent less for the open-loop compared to the closed-loop mode of operation for the highway scenario.

8.2 Component Technology GL-400

The summary results from the simulated scenario testing of a hopper-box spreader with the Component Technology GL-400 controller are given in Tables G-12 through G-17. Data are presented for solid material discharges under both closed-loop and open-loop modes of operation. Data for liquid material discharges are presented only for the closed-loop mode of operation. The software used by the controller did not provide for control of the liquid discharge under an open-loop mode of operation.

The actual solid discharge amount was consistently less by about 3 to almost 4 percent than the theoretical solid discharge amount for the closed-loop mode of operation and both the freeway and highway scenarios. The actual solid discharge was about the same as the theoretical solid discharge for the open-loop mode of operation and the freeway scenario. However, the actual solid discharge was about 7 percent less than the theoretical solid discharge for the open-loop mode of operation and the highway scenario.

The controller over-reported the actual amount of solid material discharged (by about 3 to 4 percent) for the closed-loop mode of operation and both the freeway and highway scenarios. However, the controller under-reported the amount of solid material discharged by about -10 percent for the freeway scenario and by about -1 percent for the highway scenario for the open-loop mode of operation.

The actual amount of solid material discharged for the freeway scenario was about 4 percent more for the open-loop mode compared to the closed-loop mode of operation. On the other hand, the actual amount of solid material discharged for the highway scenario was about 4 percent less for the open-loop compared to the closed-loop mode of operation. Finally, the controller reported about 9 percent less solid material discharged in the open-loop mode compared to the closed-loop mode of operation for both scenarios. The sensitivity of the controller to display almost the same difference in solid discharge between the open-loop and closed-loop mode of operation for both freeway and highway scenarios is an interesting finding.

The actual prewetting discharge amount was very close to the theoretical estimate for the freeway and highway scenarios and the closed-loop mode of operation. Likewise, the controller reported within about 1 to 2 percent, the actual amount of liquid discharged for the closed-loop mode of operation and both scenarios.

8.3 Dickey-john Control Point

The summary results from the simulated scenario testing of a tailgate spreader with the Dickey-john Control Point controller are given in Tables H-19 through H-21. Data are presented only for solid material discharges under both closed-loop and open-loop modes of operation. No data were collected for liquid material discharges because of gravity flow constraints on the prewetting system.

The actual solid discharge amount was larger by about 3 and 16 percent than the theoretical solid discharge amount for the freeway and highway scenarios, respectively, and the closed-loop mode of operation. The results for the open-loop mode of operation under the same conditions are much different. Here, the actual solid discharge amount was considerably less by about 44 and 34 percent than the theoretical solid discharge amount for the freeway and highway scenarios, respectively, and the open-loop mode of operation. The amount of solid discharge indicated by the controller was very close to the theoretical discharge amount for the closed-loop mode of operation during both of the freeway and highway scenario testing.

Finally, the actual amount of solid material discharged was about 46 to 47 percent less for the open-loop compared to the closed-loop mode of operation for both scenarios. Here again, the sensitivity of the controller to display almost the same difference in solid discharge between the open-loop and closed-loop modes of operation for both freeway and highway scenarios is an interesting finding.

8.4 FORCE America Model 2100

The summary results from the simulated scenario testing of a tailgate spreader with the FORCE America Model 2100 controller are given in Tables I-8 through I-10. Data are presented only for solid material discharges under an open-loop mode of operation. The system does not operate in a closed-loop mode of operation nor does it have prewetting capacity.

The actual solid discharge amount was about 26 percent less than the theoretical solid discharge amount for the freeway scenario and about 24 percent less than the theoretical solid discharge amount for the highway scenario. No other simulated scenario testing data were collected for this model.

8.5 FORCE America Model 5100

The summary results from the simulated scenario testing of a tailgate spreader with the FORCE America Model 5100 controller are given in Tables J-12 through J-17. Data are presented for both solid and liquid discharges under closed-loop and open-loop modes of operation.

The actual solid discharge amount was slightly larger by about 3 percent than the theoretical solid discharge amount for the freeway scenario and the closed-loop mode of operation. For the highway scenario and the closed-loop mode of operation, the actual solid discharge amount was almost identical to the theoretical solid discharge amount. The results for the open-loop mode of operation are much different. Here, the actual solid discharge amount is considerably higher by 173 and 197 percent than the theoretical solid discharge amount for the freeway and highway scenarios, respectively, and the open-loop mode of operation. The amount of solid discharge indicated by the controller was very close to the theoretical solid discharge amount for the closed-loop mode of operation during both the freeway and highway scenarios.

The actual amount of solid material discharged for the freeway scenario was about 164 percent more for the open-loop mode of operation compared to the closed-loop mode of operation. For the highway scenario, the actual amount of solid material discharged was about 207 percent more for the open-loop compared to the closed-loop mode of operation.

The actual prewetting discharge amount was larger by about 7 and 3 percent than the theoretical discharge amount for the freeway and highway scenarios, respectively, under closed-loop mode of operation. The results for the open-loop mode of operation, again, are much different. Here, the actual liquid discharge amount is considerably higher by 79 and 57 percent than the theoretical liquid discharge amounts for the freeway and highway scenarios, respectively, and the open-loop mode of operation. The amount of liquid discharge indicated by the controller was about 4 and 8 percent less than the theoretical liquid discharge amount for the freeway and highway scenarios, respectively, under the closed-loop mode of operation.

Finally, the actual amount of liquid material discharged was about 66 and 56 percent less for the open-loop compared to the closed-loop mode of operation for the freeway and highway scenarios, respectively.

8.6 Muncie Power Products MESP402D

The summary results from the simulated scenario testing of a V-box spreader with the Muncie Power Products MESP402D controller are given in Tables K-9 through K-14. Data are presented for both solid and liquid discharges under closed-loop and open-loop modes of operation. Data in Tables K-9 and K-10 were collected in December 2006 and were excluded from analysis for reasons already explained. These data are reported for completeness only. The data in Tables K-9a and K-10a resulted from retesting the system in June 2007 and are used to generate Tables K-11 through K-14.

The actual solid discharge amount was larger than the theoretical solid discharge amount for the freeway scenario but smaller by almost the same magnitude for the highway scenario. This is true for the closed-loop as well as the open-loop mode of operation. The percent of difference is greater for the closed-loop than for the open-loop mode of operation. The actual amount of solid material discharged for the freeway scenario was about 8 percent less for the open-loop compared to the closed-loop mode of operation. On the other hand, the actual amount of solid material discharge for the highway scenario was about 11 percent larger for the open-loop compared to the closed-loop mode of operation.

The actual prewetting discharge amount for the freeway scenario was much larger, by about 19 and 22 percent, than the theoretical prewetting discharge amount for the closed-loop and open-loop modes of operation, respectively. For the highway scenario, the actual prewetting discharge amount was about 9 percent less than the theoretical estimate for the closed-loop mode of operation. The actual prewetting discharge amount for the highway scenario and open-loop mode of operation was almost equal to the theoretical estimate.

Finally, the actual amount of liquid discharged for the freeway scenario was about 2 percent more for the open-loop compared to the closed-loop mode of operation. Also, the actual amount of liquid discharged for the highway scenario was about 11 percent more for the open-loop compared to the closed-loop mode of operation.

8.7 Pengwyn Model 485

The summary results from the simulated scenario testing of a tailgate spreader with the Pengwyn Model 485 controller are given in Tables L-12 through L-18. Limited data are presented for both solid and liquid discharges only for the open-loop mode of operation. The data in Tables L-12 through L-16 are from the simulated scenario testing conducted in December 2006.

A quick inspection of the actual solid and liquid discharge amounts compared to the theoretical discharge amounts shows that something was drastically wrong with the test results. The actual solid discharge amounts were over 12 percent and 20 percent less than the theoretical solid discharge amounts for the freeway and highway scenarios, respectively. In addition, the liquid discharge amounts were over 9 percent and 29 percent more than the theoretical liquid discharge amounts for the freeway and highway scenarios, respectively. These test results are presented only to demonstrate what happens when the system is not calibrated properly, when the tailgate auger is not fully charged during calibration and scenario testing, and when weight scales used to measure discharge amounts are in error. (See Section 7.2.1). The comparison of the actual discharge amount against the theoretical discharge amount demonstrates the power of the theoretical estimates to identify the presence of system operating problems.

The spreader/controller combination was retested in June 2007 using both freeway and highway scenarios. These retests were done in connection with a desire to perform comparison testing between the open-loop and manual modes of operation. The retest results for the open-loop mode of operation are given in Tables L-17 and L-18. Unfortunately, no liquid discharge measurements were made during the retests.

Referring to Table L-18, the actual solid discharge amount for the freeway scenario was slightly larger, by about 2 percent, than the theoretical solid discharge amount for the open-loop mode of operation. The actual solid discharge amount for the highway scenario was almost 6 percent more than the theoretical solid discharge amount for the open-loop mode of operation. These latter results are what one would expect from a calibrated unit when the tailgate was fully charged and correct scales were used to measure discharge amounts

SECTION 9
RESULTS FROM COMPARISON TESTING OF SPREADER/CONTROLLER COMBINATIONS OPERATED IN BOTH GROUND-SPEED-CONTROLED AND MANUAL MODES OF OPERATION

One of the research objectives of the study was to investigate the performance of calibrated ground-speed spreader controllers compared to the performance of calibrated manual spreader controllers. No new manual spreader controllers could be found for comparison testing among the participating Clear Roads states. Consequently, a decision was made to conduct the comparison tests with relatively new spreader/controller units that could be operated in both a ground-speed-controlled mode as well as a manual mode of operation. The tests were conducted in three Clear Roads states.

Comparison tests were conducted in Iowa and Missouri where the spreader/controller combinations could be operated in both closed-loop and manual modes of operation. Similar ycomparison tests were conducted in Ohio where the spreader/controller combination could be operated in both open-loop and manual modes. Only dry salt was discharged during the comparison testing.

The results of the comparison testing are given in this section. The results are presented and discussed separately by state in which the tests were conducted. This is because different spreader/controller combinations were used in each state, as well as the simulation testing scenarios. The separate scenarios used in each state are discussed in Section 7.2.2.

9.1 Iowa Comparison Testing Results

The data resulting from the comparison testing of closed-loop with manual modes of operation are given in Table F-18. Test data are presented for eight scenario runs (2 modes of operation **x** 2 dry salt application rates **x** 2 replications). Data presented for each scenario run include: theoretical solid discharge amounts; actual solid discharge amounts; total number of shaft revolutions; the percent of differences of the actual discharge amount compared to the theoretical discharge amount; and the percent of differences of actual discharge amount for manual mode compared to closed-loop mode of operation.

The local Iowa DOT personnel mounted a manual revolution counter on the auger shaft before the tests so that the total number of revolutions of the auger could be tracked during each scenario test. The initial thought was to estimate the discharge amount for each test from knowing the total number of shaft revolutions experienced during a test, and the pounds of material discharged for each revolution as determined from calibration testing. The desire was to dispense with some of the time-consuming weighing of the truck, both before and after the test, if the material discharges weight could be accurately determined using the shaft revolution counter approach.

Fortunately, the weighting of the truck before and after each scenario test continued throughout the entire comparison testing. It was additionally fortunate that the recording of the total shaft revolution count continued throughout the testing. Both of these quantities are given in Table F-18 for each scenario test.

The actual discharge amount for each test was consistently larger than the theoretical discharge amount. What was definitely a surprise were the 19 to 26 percent differences in the actual discharge amount compared to the theoretical discharge amount for the closed-loop mode of operation.

From Table F-18, the comparison testing in Iowa showed an initial material savings of 2 to 10 percent at an application rate of 200 lbs/mile and 37 to 42 percent at an application rate of 400 lbs/mile. The material savings are based on using the ground-speed-controlled, closed-loop mode results compared to the results found from the manual mode of operation.

The revolution count in Table F-18 provides a significant clue into the apparent anomaly concerning the large actual discharge amounts compared to the theoretical discharge estimates. An investigation into the root cause of this anomaly was conducted both during and following the field testing. Half way through the field comparison testing, the spreader/controller system was re-calibrated with the truck bed raised. A Calibration Constant different from the initial constant was determined. The initial Calibration Constant was determined with the truck bed in the lowered position. To not confound the data from the comparison testing, it was decided to complete the comparison testing using the initial Calibration Constant in the spreader/controller.

For the initial calibration procedure, the truck was fully loaded and the truck bed was in a lowered position. The revolution count was recorded during the calibration procedure. Measured lbs/revolution was determined by dividing the discharge weight by the revolution count. The Calibration Constant was determined as 15.85 pulses/lb and measured lbs/revolution as 4.89 lbs/rev. However, the manufacturer's representative selected to use a Calibration Constant of 15.7. No reason was given by the representative. The data for the initial calibration procedure are shown in Table F-19. For the re-calibration procedure the truck bed was raised to a level that is normally used during spreading operations. The re-calibration produced a revised Calibration Constant of 14.5 pulses/lb and a measured lbs/revolution of 5.25. The data from the re-calibration procedure with the truck in raised position are given in Table F-20.

The analysis of the field data began by comparing weighed discharge amounts to the amounts the spreader/controller would have indicated if the sensor on the auger was engaged. This value was obtained by multiplying the rate discharge value of 4.89 lbs/rev with the revolution count obtain for each of the scenarios. The 4.89 lbs/rev is the rate discharge value that was determined during the original calibration process. An examination of these two values (weighed discharge and computed discharge) indicated that something was not correct. However, the computed discharge did come very close to the theoretical discharge values, especially for the closed-loop mode of operation. The difference is 4 to 61 pounds. The next step in the analysis was to determine the actual rate of discharge. This value was determined by dividing the weighed discharge by the revolution count for each scenario. The results show that the actual rate of discharge (from 5.47 to 6.12 lbs/rev) approaches the valve that was determined during the re-calibration process. It is believed that the reasons for these high values are the results of the truck bed being raised all the time and the truck passing over many bumps in the roadway. The third step of the analysis was to determine the correct (or revised) number of revolutions if the spreader/controller were using the correct Calibration Constant. This was accomplished by multiplying the revolution count by the ratio of 14.5/15.7. This ratio was determined by using the two Calibration Constants that were identified in the two calibration procedures. By multiplying the revised revolution count by the measured discharge rate of 5.25 lbs/rev, it is possible to determine a modified actual discharge value. These values were used to calculate the percent of error of the modified actual discharge to theoretical discharge and percent of differences of modified actual discharge for manual and closed-loop. The results from the above processes can be observed in Table F-21.

From the above discussion, it can be shown that the actual discharge amounts and revolution counts in Table F-18 are larger than they should be, if appropriate calibration procedures are used. The over-estimation of these two quantities means that the percent of differences given in Table F-18 for the actual discharge for manual compared to closed-loop are actually underestimated, or smaller than they should be. The cause has to do with the calibration procedure used to generate the data in Table F-18, in particular and the calibration procedures used for tailgate spreaders in general.

From the above discussion and Table F-21, the comparison testing results show a material savings of 12 to 17 percent at an application rate of 200 lbs/mile and 42 to 47 percent at an application rate of 400 lbs/mile.

9.2 Missouri Comparison Testing Results

The data resulting from the comparison testing of closed-loop with manual mode of operation are given in Table G-18. Test data are presented for 14 test runs. Data from two of the 14 runs (Test Sets 1 and 6) were excluded from the analysis because the system's hydraulic fluid was not warmed enough for proper test results. This reduction in data provided information for four scenario runs (2 modes of operation **x** 2 dry salt application rates) for the closed-loop mode of operation and eight scenario runs (2 modes of operation **x** 2 dry salt application rates **x** 2 replications) for the manual mode of operation.

The local Missouri DOT personnel mounted a manual revolution counter on the conveyor shaft before the tests so that the total number of revolutions of the auger could be tracked during each scenario test. Data presented for each scenario run include: theoretical solid discharge amount; actual solid discharge amount; total number of shaft revolutions; solid discharge weight registered by the controller; two derived quantities based on a computed calibration constant; various percent of differences of actual and controller displayed discharges compared to theoretical discharge amounts; and the percent of differences of actual discharge amount for manual mode compared to closed-loop mode of operation. All of the percent of differences of discharge amounts (whether they be determined from actual, controller displayed, or computed discharge) compared to the theoretical discharge amounts are extremely small. The same is true for the percent of differences of actual discharge compared to the controller displayed discharge. These small percentage differences demonstrate the high degree of control the system had on the discharge amounts during the different scenario tests.

The testing results at the MoDOT facility showed a material savings of 7 to 12 percent for the freeway scenario when the application rate of 200 lbs/mile was used and a savings 9 to 11 percent for the freeway scenarios when the application rate of 400 lbs/mile was used. Material savings of 16 to 24 percent were found for the highway scenario when an application rate of 200 lbs/mile was used. Material savings of 15 to 17 percent were found for the highway scenario when an application rate of 400 lbs/mile was used. The material savings were based on comparing the ground-speed–controlled, closed-loop mode results to those results from the manual mode of operation.

9.3 Ohio Comparison Testing Results

The data resulting from the comparison testing of open-loop with manual modes of operation are given in Table L-17. Unfortunately, no direct comparison can be made from the data in Table L-17 between the two modes of operation. The simulation scenarios used for the open-loop mode tests were totally different from the simulation scenarios used for the manual mode tests. In addition, each manual mode test result can not be compared with the other manual mode test results because of changing test parameters from run to run. Consequently, the results obtained from the scenario tests in the manual mode are given only for informational purposes.

SECTION 10
CALIBRATION FACTORS AND CALIBRATION VERIFICATION PROCEDURES FOR GROUND-SPEED CONTROLLERS

A number of variables are described in Appendix C that relate to the calibration and use of solid material spreaders and associated prewetting systems. Many of these variables were investigated during the course of the study. This section of the report provides a discussion of the items that are important during the calibration and calibration verification of spreader/controller systems. The information is based on the controller manufacturers' recommendations plus notes and observations made during the yard and field tests.

A table of factors thought to be important in the calibration process was developed during the study. A copy of the table was sent to each of the six controller manufacturers involved in the study seeking their recommendations concerning the calibration factors. The table of factors is given in Appendix O.

The table of calibration factors is divided into six major categories:

- Truck speedometer and controller distance measurement check.
- Truck and spreader hydraulic system.
- Material spreader, hopper, truck body, gates and augers.
- Material to be tested.
- "Catch" or "drop" tests.
- Calibration frequency and record keeping.
- Items unique to the liquid prewetting calibration of the controllers

Responses from the controller manufacturers on the major items under each category are discussed below together with the relevant observation made during the study. General calibration items plus those pertaining to solid material spreaders are given first. These are followed by those items associated with the calibration of prewetting systems.

10.1 General Calibration Items and those Pertaining to Solid Material Spreaders

Eleven items are discussed below under this category.

10.1.1 Speedometer Calibration/Check

All the manufacturers address the importance of speedometer calibration. Some offer on-the-road verification while others rely on matching the speedometer display of the spreader truck to the speed readout on the controller.

10.1.2 Truck and Spreader Hydraulic System

All but one manufacturer addressed the importance of warming the truck's hydraulic oil to its normal operation temperature, however long that takes, before performing the calibration. This should be considered a standard operating procedure. Also, there is a strong recommendation that the calibration be conducted when the truck's engine RPM is at least 1500 RPM or at "spreading RPM" to make sure of full hydraulic pressure flow. It is necessary to engage the spreader's conveyor or auger, but not the spinner, during the calibration.

10.1.3 Recommended Load level in Truck Box or Hopper Box

There was not general agreement on this issue for hopper-box spreaders. The recommendations ranged from a minimum amount to run the calibration test, to a half load or greater. The amount used during the yard and field tests seem to work best when the hopper box was at least ½ full of dry material.

For tailgate spreader, the recommended load level ranged from the amount necessary to keep the auger fully covered with material throughout the calibration. Here again, the test seem to work best when the box was at least ½ full of dry material.

10.1.4 Box Position for Tailgate Spreaders

There was not general agreement on the box position during calibration of tailgate spreaders. The recommendations ranged from high enough to keep the auger covered at all times, to partially raised, to 45 degrees or higher. The data collected during the project strongly points to the need to calibrate tailgate spreaders with the truck bed continuously in a raised position that is normally used during snow and ice control operations. A truck bed vibrator should be used and activated periodically during the calibration of tailgate spreader/controller systems to ensure free flowing material is delivered to the auger.

10.1.5 Material to be Tested

This subject generally was not addressed by the manufacturers. However, experience gained during the yard and field test strongly indicates that the solid material should be representative and uniform, relatively lump free, and free of excessive moisture. Calibration constants i.e., lbs/rev, pulses/lb, etc. will be different for uniform, lump free, and dry salt than for salt that is aged and contains a crust or lumps from inactivity,

10.1.6 Recommended Amount of Solid Material Discharged

The recommended amount of solid material discharged during calibration depends on the controller's capability and the availability of commercial scales to determine large discharge amounts. The discharge amounts ranged from several hundred pounds, to one ton, to 25% of the truck load capacity. The amount discharged appears to be tied to the individual manufacturer's calibration procedure.

10.1.7 Recommended Time Duration of Discharge

The time duration of discharged is generally tied to the discharge amount used for calibration. Some manufacturers specified a 60 sec. time frame and one specified 5 times that duration. Thus, the recommended time duration of discharge appears to be tied to the individual manufacturer's calibration procedure.

10.1.8 Recommended Number of Tests or Other Precision Requirements

Several manufacturers specified that only a single calibration test was necessary. One manufacturer specified two tests were needed and one did not address this issue. One manufacturer recommended performing the calibration steps (with multiple discharges) and then verifying the actual output through a simulated ground-speed test. A version of this approach was followed during the field tests and proved highly successful at identifying calibration problems. This approach is referred to in other sections as a verification test. More will be said about this approach later in this section.

10.1.9 Does the Unit Allow for, or Require, "Fine Tuning" to meet Customer Expectation?

All but one manufacturer indicated that this provision was included in the calibration procedure to "back-into" the desired output by adjusting the controller solid discharge constant. This approach is also discussed later in this section in connection with running the calibration verification tests.

10.1.10 Recommended Frequency of Calibration

The response mainly given by the manufacturers on this item was annually, before snow and ice control operations begin. Provisions were also given for recalibration whenever major repair work was performed on the spreader truck. Recalibration should also be done whenever new solid material shipments are received that have bulk properties (uniformity, lump conditions, and high moisture content) that are significantly different from the material used in the pervious calibration.

10.1.11 Recommendations for Creating and Maintaining Repair and Calibration Records

All but two manufacturers recommended a file or electronic document be maintained for each spreader/controller combination that contained calibration factor(s) obtained during the (annual) calibration process. Results in Appendix F (Table F-22) demonstrate that the calibration constant for a given spreader/controller combination can vary considerably over a single snow and ice control season. The calibration constant found in the field is different than the factory default value. These results speak highly for the need to maintain a complete and up-to-date record of the calibration/repair history of each spreader/controller combination.

10.2 Calibration Items Associated with Prewetting System

Eight items are discussed below under this category.

10.2.1 Calibration or Fine Tuning of the Prewetting System

Most of the manufacturers do not provide a detailed procedure for the calibration of the prewetting system. The controller manufacturers mainly assume the liquid pump is calibrated by the pump vendor. In this case, the K-factor imprinted on the liquid pump housing, is manually entered into the controller during the calibration process. A few controller manufacturers will leave the fine tuning of the liquid pump up to the customer (highway agency) if they choose to pursue that interest.

10.2.2 Control Functions that Need to be Engaged During Liquid Calibration

Each manufacturer has their own requirements for control functions that need to be engaged during the calibration of the prewetting system. These requirements range from only having the liquid pump operating, to having the pump operating along with the solid conveyor and associated spinner.

10.2.3 Does Solid Material Need to be Discharged During Liquid Calibration?

Only one manufacturer answered "yes" to this question.

10.2.4 Are Nozzles to be left in the Liquid Discharge Line During Calibration?

The answer to this question was generally, “yes”. Most manufacturers recognize the importance of accounting for the nozzle back pressure in the operation of the system during calibration.

10.2.5 Type of Pump Used with Prewetting System

One manufacturer specified a hydraulic pump, one specified an electric pump, and the rest specified either type. Electric liquid pumps are probably falling out of preference because of the potential corrosion concern.

10.2.6 Can Water be Used During Calibration in Place of a Liquid Chemcial?

Only two manufacturers responded with a “no” answer. Here again, the requirement is left up to the manufacturer’s recommendation.

10.2.7 Recommended Amount of Liquid Discharge During Calibration

Two controller manufacturers do not address this issue. For these two manufacturers, it is up to the customer to decide if a discharge test is necessary to address any prewetting inaccuracy. Other controller manufacturers specify the amount of liquid discharge to be collected and measured.

10.2.8 Recommended Number of Tests or Other Precision Requirements

The manufacturers that specified the amount of liquid to be discharged during calibration also specified the number of tests to be performed. This and the previous item are very important for the calibration process. More will be said about these two items later in this section under verification tests.

10.2.9 Recommended Frequency of Calibration

Those controller manufacturers that address liquid calibration, specify that it should be done annually before snow and ice control operations begin. It should also be done after major work is performed on the spreader truck.

10.3 Calibration Verification Tests

Early in the field test portion of the study, it was decided that a way was needed to verify that the calibration of the spreader/controller systems were performed satisfactorily, or at least, as best as could be expected. The analysis of the yard test data showed that, immediately following the calibration of the spreader/controller system, the rate of discharge for both dry solid and liquid material could be easily verified by running a specific set of verification tests. The combination of variables selected for the calibration verification tests is shown in Table 10-1 along with the test discharge times and theoretical values for the solid and liquid discharge amounts.

Table 10-1. Calibration Verification Test Variables

Solid Application Rate (lbs/mile)	Liquid Application Rate (gal/ton)	Test Speed (mph)	Test Discharge Time (sec.)	Theoretical Values for Dry Solid Material (lbs)	Theoretical Values for Liquid Material (gals)
200	10	25	73	101.4	0.51
300	10	25	49	102.1	0.51
500	15	20	36	100.0	0.75
600	15	20	30	100.0	0.75

The calibration verification procedure amounted to running three discharge tests for each combination of variables, for a total of 12 tests. The solid discharge weight and liquid discharge volume for each of the 12 tests were recorded. The arithmetic average of the three tests for each combination of variables were computed and recorded. The discharge time for each combination of variables should produce amounts of solid material that are within ± 4 percent of the theoretical values shown in Table 10-1, at least for properly calibrated spreader/controller systems in the closed-loop mode of operation. If the discharge amounts were found to be more than ± 4 percent from expected values, the spreader/controller system would need to be recalibrated or the system would need to be "fine-tuned" to obtain, as close as possible, the theoretical discharge values given in Table 10-1 for the test discharge times.

Results are given in Table 10-2 from calibration verification tests performed with five spreader/controller combinations after they were calibrated by the respective manufacturer's representative according to the recommended procedures. The calibration verification tests for solid discharge were performed with the controller operated in the closed-loop mode. The data in the left column under Dickey-john Control Point were the results obtained after the first calibration attempt. The system was recalibrated by fine tuning the system to agree with the theoretical results of the verification tests. The improved results of this second calibration are given in the adjacent column. The data in the left column under Component Technology's units were the results obtained after calibration in connection with the comparison tests between closed-loop and open-loop modes of operation. The data in the adjacent column were obtained after calibration of the unit in connection with the comparison tests between closed-loop and manual modes of operation. It is clear that the Component Technology unit was operating closer to the theoretical discharge basis during the second set of simulation tests (second column) than during the first simulation tests. However, the system was performing satisfactorily during both sets of simulation tests.

Table 10-2. Results of Calibration Verification Tests of Five Spreader/Controller Combinations

Solid Discharge for Closed-loop Mode of Operation							
Solid Application Rate (lbs/mile)	Test Speed (mph)	Test Discharge Time (sec.)	Percent of Difference of Actual Discharge Compared to Theoretical				
			Cirus SpreadSmart	Dickey-john Control Point		Component Technology GL-400	
200	25	73	-3.4%	0.0%	-0.4%	-2.4%	-0.3%
300	25	49	-2.4%	2.3%	1.9%	-2.6%	-0.6%
500	20	36	-1.0%	5.2%	3.3%	-4.1%	0.2%
600	20	30	0.0%	5.2%	3.3%	-1.0%	-1.1%

Table 10-2. (cont.)

Solid Discharge for Closed-loop Mode of Operation				
Solid Application Rate (lbs/mile)	Test Speed (mph)	Test Discharge Time (sec.)	Percent of Difference of Actual Discharge Compared to Theoretical	
			FORCE America 5100	Muncie MESP402D
200	25	73	3.5%	-2.7%
300	25	49	6.5%	14.1%
500	20	36	4.3%	22.8%
600	20	30	9.1%	10.7%

The FORCE America 5100 unit shows some problems with the calibration, especially at the high application rate of 600 lbs/mile. The data for the Muncie unit shows definite problems with the operation of the spreader/controller combination. The calibration verification test results shown for the Muncie unit were obtained from an attempt to fine tune the system by backing into the expected verification test results. Evidently, the Muncie system either was not performing according to expectations or was performing as best as could be expected. It is not clear which is the case.

Results are given in Table 10-3 from calibration verification tests performed with three spreader/controller combinations after they were calibrated or attempted to be calibrated, according to the manufacturers' recommendation. The calibration verification tests for solid discharge were performed with the controller operated in the open-loop mode.

Table 10-3. Results of Calibration Verification Tests of Three Spreader/Controller Combinations

Solid Discharge for Open-loop Mode of Operation						
Solid Application Rate (lbs/mile)	Test Speed (mph)	Test Discharge Time (sec.)	Percent of Difference of Actual Discharge Compared to Theoretical			
			FORCE America 2100	Muncie MESP402D		Pengwyn 485
200	25	73	-24.7%	25.3%	0.0%	-19.3%
300	25	49	-13.0%	21.9%	-2.2%	12.4%
500	20	36	-18.8%	39.0%	7.9%	7.1%
600	20	30	-9.7%	46.0%	12.6%	6.2%

The data in the left column under Muncie were the results obtained after trying to calibrate the spreader/controller system without the help of the controller vendor. Subsequent tests with the unit were abandoned until the vendor could assist and direct the proper calibration of the unit. These results are given to illustrate the importance of knowing how to calibrate the Muncie unit. The data in the right column under Muncie were the results obtained after the spreader/controller combination was calibrated by a vendor representative using the manufacturer's recommended procedures.

It can be seen from Table 10-3, that controllers operated in the open-loop mode are limited in their performance, ever when calibrated according to the manufacturer's recommendations. The additional sensor that monitors the belt/auger activity in the closed-loop mode is so necessary to enhance the output performance of the spreader/control combination over that of the open-loop system.

Calibration verification test results are given in Table 10-4 for liquid discharges from four spreader/controller combinations when operated in the closed-loop mode. Similar calibration verification test results are given in Table 10-5 for liquid discharges from two spreader/controller combinations when operated in the open-loop mode. The data in the second column under Muncie in Table 10-5 are the results obtained after the unit was calibrated "properly" by the manufacturer's representative.

Table 10-4. Results of Calibration Verification Tests of Four Spreader/Controller Combinations

Liquid Discharge for Closed-loop Mode of Operation							
Solid Application Rate (lbs/mile)	Set Prewetting Rate (gals/ton)	Test Speed (mph)	Test Discharge Time (sec.)	Percent of Difference of Actual Discharge Compared to Theoretical			
				Cirus Spread Smart	Component Technology GL-400	FORCE America 5100	Muncie MESP 402D
200	10	25	73	4.5%	20.8%	18.3%	49.4%
300	10	25	49	-2.0%	20.0%	0.2%	0.0%
500	15	20	36	33.3%	0.0%	5.2%	-4.6%
600	15	20	30	4.0%	2.8%	3.9%	-7.9%

Table 10-5. Results of Calibration Verification Tests of Two Spreader/Controller Combinations

Liquid Discharge for Open-loop Mode of Operation						
Solid Application Rate, (lbs/mile)	Set Prewetting Rate, (gals/ton)	Test Speed (mph)	Test Discharge Time, (sec.)	Percent of Difference of Actual Discharge Compared to Theoretical		
				Muncie MESP402D		Pengwyn 485
200	10	25	73	0.4%	0.5%	1.6%
300	10	25	49	1.1%	0.2%	67.7%
500	15	20	36	20.0%	-9.4%	-16.3%
600	15	20	30	38.7%	-11.4%	-33.3%

It can be seen from Tables 10-4 and 10-5 that the technology for controlling the liquid discharge for prewetting applications needs some improvement in specific application rate areas.

10.4 Possible Way of Checking the Functioning of Ground-Speed Controllers Operated in Closed-loop Mode

Finally, as a side issue, it was observed from the simulated field test results (see Tables F-12, G-12, G-18, H-19, and J-12) that a way is available to determine if the spreader/controller is correctly functioning in the closed-loop mode of operation. That way is to drive (or use a speed simulator to operate) the spreader truck over a pre-determined route for a given distance (or time) at a pre-determined application rate and speed. The amount of material discharged that is registered by the controller can then be compared with the theoretical discharge amount for the pre-determined route length, application rates used (for both dry solid and liquid), and truck speed. If these two values are within ± 2 percent, one can make the judgment that the controller is functioning properly.

This approach, however, does not indicate that the actual rate of discharge is correct, but only that the controller is functioning properly. The actual discharge could be greater or less than the amount identified by the controller. This error could be attributed to the limitations of the spreader/controller system or an error in determining the rate of discharge from the tailgate auger or hopper-box conveyor.

SECTION 11
RECOMMENDATIONS FOR PROPER CALIBRATION OF SPREADER/CONTROLLER COMBINATIONS

This section of the report presents recommendations for the proper calibration of spreader/controller combinations. The recommendations are given separately for ground-speed-controlled material spreaders and for manually controlled spreaders. Ground-speed-controlled spreaders are further divided into closed-loop and open-loop modes of operation. The recommendations presented are based upon the project experience gained during the yard and field tests; from discussions and communication with the six controller manufacturers involved with the study; and from the review of published and unpublished literature.

Each manufacturer of ground-speed and manual controllers provides the user with a set of procedures for the calibration of the unit in connection with the spreader in which it is installed. The recommendations which follow for the proper calibration of spreader/controller combinations are not intended to replace the procedures specified by the controller manufacturer. Instead, the recommendations given in this report augment the manufacturers' recommendations with additional checks and balances such that the system can be operated in the field under the best possible control over material discharges. Many times, the limitations in accurate solid material discharge over the range of truck speed – application rate combinations investigated have more to do with the hydraulic flow capacity of the spreader truck than with the reliability of the controller. Similarly, the limitations observed in accurate liquid material discharge have more to do with the liquid pump design than with the design of the controller.

11.1 Calibration of Ground-Speed-Controller Salters

The calibrations of spreader/controllers operated in the ground-speed, closed-loop mode are discussed first followed by those systems operated in the ground-speed, open-loop mode.

11.1.1 Closed-loop Mode of Operations

1. Select dry, solid material for calibration that is: representative of the bulk material, uniform, relatively lump free, and free of excessive moisture.
2. Load the spreader truck to at least ½ full of the selected dry material.
3. Load the spreader truck's prewetting tanks, if available, to at least ½ full of liquid chemicals used in the prewetting process. Some controller manufacturers believe that water can be used in place of liquid chemicals during the calibration process. This condition was not investigated during the study. However, in light of the inaccuracies discovered with the prewetting systems, it is not recommended that water be substituted for the prewetting fluid. Not much difference was found during the study between the liquid discharge using sodium chloride and the liquid discharge using calcium chloride.
4. For hopper-box or V-box spreaders, select a single gate opening that will accommodate a full range of operating solid material application rates.
5. For tailgate spreaders, raise the truck-bed to an operational elevation and make sure that the auger is fully charged during the complete calibration process.
6. When calibrating the prewetting system, leave the spray nozzles in the discharge lines to account for back-pressure conditions.

7. Conduct the calibration of the spreader/controller combination according to the manufacturer's specifications. This includes performing any truck speedometer/controller distance checks required, preparing the truck and spreader hydraulic system for calibration, engaging all systems required during calibration, and performing the specified catch or drop tests.
8. Abort the calibration test(s) if a discontinuity in flow of either solid or liquid material discharge is observed.
9. Record the various solid and liquid calibration factors obtained and used during the calibration process.
10. Before conducting the calibration verification tests described next, disengage any controller feature that would cause a control valve to open to any position other than what is dictated for a specific catch or drop test. This step is necessary to eliminate the possibility of the control valve going to full open for a period of time after a start-up of the discharge mechanism. This same controller feature should also be disengaged before the calibration process is conducted, if that feature is automatically built into the controller's operation.
11. Conduct the calibration verification tests of both the solid and liquid discharges to check that the system is properly calibrated. This procedure requires running 4 sets of solid application rate – liquid application rate – truck speed combinations plus 3 replications of each set for a total of 12 tests. The combination of the calibration verification test variables is given below in Table 11-1.

Table 11-1. Calibration Verification Test Variables

Test Variable Set No.	Solid Application Rate (lbs/mile)	Liquid Application Rate (gal/ton)	Test Speed (mph)	Test Run Discharge Time (sec)
1	200	10	25	73
2	300	10	25	49
3	500	15	20	36
4	600	15	20	30

12. Record the solid and liquid discharge amounts for each test and determine the arithmetic average of both discharge amounts for each test verification set number.
13. Compare the arithmetic averages of the solid and liquid discharge amounts with the respective theoretical and acceptable range values given in Table 11-2. The acceptable ranges for both solid and liquid discharge amounts are based on ± 4 percent of the theoretical discharge amount.

Table 11-2. Theoretical and Acceptable Range Valves for Solid and Liquid Verification Discharge Amounts

Test Variable Set No.	Dry Solid Material		Liquid Material	
	Theoretical Discharge Amount (lbs)	Acceptable Discharge Range Amount (lbs)	Theoretical Discharge Amount (gals)	Acceptable Discharge Range Amount (gals)
1	101.4	97.3 to 105.5	0.51	0.49 to 0.53
2	102.1	98.0 to 106.2	0.51	0.49 to 0.53
3	100.0	96.0 to 104.0	0.75	0.72 to 0.78
4	100.0	96.0 to 104.0	0.75	0.72 to 0.78

14. Redo the calibration according to the manufacturer's specifications, if the results of the calibration verification tests do not agree with the acceptable ranges of the discharge amounts in Table 11-2. This activity might involve backing in, or "fine tuning", the calibration to obtain discharge results that agree, as best as possible, with the data in Table 11-2. It is very likely that the results of this approach will produce better agreement for some combinations of test variables than others. This is because of the system limitations discussed in Section 10 and identified during the yard tests. The main point here is to produce the best calibration possible for the range of field operations expected.
15. Record the final calibration constants in a log for each spreader/controller combination.

11.1.2 Open-loop Mode of Operations

1. Repeat the same steps used to calibrate spreader/controller combinations operated in a closed-loop mode, including those used to perform the calibration verification tests.
2. The results presented in Section 10 demonstrate that the spreader/controller systems operated in an open-loop mode, in general, can not be expected to achieve the same control over discharge rates as the closed-loop systems. However, it is very likely that fine tuning the open-loop systems with the calibration verification test results will produce better agreement for some combinations of test variables. Again, the main objective of running the calibration verification tests is to produce the best calibration possible for the range of field operations expected.
3. As in the calibration of the systems operated in a closed-loop mode, record the final calibration constants in a log for each spreader/controller combination.

11.2 Manually Controlled Salters

1. The calibration of ground-speed controlled systems that are operated in a manual mode should be conducted following the controller manufacturer's recommendation after certain preparatory steps are taken. These preparatory steps are the same as are used for the calibration of ground-speed controlled units operated in a close-loop or open-loop mode.
2. In one instance, the calibration amounted to selecting a truck speed, say 30 mph, and an application rate of 200 lbs/mile. Several catch tests were run for 60 sec until a

consistent discharge weight of 100 lbs was obtained. This approached produced a given calibration constant (lbs/pulse or lbs/revolution) within the controller.

3. The catch tests were repeated, as a check, using the same truck speed of 30 mph, but an application rate of 400 lbs/mile and 30 sec run times. The second catch tests, were performed until a consistent discharge weight of 100 lbs were obtained. The second catch tests produced a calibration constant in the controller that agreed with the constant obtained from the first catch tests.
4. The detents on the control knob provided application rates that were tied to the calibration rate of 200 lbs/mile.
5. The calibration of controllers that are designed only for manual modes of operation can be most readily accomplished by the following the procedure specified in the Salt Institute's Snowfighters Training Program (4). Here, the calibration of manually controller spreaders is simply calculating the pounds per mile discharged at various spreader control settings and truck speeds. This is accomplished by first counting the number of auger or conveyor shaft revolutions per minute, measuring the material discharged in one revolution, multiplying the two quantities together, and then finally multiplying the discharge rate by the minutes it takes to travel one mile. This procedure produces a calibration chart that provides a range of discharge (application) rates that are individually tied to specific truck speeds for a given control setting.
6. Checks of several discharge rates/control settings should be performed to verify that the calibration of the manually controlled system was performed correctly.
7. For hopper-box spreaders, the system needs to be calibrated for specific gate openings.
8. Finally, the calibration chart(s) for each spreader/controller operated in a manual mode needs to be recorded in a log and displayed in the truck cab for the operator's use.

SECTION 12
CONCLUSIONS, RECOMMENDATIONS, AND SUGGESTED RESEARCH

A number of conclusions, recommendations, and areas suggested for further research were developed from the study findings and are presented in this section. There are no priorities given to the order of the items listed under each category.

12.1 Conclusions

- Most state DOTs are currently using ground-speed controllers.
- Most ground-speed controllers in use are closed-loop systems.
- The number of manual controllers in service is much smaller than the number of ground-speed controls in use.
- Only about 6 percent of state DOT agencies are exclusively using manual controllers.
- The calibration techniques most commonly used by state DOT agencies are those recommended by the controller manufacturers.
- The calibration techniques used for determining the amount of liquid dispensed in prewetting solid material by ground-speed controllers are marginal, at best.
- Simple procedures were developed to estimate the solid and liquid discharge amounts from spreader/controller combinations.
- The theoretical discharge estimates proved highly useful in accessing the discharge capability of spreader/controller combinations.
- The yard tests of spreader/controller combinations were efficiently and effectively conducted following an experimental design.
- The yard test results provided a determination of the limitations of spreader/controller combinations relative to truck speed – material application rate combinations. Many times, the inaccurate solid material discharge amounts observed had more to do with the hydraulic flow capacity of the spreader truck than with the reliability of the controller. Similarly, the limitations observed in accurate liquid material discharge amounts had more to do with the liquid pump design than with the design of the controller.
- Statistical analysis of the yard test data provided an assessment of the bias, accuracy, and precision of all eight spreader/controller systems when distributing solid material and five of the eight systems when distributing a liquid material for prewetting purposes. No attempt was made to compare the performance of one system with another.
- Easy to use procedures were developed for documenting actual material discharge from ground-speed controllers during simulated snow and ice control operations that avoid the introduction of uncontrolled variables associated with on-the-road testing during wintertime maintenance operations.
- The simulated field testing produced solid and liquid discharge amounts that are fairly repeatable for closed-loop mode of operations.
- The simulated field testing produced results that demonstrated the solid and liquid discharge variability associated with open-loop mode of operations.
- Simulated field testing showed that the performance of the controller can be identified separately from the performance of the spreader/controller system.

- Variations in the performance of spreader/controller systems were noted from the simulation testing results.
- It was necessary to use a systems approach in the investigation of ground-speed controllers. The installation of a controller in a spreader truck does not alone guarantee the solid and liquid discharge goals will be automatically achieved.
- It was necessary to look at the truck's hydraulic system capacity, the hydraulic motor capacity for solid discharge, as well as the pumps used for liquid discharge in the evaluation of the spreader/controller combinations examined in the yard and simulated field studies.
- An evaluation of the suitability of a ground-speed controller to meet the highway agency's winter maintenance needs must not only include how well the controller functions, but also how well it interfaces with the existing truck-spreader systems. In the study, the controllers' capability was somewhat limited by the capacity of the truck-spreader systems.
- Greater discharge variation was noted with open-loop than with closed-loop modes of operation.
- Considerable savings in dry salt usage can be achieved in a rural highway environment using a closed-loop spreader/controller combination compared to a manually controlled spreader. The savings can be as large as 47 percent for an application rate of 400 lbs/mile.
- Greater savings in dry salt usage between closed-loop and manual modes of operation were noted for the highway scenario than for the freeway scenario. The savings found for the highway scenario were 2.2 and 1.6 times larger than the savings found for the freeway scenario for application rates of 200 lbs/mile and 400 lbs/mile, respectively.
- A number of variables associated with the calibration and use of solid material spreaders and prewetting systems were identified during the study.
- When calibrating tailgate spreader/controller systems, it is imperative that the truck bed be in a raised position, comparable to that used during normal snow and ice control operations. The field-operational, solid discharge amount will be about 6.5 percent higher than expected, if the tailgate spreader/controller system is calibrated with the truck bed in the lowered or level position.
- A satisfactory procedure was developed for calibration of ground-speed controller/spreader combinations that utilizes the controller manufacturer's procedure in conjunction with standardized preparation procedures and with a special verification testing protocol.

12.2 Recommendations

- The suitability of a particular ground-speed controller to meet the highway agency's winter maintenance needs must be determined from not only how well it performs, but also how well it interfaces with the truck's hydraulic capacity, the hydraulic motor capacity for solid discharge, as well as the pumps used for liquid discharge of the existing spreader-truck fleet.
- A statewide spreader/controller calibration program needs to be established using the information from the study and trained state field maintenance personnel.

- Spreader/controller systems need to be recalibrated periodically and, especially, after equipment maintenance is performed and new snow and ice control material is delivered to the maintenance garage locations.
- Procedures need to be established for maintaining calibration records for each spreader/controller combinations along with the equipment maintenance and repair histories.
- A number of issues were identified during the study that should be addressed through additional research. They are identified below.

12.3 Suggested Research

- Further yard/simulated field testing needs to be conducted with tailgate spreader/controller combinations to determine the effects of truck-bed elevation on the calibration constants and solid/liquid discharge results.
- Additional studies are needed to determine the amount of capacity variation between trucks within the fleet that use the same controller version.
- Further research is needed to develop test protocols for determining the effectiveness and efficiencies of prewetting systems. These protocols would be used to determine the limitations of the prewetting system output and also the compatibility of the prewetting systems with that of the solid discharge system.

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APPENDIX A
INSTRUMENTS USED IN THE SURVEY OF THE SNOW-BELT STATES

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Fax

To:	**From:**
Fax:	**Pages:**
Phone:	**Date:**
Re:	**CC:**

Thank you for agreeing to assist the Clear Roads pooled fund research team on a project dealing with the accuracy of snow and ice control material spreaders. Our task is to document the accuracy of ground-speed controlled material spreaders and investigate the performance of these units when compared to manually controlled spreaders. We are gathering information from many user organizations on the use of material spreaders and the products they dispense.

The following is a list of topics we would like to discuss with you.

- Types and number of ground-speed and manual controllers in use.
- Calibration techniques used for ground-speed and manual controllers.
- Spreader controller performance or calibration problems, especially those that are persistent.
- Any preferences about the use of either closed or open loop ground-speed control systems.
- Spreader material in use (salt, other dry chemicals, liquids, sand/abrasives, and mixes).
- Range of application rates used by material type.

Thank you for taking the time to review these topics. We look forward to talking with you.

Project No. 259169

CALIBRATION ACCURACY OF MANUAL AND GROUND-SPEED-CONTROLLED SALTERS

CONTACT REPORT

My name is ________________________. I am part of a research team with Blackburn and Associates working on a project for the Clear Roads pooled fund research program. The Clear Roads program focuses on field testing and evaluation of materials, methods, and equipment for winter highway maintenance. Seven mid-western state DOTs are part of the program. The project I am working on is managed by the Wisconsin Department of Transportation. The project objectives are to document the accuracy of calibrated ground-speed controlled material spreaders and investigate the performance of these units compared to manually controlled spreaders.

The purpose of this call is to obtain some basic information about spreader controllers and materials that your agency uses in your snow and ice control operations. We are also interested in any controller calibration problems you have experienced and any ideas you have for improving the calibration techniques. Information we are seeking includes such items as:

- Types and number of ground-speed and manual controllers in use.
- Calibration techniques used for ground-speed and manual controllers.
- Spreader controller performance or calibration problems, especially those that are persistent.
- Any preferences and experience relating to the use of closed and open loop ground-speed control systems.
- Materials being spread (salt, other dry chemicals, liquids, sand/abrasives, and mixes).
- Range of application rates for each material type.

The questions I have will take no more than 10 to 15 minutes of your time. The results of this study will benefit not only the states involved in the Clear Roads program but all other agencies involved in snow and ice control.

Agency: ____

Name: ___________________________________ Title: ___________________________

Address: _________________________________ Phone: __________________________

___________________________________ E-mail: __________________________

1. What are the manufacturers and models of material spreader controller units currently in use by your Agency? What are the approximate numbers of each type in service?

Manufacturer	Model	Type of Material spread		Type of Controller			Approximate number of controllers in service
					Ground Speed		
		Solid	Prewetted Solid	Manual	Open Loop	Closed Loop	

2. What manufacturers and models of spreader controller units are you currently specifying/purchasing and why?

____

____

3. Please provide the name, address and telephone number of the vendors currently supplying the spreader controllers.

Name	Address	Telephone No.

4. What calibration technique does your Agency use for the following controllers?
   a. Ground-speed controllers used for:
      1. Solid material?

      ____

      ____

      2. Prewetted solid?

      ____

b. Manual controllers? ____

____

Could you send the procedures to us? ______________________________________

5. How often are your spreader controllers calibrated? ___________________________

____

Who does the calibration in your Agency? ________________________________

____

6. What are the performance and repair histories of the controllers used by the Agency (by make and model)?

    a. Ground-speed controllers used for:

        1. Solid material?

        2. Prewetted solid?

    b. Manual controllers?

7. Are there persistent seemingly uncorrectable controller problems? If so, please specify by make and model.____

8. Can you identify any reason(s) to believe the controllers are not doing the intended job, and why? ____

9. Are the controllers user friendly? If not, why?

____

____

10. Are any data generated by the controllers used by the Agency? How?

____

____

____

11. Do you have any information relative to the performance of closed versus open loop ground-speed controller units?

____

____

____

12. What material types (salt, other dry chemicals, liquids, sand/abrasives, and mixes) and range of application rates are used by your Agency?

Solid Material type used	% Mixing ratio	Range of application rates of dry material (lbs/Lane-Mile)	Amount of liquid** used for prewetting (gal/ton)	Range of application rates of pre-wetted material (lbs/Lane-Mile)
Straight salt	100			
Other straight chemical*	100			
Straight sand/abrasive	100			
Salt/Sand or abrasive mix				

Note: * Dry chemical used: ____

** Type and % concentration of liquid used for prewetting: _______________

____

____

13. Do you have any suggestions for the team as we undertake the project? __________

____

____

____

The project team thanks you for your time and input. Do you have any questions?

APPENDIX B
SUMMARY OF RESULTS FROM THE SURVEY OF SNOW BELT STATES

Results of Snow Belt State Survey

Q 1. Number of Material Spreader Controllers in Service

State DOT	Ground-Speed Controller		Manual Controller
	Open Loop	Closed Loop	
Alaska			
Arizona	61	114	
California			
Colorado			
Connecticut		8	624
Delaware		9	**UNK**
Idaho	<20	415	
Illinois			
Indiana		965	149
Iowa		885	6
Kansas		585	
Kentucky		960	
Maine		500	
Maryland		600	900*
Massachusetts		**UNK****	
Michigan		325	
Minnesota	150	730	
Missouri		1300	500
Montana		300	300
Nebraska		210	
Nevada	75	73	
New Hampshire		**UNK**	
New Jersey		200	
New Mexico			
New York		1300	
North Carolina	1300		
North Dakota	110	70	170
Ohio		1600	
Oklahoma			
Oregon	100		300
Pennsylvania		1400	200
Rhode Island	**UNK**		
South Dakota		250	<10
Tennessee			**UNK**
Texas	60		60
Utah			
Vermont		**UNK**	300
Virginia	**UNK**	**UNK**	**UNK**
Washington	262		238
West Virginia		560	
Wisconsin	~230	~996	1292
Wyoming	10	35	10
Washington DC			100

Note: * = Operated by private contractors,
** = Premium paid to private contractors who use ground-speed controllers
UNK = Unknown number

Q2a. Manufacturers/Models of Controller Units Currently being Specified/Purchased

State DOT	Manufacturer/Model Number										
	Component Technology GL-400	Dickey-john Control Point	Dickey-john ICS 2000	FORCE America	Cirus's Spread Smart RDS	Muncie Power Products MESP 3200 Series	Pengwyn Series 5100	Raven Model 710	Tyler Zero-Velocity	Gresen/Parker	Others
Alaska											
Arizona				X							
California											
Colorado											
Connecticut					X						
Delaware	X										
Idaho				X	X			X			
Illinois											
Indiana						X					
Iowa					X			X			
Kansas				X	X						
Kentucky			X	X							
Maine											a
Maryland		X	X								a
Massachusetts											a
Michigan		X	X								
Minnesota		X	X								
Missouri	X										
Montana					X						
Nebraska	X			X				X			
Nevada											b
New Hampshire											a
New Jersey											a, c
New Mexico											
New York			X								
North Carolina											d
North Dakota	X			X						X	
Ohio				X			X				
Oklahoma											
Oregon				X							
Pennsylvania	X										
Rhode Island											c
South Dakota				X							
Tennessee											d
Texas					X						
Utah											
Vermont			X								
Virginia											f
Washington			X								
West Virginia	X	X									
Wisconsin				X	X						
Wyoming	X										
Washington DC											e

Note: a = Compu-Spread, b = IMAC Integraded System, c = Salt Mizer,
d = Specifying only ground-speed controllers - no preference
e = Specifying only manual controllers, f = Gremil

Q 2b. Reasons for Specifying/Purchasing Specific Controler Models

State DOT	Reasons						
	Uniformity of fleet/familarity	Low bid/cost	Easy to use, maintain, modify	Electric over hydraulic controls	Integrated system	Performance specification	Other
Alaska							
Arizona			x				
California							
Colorado							
Connecticut							X
Delaware							X
Idaho				X			
Illinois							
Indiana	X						
Iowa						X	
Kansas	X						
Kentucky						X	
Maine			X				
Maryland			X			X	
Massachusetts		X				X	
Michigan	X						
Minnesota	X			X	X		
Missouri				X			
Montana			X	X			
Nebraska	X						
Nevada					X		
New Hampshire			X				
New Jersey			X				
New Mexico							
New York	X		X			X	
North Carolina						X	
North Dakota			X				
Ohio	X			X			
Oklahoma							
Oregon			X				
Pennsylvania	X		X			X	
Rhode Island						X	
South Dakota	X						
Tennessee						X	
Texas			X				
Utah							
Vermont	X		X			X	
Virginia						X	
Washington			X		X		
West Virginia						X	
Wisconsin	X	X	X				
Wyoming		X					
Washington DC						X	

Q 4a.1 Calibration Technique Used for Ground-Speed Controllers of Solid Material

State DOT	Technique				
	Manufacturer's recommendation		Agency developed	Salt Institute procedure	None
	Yard test	Road test			
Alaska					
Arizona	X				
California					
Colorado					
Connecticut	X	X		X	
Delaware	X	X		X	
Idaho	X		X		
Illinois					
Indiana				X	
Iowa	X				
Kansas	X	X			
Kentucky	X				
Maine	X	X			
Maryland	X	X			
Massachusetts	X	X			
Michigan	X				
Minnesota	X				
Missouri		X			
Montana	X				
Nebraska	X				
Nevada	X		X		
New Hampshire	X	X	X		
New Jersey	X	X			
New Mexico					
New York	X	X	X		
North Carolina	X				
North Dakota	X		X		
Ohio	X				
Oklahoma					
Oregon	X		X		
Pennsylvania	X	X			
Rhode Island	X	X			
South Dakota	X				
Tennessee					N/A
Texas					X
Utah					
Vermont	X	X	X		
Virginia	X	X			
Washington	X				
West Virginia	X				
Wisconsin	X				
Wyoming		X			
Washington DC					N/A

Note: **N/A** = Not Applicable

Q 4a.2 Calibration Techniques used for Ground-Speed Controllers of Prewetted Solid Material

State DOT	Technique		
	Manufacture's recommendation	Agency developed	None
Alaska			
Arizona	X		
California			
Colorado			
Connecticut	X		
Delaware	X		
Idaho	X		
Illinois			
Indiana			X
Iowa	X		
Kansas	X		
Kentucky	X		
Maine	X		
Maryland	X		
Massachusetts	X		
Michigan	X		
Minnesota			X
Missouri			X
Montana	X		
Nebraska	X		
Nevada	X		
New Hampshire	X		
New Jersey	X		
New Mexico			
New York	X		
North Carolina	X		
North Dakota			X
Ohio	X		
Oklahoma			
Oregon	X		
Pennsylvania	X		
Rhode Island	X		
South Dakota			X
Tennessee			N/A
Texas			X
Utah			
Vermont			
Virginia	X		
Washington	X		
West Virginia			X
Wisconsin	X		
Wyoming	X		
Washington DC			N/A

Note: **N/A** = Not Applicable

Q4.b Calibration Technique Used for Manual Controllers

State DOT	Technique			
	Manufacturers's recommendation	Agency developed	Salt Institute procedure	None
Alaska				
Arizona				N/A
California				
Colorado				
Connecticut			X	
Delaware			X	
Idaho				N/A
Illinois				
Indiana			X	
Iowa			X	
Kansas				N/A
Kentucky				N/A
Maine				N/A
Maryland				UNK
Massachusetts				N/A
Michigan				N/A
Minnesota				X
Missouri	X			
Montana			X	
Nebraska				N/A
Nevada				N/A
New Hampshire				N/A
New Jersey				N/A
New Mexico				
New York				N/A
North Carolina				N/A
North Dakota	X			
Ohio				N/A
Oklahoma				
Oregon				X
Pennsylvania			X	
Rhode Island				N/A
South Dakota	X			
Tennessee				X
Texas				X
Utah				
Vermont				X
Virginia			X	
Washington			X	
West Virginia				N/A
Wisconsin			X	
Wyoming	X			
Washington DC				X

Notes: **N/A** = Not Applicable
UNK = Unknows

Q5, a & b How Often are the Controllers Calibrated and by Whom

State DOT	How Often Calibrated?					Who Does Calibration?				
	Annually	After vehicle hydraulic service	Infrequently	Do not calibrate	Unknown	Central HQ	District shop	Calibration team	Local mechanic	Operator
Alaska										
Arizona	X					X				
California										
Colorado										
Connecticut	X	X						*	X	
Delaware	X	X					X			
Idaho	X						X			
Illinois										
Indiana	X									X
Iowa	X	X ?								X
Kansas	X								X	
Kentucky	X								X	
Maine	X	X						X		
Maryland	X	X					X			
Massachusetts	X	X				**				
Michigan		X					X			
Minnesota	X	X							X	
Missouri	X						X			
Montana	X	X				X				
Nebraska	X								X	
Nevada	X								X	
New Hampshire		X					X			
New Jersey	X	X					X			
New Mexico										
New York	X	X						X		
North Carolina	X									X
North Dakota			X							X
Ohio	X	X							X	
Oklahoma										
Oregon			X						X	
Pennsylvania	X	X					X			
Rhode Island	X	X						*		
South Dakota	X	X							X	
Tennessee				X						
Texas				X						
Utah										
Vermont	X	X					X			
Virginia		X						*		
Washington	X	X							X	
West Virginia				X						
Wisconsin	X	X							X	
Wyoming	X									
Washington DC				X						

Note: * = Supervisor, ** = Vendor

Q 6a.1 Performance/Repair Histories of Ground-Speed Controllers Used with Solid Material

State DOT	Performance/Repair Problems							
	Sensor failure	Wiring failure and/or corrosion	Agency radio frequency interference	Program errors	Long time/difficult to repair	Electric plug susceptible to damage	Other	None
Alaska								
Arizona	X	X						
California								
Colorado								
Connecticut								X
Delaware	X							
Idaho					X			
Illinois								
Indiana	X							
Iowa							X	
Kansas								X
Kentucky	X	X						
Maine								X
Maryland		X						
Massachusetts								X
Michigan								X
Minnesota	X	X						
Missouri		X				X		
Montana			X					
Nebraska								X
Nevada								X
New Hampshire								X
New Jersey								X
New Mexico								
New York		X						
North Carolina								**Not Provided**
North Dakota	X				X			
Ohio	X						X	
Oklahoma								
Oregon								X
Pennsylvania								X
Rhode Island								X
South Dakota	X							
Tennessee								**N/A**
Texas								X
Utah								
Vermont								X
Virginia								X
Washington								X
West Virginia								X
Wisconsin	X	X						
Wyoming								X
Washington DC								**N/A**

Note: **N/A** = Not Applicable

Q 6a.2 Performance/Repair Histories of Ground-Speed Controllers Used with Prewetted Solid Material

State DOT	Performance/Repair Problems								
	Pump failure	Flow meter problems	Electrical problems	Filter clogging	Corrosion of wiring	Corrosion of electric pump	Not reliable	Other	None
Alaska									
Arizona					X				
California									
Colorado									
Connecticut									X
Delaware									
Idaho									X
Illinois									
Indiana									X
Iowa								X	
Kansas									X
Kentucky									X
Maine									X
Maryland									X
Massachusetts									X
Michigan									X
Minnesota									None Provided
Missouri									X
Montana	X		X						
Nebraska									X
Nevada						X			
New Hampshire									X
New Jersey									X
New Mexico									
New York									X
North Carolina									None Provided
North Dakota	X								
Ohio	X							X	
Oklahoma									
Oregon			X						
Pennsylvania									X
Rhode Island									
South Dakota									X
Tennessee									N/A
Texas								X	
Utah									
Vermont									
Virginia									X
Washington									X
West Virginia									X
Wisconsin	X	X	X	X			X		
Wyoming								X	
Washington DC									N/A

Note: **N/A** = Not Applicable

Q 6b. Performance/Repair Histories of Manual Controllers

State DOT	Performance/Repair Problems			
	Very few problems	User friendly	Other	None
Alaska				
Arizona				**N/A**
California				
Colorado				
Connecticut				**X**
Delaware				**X**
Idaho				**N/A**
Illinois				
Indiana				**X**
Iowa			**X**	
Kansas				**N/A**
Kentucky				**N/A**
Maine				**N/A**
Maryland				**X**
Massachusetts				**N/A**
Michigan				**N/A**
Minnesota				**N/A**
Missouri				**X**
Montana				**X**
Nebraska				**N/A**
Nevada				**N/A**
New Hampshire				**N/A**
New Jersey				**N/A**
New Mexico				
New York				**N/A**
North Carolina				**N/A**
North Dakota	**X**			
Ohio				**N/A**
Oklahoma				
Oregon			**X**	
Pennsylvania				**X**
Rhode Island				**N/A**
South Dakota				**X**
Tennessee				**X**
Texas				**X**
Utah				
Vermont				**X**
Virginia				**X**
Washington				**X**
West Virginia				**N/A**
Wisconsin	**X**	**X**		
Wyoming			**X**	
Washington DC				**X**

Note: **N/A** = Not Applicable

Q 7. Persistent Seemingly Uncorrectable Controller Problems

State DOT	Type of Problems									
	Cable connection corrosion	Vibration	Electronics	Defalt to manual/blast mode	Sensor assembly	Difficult to repair	Liquid rate unknown	Solid material output inaccurate	Other	None indentified
Alaska										
Arizona	X			X				X		
California										
Colorado										
Connecticut										X
Delaware										X
Idaho					X					
Illinois										
Indiana										X
Iowa										X
Kansas										X
Kentucky										X
Maine										X
Maryland										X
Massachusetts										X
Michigan										X
Minnesota										X
Missouri	X									
Montana										X
Nebraska										X
Nevada							X			
New Hampshire										X
New Jersey										X
New Mexico										
New York										X
North Carolina										X
North Dakota						X				
Ohio					X					
Oklahoma										
Oregon									X	
Pennsylvania										X
Rhode Island										X
South Dakota										X
Tennessee										X
Texas										X
Utah										
Vermont										X
Virginia										X
Washington										X
West Virginia										X
Wisconsin	X	X	X							
Wyoming										X
Washington DC										X

Q 8. Reasons to Believe Controllers Not Doing Intended Job

State DOT	Reasons Controllers not Doing Intended Job				
	No	Material moisture content	Salt gradation/tunneling	Sensor(s) failure not evident to operator	Other
Alaska					
Arizona			X		
California					
Colorado					
Connecticut	X				
Delaware	X				
Idaho	X				
Illinois					
Indiana	X				
Iowa	X				
Kansas	X				
Kentucky	X				
Maine	X				
Maryland	X				
Massachusetts	X				
Michigan	X				
Minnesota				X	
Missouri				X	
Montana	X				
Nebraska	X				
Nevada	X				
New Hampshire	X				
New Jersey	X				
New Mexico					
New York	X				
North Carolina	X				
North Dakota	X				
Ohio	X				
Oklahoma					
Oregon					X
Pennsylvania	X				
Rhode Island	X				
South Dakota	X				
Tennessee	X				
Texas	X				
Utah					
Vermont	X				
Virginia	X				
Washington	X				
West Virginia	X				
Wisconsin		X	X		
Wyoming	X				
Washington DC	X				

Q 9. Controllers User Friendly

State DOT	User Friendly?						
	Yes	More than one type of controller causes confusion	Too many control buttons	Scrolled display confusing	Hard to set calibration factors	Controller console not positioned well in cab	Other
Alaska							
Arizona						X	
California							
Colorado							
Connecticut	X						
Delaware	X						
Idaho			X				
Illinois							
Indiana							X
Iowa	X						
Kansas		X					
Kentucky	X						
Maine	X						
Maryland	X*						
Massachusetts	X*						
Michigan	X						
Minnesota	X						
Missouri				X	X		
Montana	X						
Nebraska	X						
Nevada	X					X	
New Hampshire	X						
New Jersey	X						
New Mexico							
New York	X						
North Carolina	X						
North Dakota	X						
Ohio	X						
Oklahoma							
Oregon			X				
Pennsylvania	X						
Rhode Island	X						
South Dakota							X
Tennessee	X						
Texas							X
Utah							
Vermont	X						
Virginia	X						
Washington	X						
West Virginia							X
Wisconsin	X	X					
Wyoming	X						
Washington DC	X						

Note: * = User friendy through manufacturer training

Q 10. Any Data Generated by the Controllers Used by Agency?

State DOT	Controlller Data Used?				
	Yes			Not yet, but planned	No
	Supervisors operators, and mechanics use for material inventory reporting	Download data into spreadsheets	Some, but unknown		
Alaska					
Arizona			X		
California					
Colorado					
Connecticut					X
Delaware					X
Idaho				X	
Illinois					
Indiana					X
Iowa					X
Kansas	X				
Kentucky			X		
Maine				X	
Maryland				X	
Massachusetts				X	
Michigan	X				
Minnesota	X				
Missouri	X	X			
Montana				X	
Nebraska			X		
Nevada		X			
New Hampshire					X
New Jersey					X
New Mexico					
New York	X				
North Carolina					X
North Dakota		X			
Ohio					?
Oklahoma					
Oregon				X	
Pennsylvania				X	
Rhode Island					X
South Dakota					X
Tennessee					X
Texas					X
Utah					
Vermont					X
Virginia					X
Washington		X			
West Virginia					X
Wisconsin	X		X		X
Wyoming					X
Washington DC					

Q 11. Any Information on Performance of Closed vs. Open Loop Systems?

State DOT	Any Information?			
	Closed loop better	**Open loop better**	**Both have problems**	**No**
Alaska				
Arizona	X			
California				
Colorado				
Connecticut				X
Delaware				X
Idaho	X			
Illinois				
Indiana		X		
Iowa	X			
Kansas	X			
Kentucky				X
Maine				X
Maryland				X
Massachusetts				X
Michigan	X			
Minnesota	X			
Missouri	X			
Montana				X
Nebraska				X
Nevada				X
New Hampshire	X			
New Jersey				X
New Mexico				
New York				X
North Carolina				X
North Dakota	X			
Ohio	X			
Oklahoma				
Oregon				X
Pennsylvania				
Rhode Island				
South Dakota	X			
Tennessee				**N/A**
Texas				X
Utah				
Vermont				X
Virginia				X
Washington				
West Virginia	X			
Wisconsin	X		X	X
Wyoming				X
Washington DC				**N/A**

Note: **N/A** = Not Applicable

Q 12. What Material Types and Ranges of Application Rates Used?

State DOT	Material Types and Application Rate Range				
	Straight salt (lbs/lane-mile)	Other straight chemical (lbs/land-mile)	Straight sand/abrasive (lbs/lane mile)	Salt/sand or abrasive mix (lbs/lane-mile)	Amount of liquid chemical used for prewetting (gal/ton)
Alaska					
Arizona	50-300	50-300	500-3000	500-3000	5 to 7
California					
Colorado					
Connecticut	215			150	
Delaware	300-400				8 to 10
Idaho			500-550		5 to 7.5
Illinois					
Indiana	250				10
Iowa	80-400				17-24
Kansas	200-500			200-500	8 to 10
Kentucky	250-400				8
Maine	110-400			400-800	6 to 10
Maryland	300-1000				10
Massachusetts	240			300	8 to 10
Michigan	200-450				6 TO7
Minnesota	100-400			Variable	6 TO 10
Missouri	100-400			200-800	10 TO 15
Montana	≤200			850-2000	6
Nebraska	100-1000				10
Nevada	50-200			70-300	What looks good
New Hampshire	150-750			750	
New Jersey	350±				10
New Mexico					
New York	90-450			600-900	8 to 10
North Carolina	150-500	VARIES	200	50/50 500	
North Dakota	0-2000			10/90 TO 50/50	8 to 10
Ohio	50-600				8 to 10
Oklahoma					
Oregon	?		3/8*		5
Pennsylvania	250			250-1000	6 to 8
Rhode Island	200-500				20 to 30
South Dakota	Not known				
Tennessee	200-350	CMA***			10
Texas	None				
Utah					
Vermont	100-300				
Virginia	250-500			250	
Washington	50-250		60-800		15
West Virginia	100-450		750	50/50 450	
Wisconsin	100-400			200-600	4 to 10
Wyoming	100-200			500-1000	12 to 15
Washington DC	100-400				30 to 50**

Note: * = 3/8 cubic-yard/lane-mile
** = liquid brine application
*** = Unknown rate

Q 13. Suggestions for Project?

- Solicit controller manufacturers' participation in, and observation of, yard and field tests.

- Need to look at compatibility of systems i.e., controller, solid material spreader, and prewetting

- Need to know what controllers are marketed and what experience/guidance is available for selecting appropriate units

- Controller manufacturers need to know data elements of use to winter highway maintenance agencies

- Need to know when the solid material discharge is prematurely disrupted.

- None

- Consider moisture content and gradation

APPENDIX C

VARIABLES ASSOCIATED WITH THE CALIBRATION AND USE OF SOLID AND LIQUID DISTRIBUTION AND PREWETTING SYSTEMS

Controlling Variables During The Calibration And Use of Solid Material Spreaders

A number of variables associated with the calibration and real world usage of solid material spreaders were identified in the team's proposal for the project. Additional variables and equipment control measures were identified in the course of gathering information from highway agencies, equipment manufacturers, and other interested parties. The key variables are product delivery, product consistency, truck/spreader hydraulic system, amount of material discharged during calibration test method, speed/rate of discharge dynamics, flight bars on conveyor belts, calibration test method equipment, and various items associated with determining the speed and delivery constants for computer based material application controllers. Each of these variables is summarized below together with an associated list of identified calibration/use control measures and the team's recommended approach to control the variables during calibration/use.

Product Delivery Variables

The uniformity of product delivery through the "gate" or auger can vary. Common causes of this variation include: "tunneling" of material in the dump/hopper body, chunks clogging the gate and inconsistent delivery of product to the auger (tailgate spreaders).

Identified Control Measures

- Use body or hopper vibrators, if available.
- Control gradation and moisture content of product.
- Cover loads (to prevent additional water).
- Keep body up at cab level.
- Use timer to know when to raise body
- Use "non delivery" sensors
- Screen product material before it enters the hopper or dump body.
- Mix composite materials in drum or pug mill mixer.

Team Recommendation

The impact of product delivery variables will be determined, initially after the yard testing, and finally, after the field testing is complete.

Product Variability

Here the real world has to be addressed. The common snow and ice materials, of necessity, have inherent variability in terms of particle size distribution, moisture content, "chunking", compaction within dump/hopper body, and blending ratios.

Identified Control Measures

- Pre-mix material in pug mill or drum mixer.
- Specify and test: particle size distribution, moisture content and purity.
- Screen product before loading (truck screens or grizzly).
- Use volumetric measurements for calibration and on-road distribution.
- Abort calibration test if discontinuity is observed (particularly with spring release gates).

Team Recommendation

For calibration purposes, the team recommends that the product should be as uniform as reasonably possible. This may mean the creation of a small pile of material for the purpose of calibration that has been selected and mixed to be reasonably uniform (some hand work may be necessary). Recommendations for field control will follow the yard and field test phases of this project.

Truck/Spreader Hydraulic System

The primary issues are temperatures of the hydraulic fluid (in the reservoir) and the pumping capacity of the system.

Identified Control Measures

- Warm engine 10-15 minutes.
- Calibrate only after "significant" hydraulic use.
- Measure temperatures and fill level of hydraulic fluid in reservoir.
- Perform annual calibration.
- Engage all hydraulic functions that are normally used during spreading operations.

Team Recommendation

The team recommends warming the hydraulic system by high volume usage for at least 15 minutes prior to calibration. Pumping capacity issues will show up during calibration if all hydraulic functions that are normally in operation during plowing and spreading operations, are engaged.

Amount of Material Discharged During Calibration

There must be a sufficient amount of material discharged during a calibration test to "represent" the process.

Identified Control Measures

- Use "sufficient" material.
- Use a truckload of material.
- Use one full revolution of shaft.

Team Recommendation

The team recommends that minimum captured discharge amount "float" with the rate of discharge. This is: approximately a 2 minute discharge for the lowest rate setting and approximately a one (1) minute discharge for the highest rate setting

Load Pressure on Conveyor

The loading on the conveyor varies with the amount of material in the hopper. The impact of this variable is unknown.

Identified Control Measures

- Use one-half (½ load).
- Use full load.
- Shield conveyor (this does not work well).

Team Recommendation

The team recommends using at least one-half (1/2) load during calibration and testing for this impact in the yard study phase of this project.

Accuracy and Precision of Calibration Test Method

Accuracy and precision attributes are usually defined by taking multiple samples of a process or product. There is little of that being done in the industry.

Identified Control Measures

- Take at least three samples.

- Take samples until range is within limits based on number of samples.
- Test at different discharge rates.

Team Recommendation

The impact of this variable will be addressed in the “yard test” phase of the project.

Speed/Rate of Discharge Dynamics

It is not known if the conveyor/auger speed produces a truly linear relationship with product discharge.

Identified Control Measures

- Calibration tests at high and low end of discharge rate range.

Team Recommendation

The impact of this variable will be addressed in the “yard test” phase of the project.

Flight Bars on Conveyor Belts

These devices are placed on conveyor belts to assist in product movement. At low conveyor speeds, they can result in inconsistent on-road delivery.

Identified Control Measures

- Highest possible conveyor speeds
- Uniform positioning of flight bars prior to calibration test
- Over-wrapping conveyor flight bars with belting or similar material.

Team Recommendation

The team recommends the highest possible conveyor speed (consistent with application rate requirements) and uniform positioning of flight bars prior to material capture as control measures.

Calibration Test Method Equipment Variables (Team Recommendations)

These include the accuracy of weighing equipment, devices used to measure shaft rotation, time measuring devices and any volumetric devices. The variables and recommended control measures follow.

Weighing Equipment

- Calibrate with certified weighing equipment.
- Calibrate with standard weights.
- Calibrate with known volumes of water.

Shaft Rotation Measurement Devices

- Calibrate electrical devices with mechanical devices.
- Use percentage protractors to assist in counting small numbers or shaft revolutions.

Devices used to Volumetrically Measure Material Discharged

- Make sure measurement device has a uniform cross section and an integral bottom.

Time Measurement Devices

- Calibrate measuring device with atomic clock

Variables Associated with Determining "Speed" and "Delivery" Constants for Computer Based Material Application Controllers (Team Recommendations)

Measured Distance on Highway or other Area

- Establish distance by survey, or
- Establish distance with a calibrated electronic distance measuring device.

Starting and Stopping Discharge or Speed Test

- Use "aiming point" system on truck.

Minimum Measured Distance

- Use 2640 ft. as a minimum.

Minimum Amount of Material in a Test Sample

- Use 1 minute of time as a minimum.

Discharge Speeds Tested

- Test at the high and low ends as a minimum.

CALIBRATION OF LIQUID SNOW AND ICE MATERIALS DISTRIBUTION AND PREWETTING SYSTEMS

There are basically three control mechanisms for the liquid systems:

- Fixed output (limited control)
- Gravity output (limited control)
- Proportional control (where the hydraulic flow to the pump motor is proportional to that of the solid material spreader)
- True ground speed control (where pump motor speed is related to ground speed)

Fixed output systems (electric or hydraulic) provide one output rate that is controlled by nozzle size, electric motor speed or hydraulic valve mechanism to dispense the desired amount of liquid for the most common application rate. They do not change application flow rate with changes in ground speed or solid material application rate. There may be cab control of application rate if a variable control valve or motor control is used.

Some agencies use "gravity" systems for road treatment to eliminate problems with pumps and wiring. As the liquid becomes lower in the tank, truck speed must be reduced to achieve the same application rate as when the tank was full. For reasonable accuracy in application rate, a calibrated relationship between tank fill level and truck speed must be established.

Proportional control is exclusively found in prewetting systems. Here, increased flow to the solid material spreader results in increased flow to the prewetting system.

The recommended calibration procedure for all of these systems is about the same as it is for solid materials. It involves capturing and weighing, or volumetrically measuring, liquid discharge amounts for various solid product output rates and/or ground speed. The single most important issue is to be sure that the output conditions are the same as in field use (nozzle size, valve opening, etc. The goal being, to keep the downstream pressure as constant as possible for all discharge rates. In reality, this is only achieved with pressure sensitive nozzles.

APPENDIX D
BACKGROUND OF PROJECT AND ASSISTANCE NEEDED FROM CLEAR ROADS STATES FOR YARD AND FIELD STUDIES

Accuracy of Ground-Speed-Controlled Snow and Ice Control Material Spreaders

The purpose of this document is to provide some background on a Clear Roads project and the assistance needed from the Clear Roads states involved in the maintenance yard and field studies of that project

Background

Ground-speed controllers have been used on snow plow and material (salt and sand) spreader trucks in place of manual controllers since the early 1990s. The accuracy of ground-speed controllers has not been fully determined through systematic testing and evaluation.

A Clear Roads Pooled Fund research study was initiated in October 2005 with the consulting firm of Blackburn and Associates to investigate the calibration accuracy of manual and ground-speed-controlled salters. The Clear Roads program focuses on field testing and evaluation of material, methods, and equipment used in winter highway maintenance. Seven mid-western state DOTs, including Indiana, Iowa, Ohio, Michigan, Minnesota, Missouri, and Wisconsin, are part of the program which is also supported by the Federal Highway Administration. The spreader accuracy project is managed by the Wisconsin Department of Transportation and will be conducted over a two-year period.

The overall objective of the research is to document the accuracy of calibrated ground-speed-controller units along with the performance of these units as compared to manual spreader controls. Actual salt, abrasive, and prewetting liquid chemical dispensing rates from spreader trucks with various types of manual and ground-speed-controller units will be determined and documented from both a maintenance yard study and in the field during winter storm events. The recommended calibration procedure for determining the accuracy of manual and ground-speed controlled spreaders will be applicable to both state and local highway agencies.

The scope of the research is divided into three phases. The first phase has been completed and consisted of a literature search and survey of Snow Belt states to access the types of manual and ground-speed-controller equipment in use, and their calibration and operational experiences with the equipment. Manufacturers of ground-speed controllers in use by the Clear Roads members were surveyed to determine their recommended calibration procedures.

The second phase, now underway, will be a yard or bench study of new ground-speed and manual controllers. The new equipment will be calibrated according to the manufacturer's recommendations or a newly developed one and then tested in accordance with a developed protocol in the maintenance yard to document actual discharge amounts.

The third phase of the study will document actual material usage in the field during winter storm events for both manually controlled units and ground-speed-controller units. The fieldwork will be conducted over one winter season.

Assistance Needed from Clear Roads States Involved in Yard/Field Studies

The levels of assistance that are needed from the Clear Roads states involved in the yard and field studies are described below, beginning with the yard/bench study (Phase 2).

Phase 2 – Yard or bench Study

The yard or bench study will be conducted over a six-month period starting about mid-March and continuing until mid-September. The actual testing in the maintenance yards will begin sometime in early May and will continue into late June depending on when the yard tests in the selected states can be scheduled. The Phase 2 work is to be done with new or recently purchased ground-speed and manual controllers. It is possible that new manual controllers will not be available for testing, but that some tests will need to be conducted with ground-speed controllers that are operated in a manual mode. The yard tests will involve:

3. Calibrating the units according to the manufacturer's recommendations; and
4. Multiple (verification) testing of the newly calibrated units to document the actual discharge rates at various settings.

A member of the project team will be overseeing the calibration and verification testing at a given work location. He will work closely with, and seek the advice of, the work location DOT maintenance personnel during the yard study. **The maintenance yard personnel will be performing the tests.**

During the yard tests, it will be necessary to jack up the rear axels and block the front wheels of the spreader truck and make multiple measurements of discharge rates at various speeds as indicated by the speedometer. The discharged material being collected includes: straight salt, a 95/5 sand/salt mix (in one location), and a prewetting liquid chemical(s) that is used by the highway agency. The maintenance yard equipment, facilities, and material needed for the yard testing include:

- The same spreader truck that will be used in both the yard and field studies with the appropriate controller and necessary prewetting system mounted.
- A known road distance near the maintenance yard where the spreader truck odometer and speedometer can be checked.
- About 5 cu yd of each uniformly prepared granular material to be tested that is stored under cover and free of chunks with dimensions larger than the discharge gate opening.
- A calibrated weighing device that will accommodate up to 200 pounds of discharged granular weight.

- A device for catching the discharged granular material. (A plastic 2'x3'x1' deep or deeper mason tub used for mixing mortar might work.)
- Enough prewetting liquid chemical in the truck tanks to carry out a number of tests (tanks at least ½ full).
- Adaptor hoses suited to capture the entire liquid chemical released from the spray nozzles during prewetting tests.
- A 4 to 5-gallon graduated container for catching the discharged liquid chemical material plus several 1-gallon graduated containers.
- A mechanism for storing the discharged liquid chemical for reuse.
- A stop watch.
- A way to mechanically keep a constant vehicle speed during each discharge test (such as with a throttle, if equipped). Perhaps a fan belt tensioner and a stick might work in the absence of a throttle.
- A set of highway cones to warn people of rotating rear truck wheels.
- Hard hats.
- A small tarp to help retain discharged granular material.
- Shovels, brooms, wheelbarrows, etc. to help in collecting the discharged granular material.

It is anticipated the team will require the assistance of 3 to 4 agency people to conduct the tests which includes at least one operator plus the use of one loader.

A representative of the controller manufacturer will be encouraged to observe the yard tests. This activity will be coordinated by the project team member overseeing the yard tests at a given location.

The team estimates that it will take up to 4 days to complete the yard testing of a given controller. The schedule for testing is somewhat at the discretion of the work location, but it would be highly beneficial for the project if the testing days are consecutive. Rainy days are okay as long as the work can be done in a salt storage building or other covered location.

Phase 3 – Field Study

The field study will be conducted during the winter of 2006/2007 with test preparation work starting as early as September 2006. The field testing will consist of equipment calibration plus documentation of actual material usage in the field during winter storm events. The team will be comparing the output of the spreader(s) as indicated by the controller with computations based on motor shaft revolutions as indicated by a mechanical counter for as many spreading runs as possible during the 2006/2007 winter season. The actual methodology for the field study will be developed based on the results of the yard testing. It would be good to have the same work location for both the yard and field studies in a given state and necessary to utilize the same spreader truck/controller for both studies.

The field testing will be pretty much incidental to normal snow and ice control operations with the exception of data collection training, data collection, and the installation of a mechanical revolution counter near the spreader motor drive shaft.

The team member overseeing the yard testing at a given work location will also be the one providing the data reporting training, the associated data recording forms, and the necessary oversight for the field testing at that work location.

APPENDIX E
PROCEDURE FOR COMPUTING THEORETICAL SOLID AND LIQUID DISCHARGE AMOUNT

Theoretical Discharge

Purpose

The rate of discharge material from a ground-speed-controller is dependent on a number of variables. For solid material discharge, there are two variables; speed (MPH) of the spreader vehicle and the dial-in application rate (lbs/mile) for the controller. For liquid material discharge, there are three variables; speed (MPH) of the spreader vehicle, dial-in solid application rate (lbs/mile) for the controller, and dial-in prewetting application rate (gallons/ton) for the controller. In order to make evaluations of the various rates of discharging material from the ground-speed-controller, an approach was developed where as the number of variables are reduced to only one variable; for solid material discharge: lbs/second, and for liquid discharge: liquid ounces/second. These computed rates are identified as "Theoretical Rates" and are used to determine the theoretical discharge rate for a given speed and dial-in application rate. These computed theoretical discharges rates are considered as the "gold standard" when evaluating the actual discharges from a ground-speed-controller. The external influencing variables such as; test time, timing errors, limitations of the hydraulic system, and operator influences are not factored into these theoretical rates.

Computation for Determining Theoretical Material Dispensing per Second

<u>Solid Discharge Rate</u>

The first step in computing the theoretical solid discharge rate (lbs/sec.) is to convert the dial-in solid application rate of lbs/mile to lbs/foot.

(1) $$\text{lbs/foot} = \frac{\text{lbs / mile}}{5280 \text{ ft / mile}}$$

Step two is to convert the vehicle speed (MPH) to distance traveled in one second.

(2) $$\text{ft/sec} = \frac{\text{miles / hour} \times 5280 \text{ ft / mile}}{60 \text{ min/ hour} \times 60 \text{ sec/ min}}$$

$$= \text{miles / hour} \times 1.467 \frac{\text{feet} \times \text{hour}}{\text{mile} \times \text{sec.}}$$

Step three is to determine the rate of solid material being dispensed while traveling at a given speed per second. Multiply equation #1 by equation #2 provides the expression for lbs/sec:

(3) $\text{lbs/sec.} = \text{lbs/foot} \times \text{feet/sec}$.

Liquid Discharge Rate

To determine the theoretical liquid discharge rate (ounces/second), it is necessary to convert the dial-in prewetting rate of gallons/ton to dispensed liquid in ounces/second. The first step is to convert the dial-in prewetting rate (gals/ton) to liquid ounces/pound.

$$\text{ounces/lb} = \frac{\text{gals/ton} \times 128 \text{ liquidounces/gallon}}{2000 \text{ lbs/ton}}$$

$$= \text{gals/ton} \times 0.064 \frac{\text{ozs} \times \text{ton}}{\text{gallons} \times \text{lbs}}$$

The next step is to determine amount of liquid ounces dispensed per second for a given dial-in prewetting rate and a given speed of vehicle (MPH). This is accomplished by multiply rate of solid material dispense (lbs/sec) for a given speed (MPH) by the rate of dispensed liquid ounces per pound. Multiply equation #3 by equation #4, yields:

(5) $\text{ounces/sec.} = \text{lbs/sec.} \times \text{ounces/lb}$

Using the above equations, various computations have been made to develop a number of tables that provides the theoretical rates for solid and liquid discharges. The parameters of the three identified variables that were used in the development of those tables are as follows:

1. Vehicle speed of 5 MPH to 45 MPH with intervals of 5 MPH
2. Dial-in solid application rate of 50 lbs/mile to 800 lbs/mile with intervals of 50 lbs/mile
3. Dial-in prewetting application rate of 5 gals/ton to 30 gals/ton with intervals of 5 gals/ton.

The results from those computations are contained in Tables E-1 thru E-7.

Table E-1 provides the theoretical rate of solid material being dispensed for various combinations of vehicle speed and dial-in solid application rates. Tables E-2 thru E-7 provides the theoretical rates of liquid material being dispensed for the various dial-in application rates combinations for solid and prewetting material at a given vehicle speed.

Application

Using the data sets that were collected from the various ground-speed-controllers during the yard study, the data was converted to actual solid discharge rates in lbs/second and liquid discharge in ounces/second. These data values along with the theoretical discharge rates taken from the tables were compared by plotting the theoretical and actual discharge rates versus test set numbers.

In the field study, the theoretical amount of discharge for each simulate scenarios were computed by multiply the theoretical dispensing rate by amount of time for each task to obtain the theoretical discharge quantity of material (solid, liquid).

Table E-1. Rate of Solid Material Dispense per Second at Various Vehicle Speeds

Vehicle Speed	Distance traveled in one second	Pounds/Mile															
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800
		Pounds/Foot															
MPH	Feet	0.00947	0.018939	0.028409	0.037879	0.047348	0.056818	0.066288	0.075758	0.085227	0.094697	0.104167	0.113636	0.123106	0.132576	0.142045	0.151515
5	7.333	0.069	0.139	0.208	0.278	0.347	0.417	0.486	0.556	0.625	0.694	0.764	0.833	0.903	0.972	1.042	1.111
10	14.667	0.139	0.278	0.417	0.556	0.694	0.833	0.972	1.111	1.250	1.389	1.528	1.667	1.806	1.944	2.083	2.222
15	22.000	0.208	0.417	0.625	0.833	1.042	1.250	1.458	1.667	1.875	2.083	2.292	2.500	2.708	2.917	3.125	3.333
20	29.333	0.278	0.556	0.833	1.111	1.389	1.667	1.944	2.222	2.500	2.778	3.056	3.333	3.611	3.889	4.167	4.444
25	36.667	0.347	0.694	1.042	1.389	1.736	2.083	2.431	2.778	3.125	3.472	3.819	4.167	4.514	4.861	5.556	5.556
30	44.000	0.417	0.833	1.250	1.667	2.083	2.500	2.917	3.333	3.750	4.167	4.583	5.000	5.417	5.833	6.250	6.667
35	51.333	0.486	0.972	1.458	1.944	2.431	2.917	3.403	3.889	4.375	4.861	5.347	5.833	6.319	6.806	7.292	7.778
40	58.667	0.556	1.111	1.667	2.222	2.778	3.333	3.889	4.444	5.000	5.556	6.111	6.667	7.222	7.778	8.333	8.889
45	66.000	0.625	1.250	1.875	2.500	3.125	3.750	4.375	5.000	5.625	6.250	6.875	7.500	8.125	8.750	9.375	10.000

Table E-2. Rate of Liquid Ounces Dispense per Second for Various Dial-In Prewetting Rates for Vehicle Speed of 20 mph

Prewetting Rate in Gallons/Ton	Dispense Liquid Ounces per Second	Pounds/Mile															
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800
		Pounds/Foot															
		0.00947	0.018939	0.028409	0.037879	0.047348	0.056818	0.066288	0.075758	0.085227	0.094697	0.104167	0.113636	0.123106	0.132576	0.142045	0.151515
		Rate of Solid Material Dispense per Second at Vehicle Spreed of 20 MPH															
		0.278	0.556	0.833	1.111	1.389	1.667	1.944	2.222	2.500	2.778	3.056	3.333	3.611	3.889	4.167	4.444
5	0.320	0.089	0.178	0.267	0.356	0.444	0.533	0.622	0.711	0.800	0.889	0.978	1.067	1.156	1.244	1.333	1.422
10	0.640	0.178	0.356	0.533	0.711	0.889	1.067	1.244	1.422	1.600	1.778	1.956	2.133	2.311	2.489	2.667	2.844
15	0.960	0.267	0.533	0.800	1.067	1.333	1.600	1.867	2.133	2.400	2.667	2.933	3.200	3.467	3.733	4.000	4.267
20	1.280	0.356	0.711	1.067	1.422	1.778	2.133	2.489	2.844	3.200	3.556	3.911	4.267	4.622	4.978	5.333	5.689
25	1.600	0.444	0.889	1.333	1.778	2.222	2.667	3.111	3.556	4.000	4.444	4.889	5.333	5.778	6.222	6.667	7.111
30	1.920	0.533	1.067	1.600	2.133	2.667	3.200	3.733	4.267	4.800	5.333	5.867	6.400	6.933	7.467	8.000	8.533

Table E-3. Rate of Liquid Ounces Dispense per Second for Various Dial-In Prewetting Rates for Vehicle Speed of 25 mph

Prewetting Rate in Gallons/Ton	Dispense Liquid Ounces per Second	Pounds/Mile															
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800
		Pounds/Foot															
		0.00947	0.018939	0.028409	0.037879	0.047348	0.056818	0.066288	0.075758	0.085227	0.094697	0.104167	0.113636	0.123106	0.132576	0.142045	0.151515
		Rate of Solid Material Dispense per Second for Vehicle Spreed of 25 MPH															
		0.347	0.694	1.042	1.389	1.736	2.083	2.431	2.778	3.125	3.472	3.819	4.167	4.514	4.861	5.208	5.556
5	0.320	0.111	0.222	0.333	0.444	0.556	0.667	0.778	0.889	1.000	1.111	1.222	1.333	1.444	1.556	1.667	1.778
10	0.640	0.222	0.444	0.667	0.889	1.111	1.333	1.556	1.778	2.000	2.222	2.444	2.667	2.889	3.111	3.333	3.556
15	0.960	0.333	0.667	1.000	1.333	1.667	2.000	2.333	2.667	3.000	3.333	3.667	4.000	4.333	4.667	5.000	5.333
20	1.280	0.444	0.889	1.333	1.778	2.222	2.667	3.111	3.556	4.000	4.444	4.889	5.333	5.778	6.222	6.667	7.111
25	1.600	0.556	1.111	1.667	2.222	2.778	3.333	3.889	4.444	5.000	5.556	6.111	6.667	7.222	7.778	8.333	8.889
30	1.920	0.667	1.333	2.000	2.667	3.333	4.000	4.667	5.333	6.000	6.667	7.333	8.000	8.667	9.333	10.000	10.667

Table E-4. Rate of Liquid Ounces Dispense per Second for Various Dial-In Prewetting Rates for Vehicle Speed of 30 mph

Prewetting Rate in Gallons/Ton	Dispense Liquid Ounces per Second	Pounds/Mile															
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800
		Pounds/Foot															
		0.00947	0.018939	0.028409	0.037879	0.047348	0.056818	0.066288	0.075758	0.085227	0.094697	0.104167	0.113636	0.123106	0.132576	0.142045	0.151515
		Rate of Solid Material Dispense per Second for Vehicle Spreed of 30 MPH															
		0.417	0.833	1.250	1.667	2.083	2.500	2.917	3.333	3.750	4.167	4.583	5.000	5.417	5.833	6.250	6.667
5	0.320	0.133	0.267	0.400	0.533	0.667	0.800	0.933	1.067	1.200	1.333	1.467	1.600	1.733	1.867	2.000	2.133
10	0.640	0.267	0.533	0.800	1.067	1.333	1.600	1.867	2.133	2.400	2.667	2.933	3.200	3.467	3.733	4.000	4.267
15	0.960	0.400	0.800	1.200	1.600	2.000	2.400	2.800	3.200	3.600	4.000	4.400	4.800	5.200	5.600	6.000	6.400
20	1.280	0.533	1.066	1.600	2.134	2.666	3.200	3.734	4.266	4.800	5.334	5.866	6.400	6.934	7.466	8.000	8.534
25	1.600	0.667	1.333	2.000	2.667	3.333	4.000	4.667	5.333	6.000	6.667	7.333	8.000	8.667	9.333	10.000	10.667
30	1.920	0.800	1.599	2.400	3.201	3.999	4.800	5.601	6.399	7.200	8.001	8.799	9.600	10.401	11.199	12.000	12.801

Table E-5. Rate of Liquid Ounces Dispense per Second for Various Dial-In Prewetting Rates of Vehicle Speed of 35 mph

Prewetting Rate in Gallons/Ton	Dispense Liquid Ounces per Second	Pounds/Mile															
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800
		Pounds/Foot															
		0.00947	0.018939	0.028409	0.037879	0.047348	0.056818	0.066288	0.075758	0.085227	0.094697	0.104167	0.113636	0.123106	0.132576	0.142045	0.151515
		Rate of Solid Material Dispense per Second for Vehicle Spreed of 35 MPH															
		0.486	0.972	1.458	1.944	2.431	2.917	3.403	3.889	4.375	4.861	5.347	5.833	6.319	6.806	7.292	7.778
5	0.320	0.156	0.311	0.467	0.622	0.778	0.933	1.089	1.244	1.400	1.556	1.711	1.867	2.022	2.178	2.333	2.489
10	0.640	0.311	0.622	0.933	1.244	1.556	1.867	2.178	2.489	2.800	3.111	3.422	3.733	4.044	4.356	4.667	4.978
15	0.960	0.467	0.933	1.400	1.866	2.334	2.800	3.267	3.733	4.200	4.667	5.133	5.600	6.066	6.534	7.000	7.467
20	1.280	0.622	1.244	1.866	2.488	3.112	3.734	4.356	4.978	5.600	6.222	6.844	7.466	8.088	8.712	9.334	9.956
25	1.600	0.778	1.555	2.333	3.110	3.890	4.667	5.445	6.222	7.000	7.778	8.555	9.333	10.110	10.890	11.667	12.445
30	1.920	0.933	1.866	2.799	3.732	4.668	5.601	6.534	7.467	8.400	9.333	10.266	11.199	12.132	13.068	14.001	14.934

TableE-6. Rate of Liquid Ounces Dispense per Second for Various Dial-In Prewetting Rates for Vehicle Speed of 40 mph

Prewetting Rate in Gallons/Ton	Dispense Liquid Ounces per Second	Pounds/Mile															
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800
		Pounds/Foot															
		0.00947	0.018939	0.028409	0.037879	0.047348	0.056818	0.066288	0.075758	0.085227	0.094697	0.104167	0.113636	0.123106	0.132576	0.142045	0.151515
		Rate of Solid Material Dispense per Second for Vehicle Spreed of 40 MPH															
		0.556	1.111	1.667	2.222	2.778	3.333	3.889	4.444	5.000	5.556	6.111	6.667	7.222	7.778	8.333	8.889
5	0.320	0.178	0.356	0.533	0.711	0.889	1.067	1.244	1.422	1.600	1.778	1.956	2.133	2.311	2.489	2.667	2.844
10	0.640	0.356	0.711	1.067	1.422	1.778	2.133	2.489	2.844	3.200	3.556	3.911	4.267	4.622	4.978	5.333	5.689
15	0.960	0.533	1.067	1.600	2.133	2.667	3.200	3.733	4.267	4.800	5.333	5.867	6.400	6.933	7.467	8.000	8.533
20	1.280	0.711	1.422	2.133	2.844	3.556	4.267	4.978	5.689	6.400	7.111	7.822	8.533	9.244	9.956	10.667	11.378
25	1.600	0.889	1.778	2.667	3.556	4.444	5.333	6.222	7.111	8.000	8.889	9.778	10.667	11.556	12.444	13.333	14.222
30	1.920	1.067	2.133	3.200	4.267	5.333	6.400	7.467	8.533	9.600	10.667	11.733	12.800	13.867	14.933	16.000	17.067

Table E-7. Rate of Liquid Ounces Dispense per Second for Various Dial-In Prewetting Rates for Vehicle Speed of 45 mph

Prewetting Rate in Gallons/Ton	Dispense Liquid Ounces per Second	Pounds/Mile															
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800
		Pounds/Foot															
		0.00947	0.018939	0.028409	0.037879	0.047348	0.056818	0.066288	0.075758	0.085227	0.094697	0.104167	0.113636	0.123106	0.132576	0.142045	0.151515
		Rate of Solid Material Dispense per Second for Vehicle Spreed of 45 MPH															
		0.625	1.250	1.875	2.500	3.125	3.750	4.375	5.000	5.625	6.250	6.875	7.500	8.125	8.750	9.375	10.000
5	0.320	0.200	0.400	0.600	0.800	1.000	1.200	1.400	1.600	1.800	2.000	2.200	2.400	2.600	2.800	3.000	3.200
10	0.640	0.400	0.800	1.200	1.600	2.000	2.400	2.800	3.200	3.600	4.000	4.400	4.800	5.200	5.600	6.000	6.400
15	0.960	0.600	1.200	1.800	2.400	3.000	3.600	4.200	4.800	5.400	6.000	6.600	7.200	7.800	8.400	9.000	9.600
20	1.280	0.800	1.600	2.400	3.200	4.000	4.800	5.600	6.400	7.200	8.000	8.800	9.600	10.400	11.200	12.000	12.800
25	1.600	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10.000	11.000	12.000	13.000	14.000	15.000	16.000
30	1.920	1.200	2.400	3.600	4.800	6.000	7.200	8.400	9.600	10.800	12.000	13.200	14.400	15.600	16.800	18.000	19.200

APPENDIX F
TEST RESULTS FOR CIRUS SPREADSMART RDS

Results from Yard Tests

Table F-1. Values of Truck Speed, Solid Discharge Rate, Prewetting Rate, and Test Run Time for Each Test Number Used in Yard Testing

Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec
1	20	100	20	60	16	35	200	5	60
2	20	200	25	60	17	35	300	25	45
3	20	400	10	60	18	35	600	30	30
4	20	600	15	60	19	35	700	10	30
5	20	800	30	45	20	35	800	15	30
6	25	100	15	60	21	40	200	20	60
7	25	300	10	60	22	40	300	15	45
8	25	500	20	60	23	40	400	5	30
9	25	600	5	60	24	40	500	25	30
10	25	700	25	30	25	40	700	30	30
11	30	100	30	60	26	45	100	10	60
12	30	300	5	60	27	45	400	30	30
13	30	400	20	45	28	45	500	5	20
14	30	600	25	30	29	45	700	15	20
15	30	800	10	30	30	45	800	20	20

Summary Tabulations of Solid and Liquid Discharge Rates

Table F-2. Actual and Estimated Solid Discharge Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	91.5	189.0	**350.8**	390.5	**468.6**	609.0	**586.4**	797.0
25	102.0	**259.8**	297.2	**377.6**	496.4	588.8	576.8	**613.2**
30	111.0	**227.7**	309.4	395.6	**404.4**	544.7	**522.2**	532.6
35	**136.7**	201.7	314.1	**313.4**	**372.3**	431.4	457.7	446.3
40	**104.6**	193.8	291.7	400.8	388.0	**399.1**	388.5	**516.9**
45	102.9	**131.5**	**190.4**	316.9	347.3	**367.1**	322.0	318.7

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table F-3. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	-8.5%	-5.5%	**16.9%**	-2.4%	**-6.3%**	1.5%	**-16.2%**	-0.4%
25	2.0%	**29.9%**	-0.9%	**-5.6%**	-0.7%	-1.9%	-17.6%	**-23.4%**
30	11.0%	**13.9%**	3.1%	-1.1%	**-19.1%**	-9.2%	**-25.4%**	-33.4%
35	**36.7%**	0.8%	4.7%	**-21.7%**	**-25.5%**	-28.1%	-34.6%	-44.2%
40	**4.6%**	-3.1%	4.7%	0.2%	-22.4%	**-33.5%**	-44.5%	**-35.4%**
45	2.9%	**-34.3%**	**-36.5%**	-20.8%	-30.5%	**-38.8%**	-54.0%	-60.2%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table F-4. Actual and Estimated Discharge Prewetting Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial–In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**9.6**	9.8	14.4	21.3	25.2	18.5
25	5.1	10.1	17.4	19.8	21.9	**23.2**
30	5.6	14.6	**14.6**	18.6	17.4	**22.9**
35	6.7	13.2	17.5	**17.0**	23.8	18.5
40	5.2	**11.2**	14.6	18.8	17.3	17.1
45	7.5	11.3	18.6	19.1	**19.2**	18.6

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table F-5. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed

Speed in mph	Dial–In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**92.0%**	-2.0%	-4.0%	6.5%	0.8%	-38.3%
25	2.0%	1.0%	16.0%	-1.0%	-12.4%	**-22.7%**
30	12.0%	46.0%	**-2.7%**	-7.0%	-30.4%	**-23.7%**
35	34.0%	32.0%	16.7%	**-15.0%**	-4.8%	-38.3%
40	4.0%	**12.0%**	-2.7%	-6.0%	-30.8%	-43.0%
45	50.0%	13.0%	24.0%	-4.5%	**-23.2%**	-38.0%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table F-6. Regression Coefficients for Determination of Missing Test Discharge Values

Material	Rate Coefficient	Speed Coefficient	Intercept	R - squared
	A1	A2	B	(as percent)
Solid	0.589	-6.416	302.387	76.4%
Liquid	0.555	-0.062	8.102	68.2%

Table F-7. Percent of Error for Solid Discharge as a Function of Time

Set #	Test Run Time, sec.	Truck Speed, mph	Theoretical Solid Discharge, lbs/sec	Test Solid Discharge, lbs/sec	Percent of Error	Set Solid Discharge Rate, lbs/mile	Test Solid Discharge Rate, lbs/mile	Percent of Error
1	60	20	0.556	0.508	-8.63%	100	91.5	-8.50%
2	60	20	1.111	1.050	-5.49%	200	189.0	-5.50%
3	60	20	2.222	2.170	-2.34%	400	390.5	-2.38%
4	60	20	3.333	3.383	1.50%	600	609.0	1.50%
6	60	25	0.694	0.708	2.02%	100	102.0	2.00%
7	60	25	2.083	2.063	-0.96%	300	297.2	-0.93%
8	60	25	3.472	3.447	-0.72%	500	496.4	-0.72%
9	60	25	4.167	4.088	-1.90%	600	588.8	-1.87%
11	60	30	0.833	0.925	11.04%	100	111.0	11.00%
12	60	30	2.500	2.578	3.12%	300	309.4	3.13%
16	60	35	1.944	1.962	0.93%	200	201.7	0.85%
21	60	40	2.222	2.153	-3.11%	200	193.8	-3.10%
26	60	45	1.250	1.287	2.96%	100	102.9	2.90%
5	45	20	4.444	4.429	-0.34%	800	797.0	-0.38%
13	45	30	3.333	3.296	-1.11%	400	395.6	-1.10%
17	45	35	2.917	3.053	4.66%	300	314.1	4.70%
22	45	40	3.333	3.240	-2.79%	300	291.7	-2.77%
10	30	25	4.861	4.007	-17.57%	700	576.8	-17.60%
14	30	30	5.000	4.540	-9.20%	600	544.7	-9.22%
15	30	30	6.667	4.437	-33.45%	800	532.6	-33.43%
18	30	35	5.833	4.193	-28.12%	600	431.4	-28.10%
19	30	35	6.806	4.450	-34.62%	700	457.7	-34.61%
20	30	35	7.778	4.340	-44.20%	800	446.3	-44.21%
23	30	40	4.444	4.453	0.20%	400	400.8	0.20%
24	30	40	5.555	4.310	-22.41%	500	388.0	-22.40%
25	30	40	7.778	4.317	-44.50%	700	388.5	-44.50%
27	30	45	5.000	3.960	-20.80%	400	316.9	-20.78%
28	20	45	6.250	4.340	-30.56%	500	347.3	-30.54%
29	20	45	8.750	4.025	-54.00%	700	322.0	-54.00%
30	20	45	10.000	4.140	-58.60%	800	318.7	-60.16%

Table F-8. Percent of Error for Prewetting Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Liquid Discharge, ozs/sec	Test Liquid Discharge, ozs/sec	Percent of Error	Set Prewetting Application Rate, gals/ton	Test Prewetting Discharge Rate, gals/ton	Percent of Error
1	60	20	0.711	0.692	-2.67%	20	21.3	6.50%
2	60	20	1.778	1.693	-4.78%	25	25.2	0.80%
3	60	20	1.422	1.362	-4.22%	10	9.8	-2.00%
4	60	20	3.200	3.115	-2.66%	15	14.4	-4.00%
6	60	25	0.667	0.788	18.14%	15	17.4	16.00%
7	60	25	1.333	1.337	0.30%	10	10.1	1.00%
8	60	25	4.444	4.367	-1.73%	20	19.8	-1.00%
9	60	25	1.333	1.333	0.00%	5	5.1	2.00%
11	60	30	1.599	2.943	84.05%	30	N/D	
12	60	30	0.800	0.930	16.25%	5	5.6	12.00%
16	60	35	0.622	0.845	35.85%	5	6.7	34.00%
21	60	40	2.844	2.593	-8.83%	20	18.8	-6.00%
26	60	45	0.800	0.933	16.63%	10	11.3	13.00%
5	45	20	8.533	5.304	-37.84%	30	18.7	-37.67%
13	45	30	4.266	3.918	-8.16%	20	18.6	-7.00%
17	45	35	4.667	4.656	-0.24%	25	23.8	-4.80%
22	45	40	3.200	3.038	-5.06%	15	14.6	-2.67%
10	30	25	7.778	5.607	-27.91%	25	21.9	-12.40%
14	30	30	8.000	5.047	-36.91%	25	17.4	-30.40%
15	30	30	4.267	4.147	-2.81%	10	14.6	46.00%
18	30	35	11.199	4.973	-55.59%	30	18.5	-38.33%
19	30	35	4.356	3.773	-13.38%	10	13.2	32.00%
20	30	35	7.467	4.857	-34.95%	15	17.5	16.67%
23	30	40	1.422	1.463	2.88%	5	5.2	4.00%
24	30	40	8.889	4.767	-46.37%	25	17.3	-30.80%
25	30	40	14.933	4.733	-68.31%	30	17.1	-43.00%
27	30	45	9.600	4.713	-50.91%	30	18.6	-38.00%
28	20	45	2.000	2.085	4.25%	5	7.5	50.00%
29	20	45	8.400	4.790	-42.98%	15	18.6	24.00%
30	20	45	12.800	4.865	-61.99%	20	19.1	-4.50%

Note: N/D = No Data

Table F-9. Theoretical and Test Solid Discharges as a Function of Increasing Theoretical Solid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Theoretical Solid Discharge, lbs/sec	Test Solid Discharge, lbs/sec
1	20	100	20	60	0.556	0.508
6	25	100	15	60	0.694	0.708
11	30	100	30	60	0.833	0.925
2	20	200	25	60	1.111	1.050
26	45	100	10	60	1.250	1.287
16	35	200	5	60	1.944	1.962
7	25	300	10	60	2.083	2.063
3	20	400	10	60	2.222	2.170
21	40	200	20	60	2.222	2.153
12	30	300	5	60	2.500	2.578
17	35	300	25	45	2.917	3.053
4	20	600	15	60	3.333	3.383
13	30	400	20	45	3.333	3.296
22	40	300	15	45	3.333	3.240
8	25	500	20	60	3.472	3.447
9	25	600	5	60	4.167	4.088
5	20	800	30	45	4.444	4.429
23	40	400	5	30	4.444	4.453
10	25	700	25	30	4.861	4.007
14	30	600	25	30	5.000	4.540
27	45	400	30	30	5.000	3.960
24	40	500	25	30	5.555	4.310
18	35	600	30	30	5.833	4.193
28	45	500	5	20	6.250	4.340
15	30	800	10	30	6.667	4.437
19	35	700	10	30	6.806	4.450
20	35	800	15	30	7.778	4.340
25	40	700	30	30	7.778	4.317
29	45	700	15	20	8.750	4.025
30	45	800	20	20	10.000	4.140

Table F-10. Theoretical and Test Liquid Discharges as a Function of Increasing Theoretical Liquid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Theoretical Liquid Discharge, ozs/sec	Test Liquid Discharge, ozs/sec
16	35	200	5	60	0.622	0.711
6	25	100	15	60	0.667	1.778
1	20	100	20	60	0.711	1.422
12	30	300	5	60	0.800	3.200
26	45	100	10	60	0.800	0.667
7	25	300	10	60	1.333	1.333
9	25	600	5	60	1.333	4.444
3	20	400	10	60	1.422	1.333
23	40	400	5	30	1.422	1.599
11	30	100	30	60	1.599	0.800
2	20	200	25	60	1.778	0.622
28	45	500	5	20	2.000	2.844
21	40	200	20	60	2.844	0.800
4	20	600	15	60	3.200	8.533
22	40	300	15	45	3.200	4.266
13	30	400	20	45	4.266	4.667
15	30	800	10	30	4.267	3.200
19	35	700	10	30	4.356	7.778
8	25	500	20	60	4.444	8.000
17	35	300	25	45	4.667	4.267
20	35	800	15	30	7.467	11.199
10	25	700	25	30	7.778	4.356
14	30	600	25	30	8.000	7.467
29	45	700	15	20	8.400	1.422
5	20	800	30	45	8.533	8.889
24	40	500	25	30	8.889	14.933
27	45	400	30	30	9.600	9.600
18	35	600	30	30	11.199	2.000
30	45	800	20	20	12.800	8.400
25	40	700	30	30	14.933	12.800

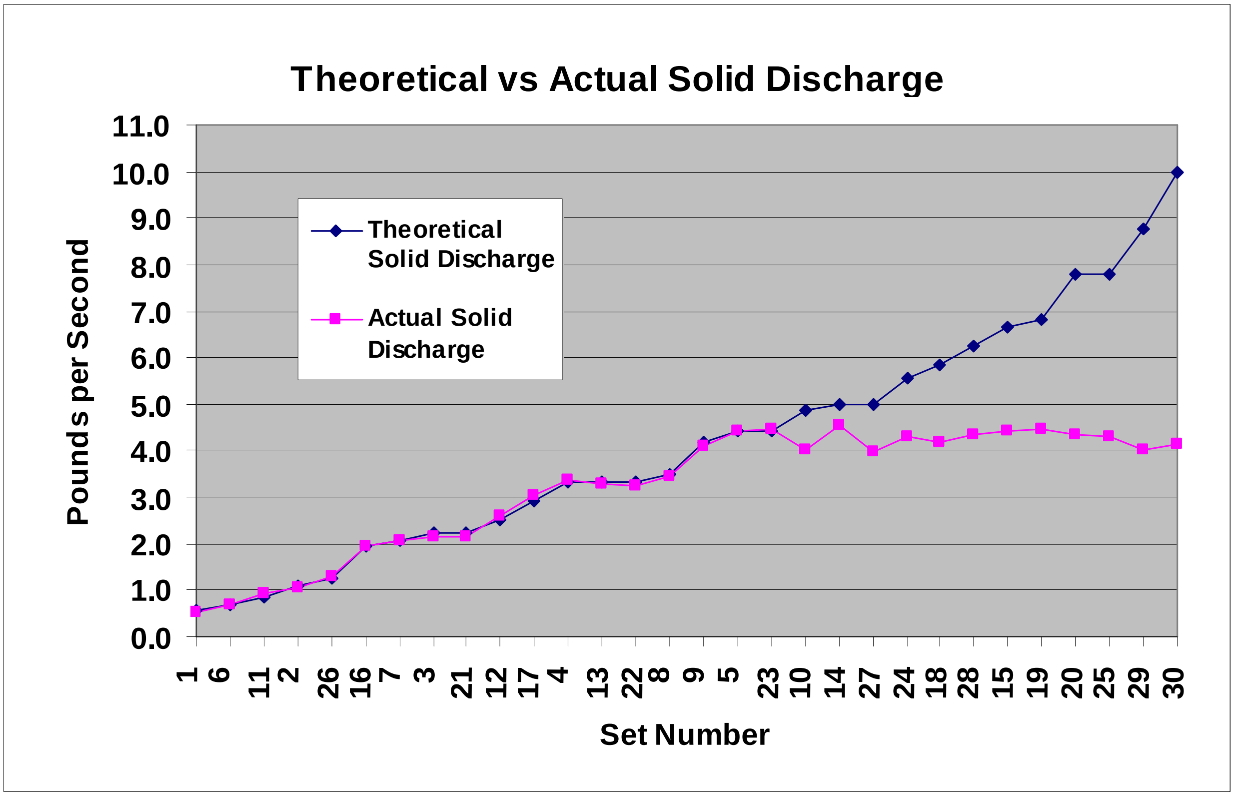

Figure F-1. Theoretical vs Actual Solid Discharge Rate

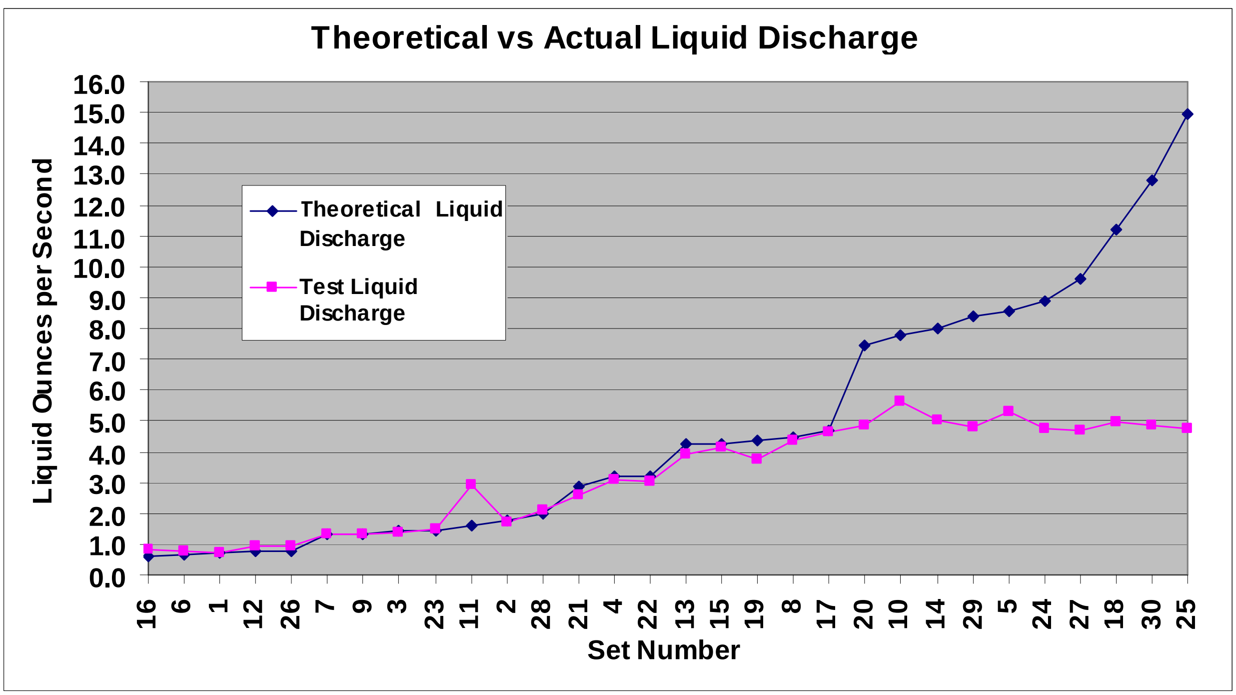

Figure F-2. Theoretical vs Actual Liquid Salt Brine Discharge Rate

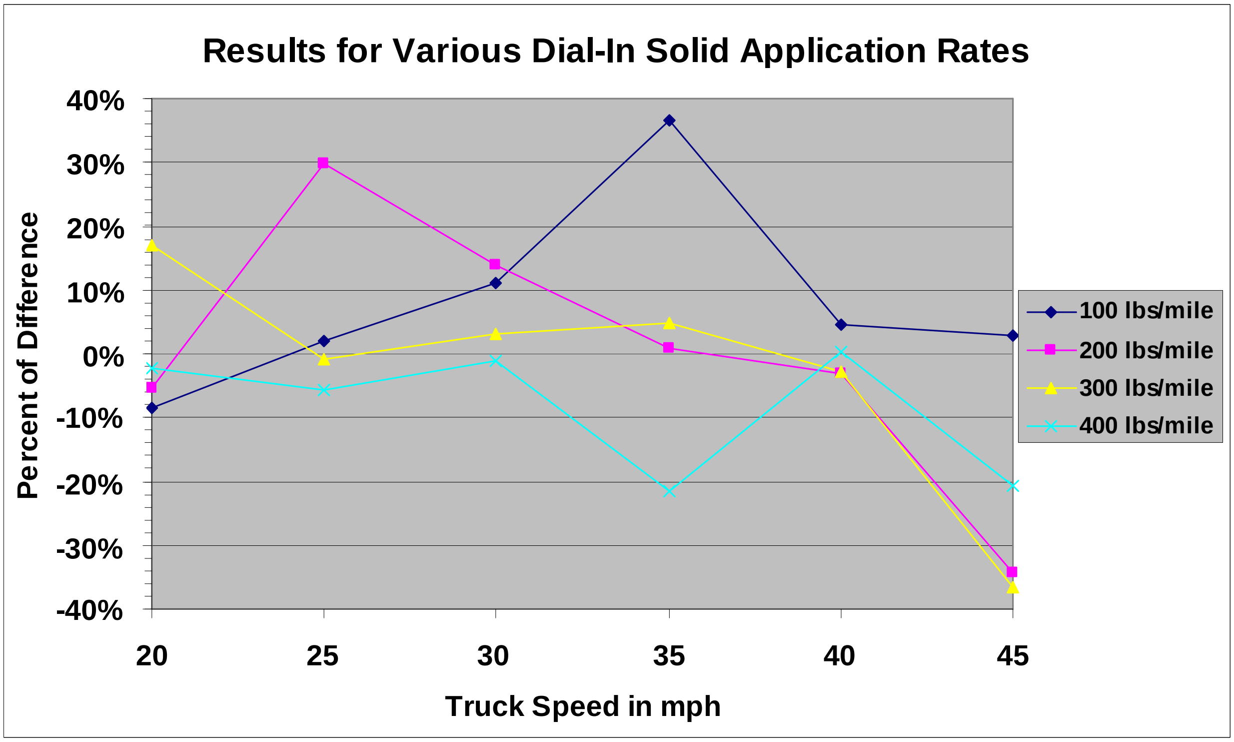

Figure F-3. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

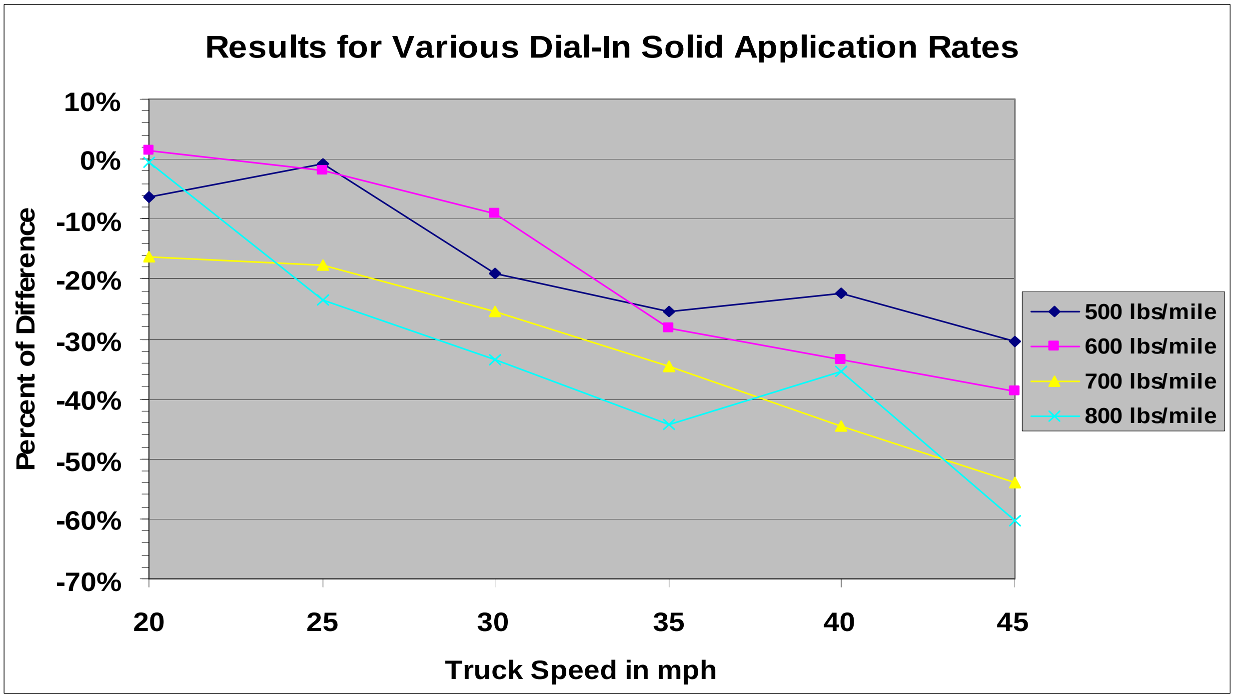

Figure F-4. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

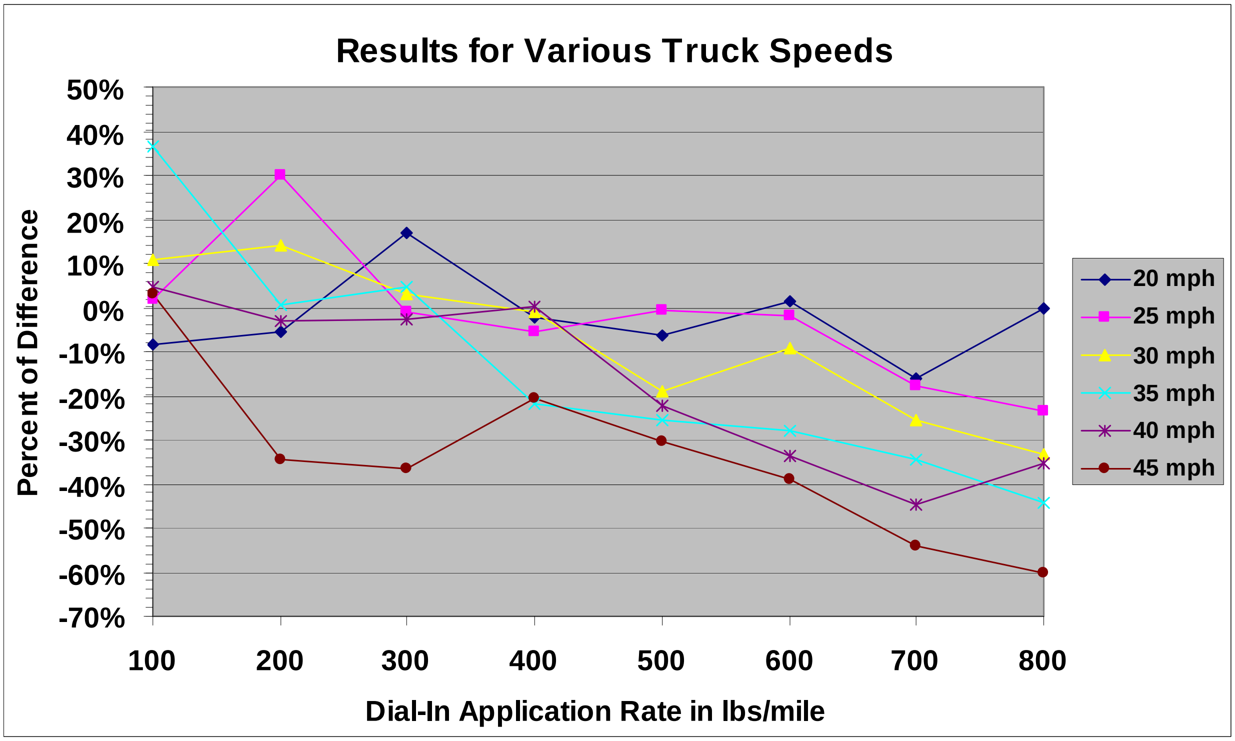

Figure F-5. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Dial-In Solid Application Rate

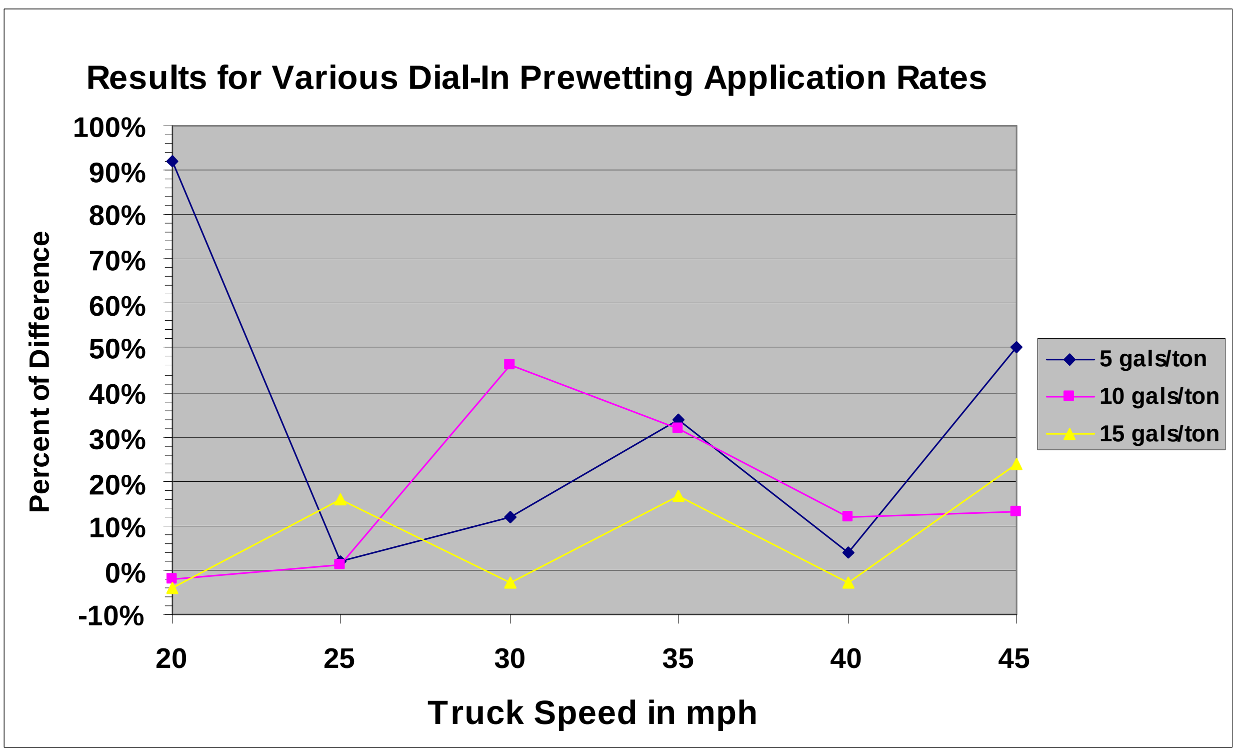

Figure F-6. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed

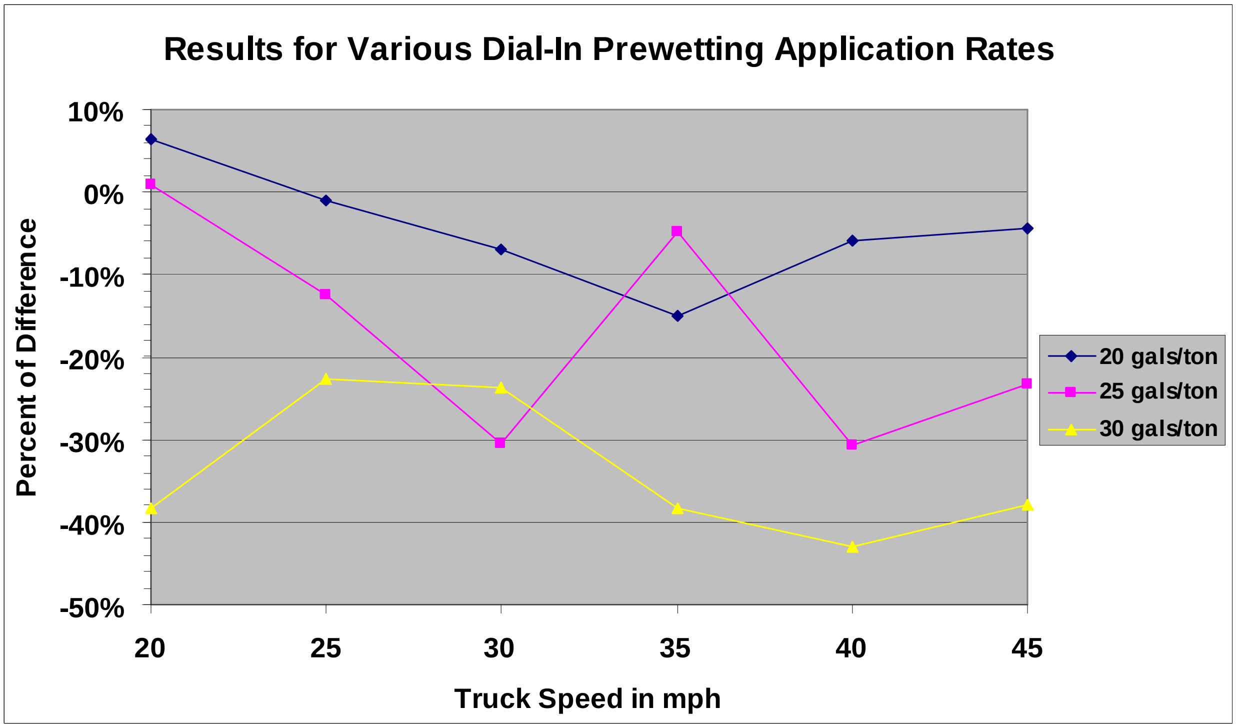

Figure F-7. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed

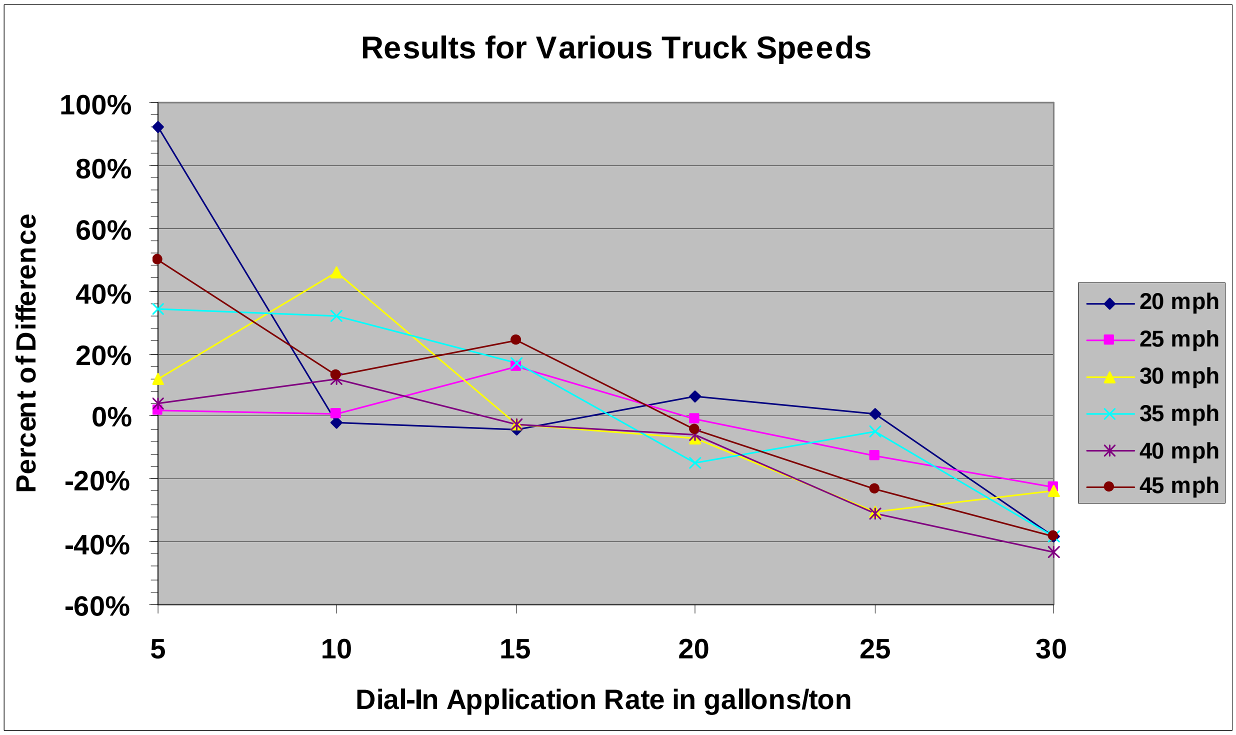

Figure F-8. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Dial-In Prewetting Application Rate

Table F-11. Statistical Analysis Results for Yard Tests

Yard Test Results for Bias, Accuracy, and Precision	
Solid Discharge	
Bias (lbs/mile)	-92.9
Accuracy	84.2%
Precision	20.8%
Prewetting Discharge	
Bias (gals/ton)	-2.6
Accuracy	77.8%
Precision	29.4%

Results from Simulated Scenario Testing

Table F-12. Solid Discharges for Closed-loop and Open-loop Modes from Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (lbs)	Actual Discharge (lbs)	Discharge Amount According to Controller	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	3849.5	3993	3849	3.73%	-0.01%	-3.61%	3.74%	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	4	3849.5	4283	3853	11.26%	0.09%	-10.04%	11.16%	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	5	3849.5	3903	3855	1.39%	0.14%	-1.23%	1.25%	
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	2	3299.6	3478	3299	5.40%	-0.03%	-5.15%	5.43%	
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	3299.9	3447	3030	4.46%	-8.18%	-12.10%	13.76%	-0.89%

Table F-13. Liquid Discharges for Closed-loop and Open-loop Modes from Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (gal.)	Actual Discharge (gal.)	Discharge Amount According to Controller (gal.)	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	25.078	26.650	22	6.27%	-12.27%	-17.45%	21.14%	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	4	25.081	25.925	22	3.37%	-12.28%	-15.14%	17.84%	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	5	25.081	25.950	23	3.46%	-8.30%	-11.37%	12.83%	
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	2	19.125	19.360	15	1.23%	-21.57%	-22.52%	29.07%	
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	19.125	17.500	14	-8.50%	-26.80%	-20.00%	25.00%	-9.61%

Table F-14. Solid Discharge Comparison for Freeway and Highway Scenarios in both Closed-loop and Open-loop Modes of Operation

Scenario/Mode of Operation	Percent of Difference in Discharge		
	Actual Compared to Theoretical	Controller Display Compared to Theoretical	Controller Display Compared to Actual
Freeway:			
Closed-loop	5.46%	0.07%	-5.11%
Open-loop	No Data	No Data	No Data
Highway:			
Closed-loop	5.40%	-0.03%	-5.15%
Open-loop	4.46%	-8.18%	-12.10%

Table F-15. Solid Discharge Comparison of Open-loop to Closed-loop Operations for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	No Data
Controller Display Discharge	No Data
Highway:	
Actual Discharge	-0.89%
Controller Display Discharge	-8.15%

Table F-16. Prewetting Discharge Comparison for Freeway and Highway Scenarios in both Closed-loop and Open-loop Modes of Operation

Scenario/Mode of Operation	Percent of Difference in Discharge		
	Actual Compared to Theoretical	Controller Display Compared to Theoretical	Controller Display Compared to Actual
Freeway:			
Closed-loop	4.36%	-10.97%	-14.68%
Open-loop	No Data	No Data	No Data
Highway:			
Closed-loop	1.23%	-21.57%	-22.52%
Open-loop	-8.50%	-26.80%	-20.00%

Table F-17. Prewetting Discharge Comparison of Open-loop to Closed-loop Modes of Operation for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	No Data
Controller Display Discharge	No Data
Highway:	
Actual Discharge	-9.61%
Controller Display Discharge	-6.67%

Table F-18. Comparison of Closed-loop and Manual Modes of Operation

Scenario	Theoretical Discharge (lbs)	Actual Discharge (lbs)	Revolution Count	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Actual Discharge for Manual and Closed-loop Operations
First Scenario - Manual Mode Test Parameter:200 lbs/mile for 30 MPH Drive:20 MPH and 30 MPH	2000	2100	384	5.00%	
Second Scenario - Manual Mode Test Parameter:200 lbs/mile for 30 MPH Drive:20 MPH and 30 MPH	2000	2070	371	3.50%	
Third Scenario - Manual Mode Test Parameter:400 lbs/mile for 30 MPH Drive:20 MPH and 30 MPH	4000	5410	981	35.25%	
Fourth Scenario - Manual Mode Test Parameter:400 lbs/mile for 30 MPH Drive:20 MPH and 30 MPH	4000	5210	946	30.25%	
Fifth Scenario - Closed Loop Mode Test Parameter:200 lbs/mile Drive:20 MPH and 30 MPH	1600	1910	328	19.38%	9.95%
Sixth Scenario - Closed Loop Mode Test Parameter:200 lbs/mile Drive:20 MPH and 30 MPH	1600	2020	330	26.25%	2.48%
Seventh Scenario - Closed Loop Mode Test Parameter:400 lbs/mile Drive:20 MPH and 30 MPH	3200	3800	668	18.75%	42.37%
Eighth Scenario - Closed Loop Mode Test Parameter:400 lbs/mile Drive:20 MPH and 30 MPH	3200	3810	667	19.06%	36.75%

Table F-19. Calibration Results (Truck Bed Lowered)

No.	Discharge Weight	Calibration Constant	Revolution Count, rpm	Measured, lbs/rev
1	505	15.9	102.4	4.93
2	502	15.8	103.3	4.86
3	492	16.2	104.57	4.70
4	428	15.5	84.5	5.07
Average		15.85		4.89
Value used in Scenarios		15.7		

Table F-20. Calibration Results (Truck Bed Raised)

No.	Discharge Weight	Calibration Constant	Revolution Count, rpm	Measured, lbs/rev.
1	506	14.5	95.73	5.29
2	510	14.7	97.73	5.22
3	502	14.4	95.55	5.25
Average		14.5		5.25

Table F-21. Revised Comparison of Closed-loop and Manual Modes of Operation when Raised Bed Calibration Factors are Used

Scenario	Theoretical Discharge (lbs)	Weighed Discharge (lbs)	Revolution Count	Computed Discharge[A] (lbs)	Computed[B] (lbs/rev)	Revised Revolution Count[C]	Modified Actual Discharge[D] (lbs)	Percent of Difference of Modified Actual Compared to Theoretical Discharge	Percent of Difference of Modified Actual Discharge for Manual and Closed-loop
First Scenario - Manual Mode Test Parameter:200 lbs/mile for 30 MPH Drive:20 MPH and 30 MPH	2000	2100	384	1877.76	5.47	354.6	1861.91	-6.9%	
Second Scenario - Manual Mode Test Parameter:200 lbs/mile for 30 MPH Drive:20 MPH and 30 MPH	2000	2070	371	1814.19	5.58	342.6	1798.88	-10.1%	
Third Scenario - Manual Mode Test Parameter:400 lbs/mile for 30 MPH Drive:20 MPH and 30 MPH	4000	5410	981	4797.09	5.51	906.0	4756.60	18.9%	
Fourth Scenario - Manual Mode Test Parameter:400 lbs/mile for 30 MPH Drive:20 MPH and 30 MPH	4000	5210	946	4625.94	5.51	873.7	4586.89	14.7%	
Fifth Scenario - Closed Loop Mode Test Parameter:200 lbs/mile Drive:20 MPH and 30 MPH	1600	1910	328	1603.92	5.82	302.9	1590.38	-0.6%	17.07%
Sixth Scenario - Closed Loop Mode Test Parameter:200 lbs/mile Drive:20 MPH and 30 MPH	1600	2020	330	1613.7	6.12	304.8	1600.08	0.0%	12.42%
Seventh Scenario - Closed Loop Mode Test Parameter:400 lbs/mile Drive:20 MPH and 30 MPH	3200	3800	668	3266.52	5.69	616.9	3238.95	1.2%	46.86%
Eighth Scenario - Closed Loop Mode Test Parameter:400 lbs/mile Drive:20 MPH and 30 MPH	3200	3810	667	3261.63	5.71	616.0	3234.10	1.1%	41.83%

Note: A = Multiplied revolution count by a constant of 4.89 (lbs/rev that was determined in calibration with lowered bed)
B = Divide actual discharge by revolution count
C = Multiply the revolution count by (14.5/15.7), the ratio of calibration constants for raised bed to lowered bed
D = Multiply the revised revolution count by 5.25 (lbs/rev that was determined in calibration with raised bed)

Table F-22. History of Calibration Constants for Truck #A31768

Factory default Value	20.0 pulses per pound
April 11, 2006	13.5 pulses per pound
Late September 2006	14.2 pulses per pound
November 13, 2006	17.6 pulses per pound
November 15, 2006	15.7 pulses per pound
April 10, 2007 (truck bed lowered)	15.7 pulses per pound
April 12, 2007 (truck bed raised)	14.5 pulses per pound

APPENDIX G
TEST RESULTS FOR COMPONENT TECHNOLOGY GL-400

Results from Yard Tests

Table G-1. Values of Truck Speed, Solid Discharge Rate, Prewetting Rate, and Test Run Time for Each Test Set Number Used in Yard Testing

Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec
1	20	100	20	60	16	35	200	5	25
2	20	200	25	45	17	35	300	25	18
3	20	400	10	25	18	35	600	30	15
4	20	600	15	15	19	35	700	10	15
5	20	800	30	15	20	35	800	15	15
6	25	100	15	60	21	40	200	20	22
7	25	300	10	25	22	40	300	15	15
8	25	500	20	15	23	40	400	5	15
9	25	600	5	15	24	40	500	25	15
10	25	700	25	15	25	40	700	30	15
11	30	100	30	45	26	45	100	10	35
12	30	300	5	20	27	45	400	30	15
13	30	400	20	15	28	45	500	5	15
14	30	600	25	15	29	45	700	15	15
15	30	800	10	15	30	45	800	20	15

Summary Tabulations of Solid and Liquid Discharge Rates

Table G-2. Actual and Estimated Solid Discharge Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	108.4	196.6	**350.1**	401.3	**544.5**	651.2	**738.9**	927.6
25	106.9	**238.7**	298.2	**433.1**	552.0	673.1	787.2	**821.9**
30	107.9	**224.6**	301.5	468.8	**502.1**	672.3	**710.6**	803.2
35	**113.3**	211.8	309.2	**404.9**	**502.1**	636.5	698.5	736.8
40	**99.2**	209.1	312.3	453.9	557.0	**585.2**	628.4	**779.6**
45	110.7	**182.2**	**279.4**	461.7	554.0	**571.0**	573.2	566.2

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table G-3. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**
20	8.4%	-1.7%	**16.7%**	0.3%	**8.9%**	8.5%	**5.6%**	16.0%
25	6.9%	**19.4%**	-0.6%	**8.3%**	10.4%	12.2%	12.5%	**2.7%**
30	7.9%	**12.3%**	0.5%	17.2%	**3.2%**	12.1%	**1.5%**	0.4%
35	**13.3%**	5.9%	3.1%	**1.2%**	**0.4%**	6.1%	-0.2%	-7.9%
40	**-0.8%**	4.6%	4.1%	13.5%	11.4%	**-2.5%**	-10.2%	**-2.6%**
45	11.5%	**-8.9%**	**-6.9%**	15.4%	10.8%	**-4.8%**	-18.1%	-29.2%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table G-4. Actual and Estimated Discharge Prewetting Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial –In Application Rate in gallons/ton					
	5	**10**	**15**	**20**	**25**	**30**
20	**4.8**	9.8	11.7	17.0	19.2	19.7
25	4.6	10.7	17.1	16.4	18.5	**24.9**
30	5.5	9.7	**13.8**	15.4	20.7	30.1
35	7.8	10.1	14.9	**18.3**	23.6	25.0
40	4.9	**11.1**	14.0	19.6	20.7	28.6
45	5.0	11.9	17.0	25.8	**23.3**	23.0

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table G-5. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed

Speed in mph	Dial –In Application Rate in gallons/ton					
	5	**10**	**15**	**20**	**25**	**30**
20	**-4.0%**	-2.0%	-22.0%	-15.0%	-23.2%	-34.3%
25	-8.0%	7.0%	14.0%	-18.0%	-26.0%	**-17.0%**
30	10.0%	-3.0%	**-8.0%**	-23.0%	-17.2%	0.3%
35	56.0%	1.0%	-0.7%	**-8.5%**	-5.6%	-16.7%
40	-2.0%	**11.0%**	-6.7%	-2.0%	-17.2%	-4.7%
45	0.0%	17.0%	13.3%	29.0%	**-6.8%**	-23.3%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table G-6. Regression Coefficients for Determination of Missing Test Discharge Values

Material	Rate Coefficient	Speed Coefficient	Intercept	R - squared
	A1	**A2**	**B**	**(as percent)**
Solid	0.972	-2.825	144.971	92.9%
Liquid	0.778	0.117	-1.385	86.8%

Table G-7. Percent of Error for Solid Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Solid Discharge, lbs/sec	Test Solid Discharge, lbs/sec	Percent of Error	Set Solid Discharge Rate, lbs/mile	Test solid Discharge Rate, lbs/mile	Percent of Error
1	60	20	0.556	0.602	8.27%	100	108.4	8.40%
6	60	25	0.694	0.742	6.92%	100	106.9	6.90%
2	45	20	1.111	1.093	-1.62%	200	196.6	-1.70%
11	45	30	0.833	0.900	8.04%	100	107.9	7.90%
26	35	45	1.250	1.394	11.52%	100	111.5	11.50%
3	25	20	2.222	2.228	0.27%	400	401.3	0.33%
7	25	25	2.083	2.072	-0.53%	300	298.2	-0.60%
16	25	35	1.944	2.036	4.73%	200	211.8	5.90%
21	22	40	2.222	2.323	4.55%	200	209.1	4.55%
12	20	30	2.500	2.515	0.60%	300	301.5	0.50%
17	18	35	2.917	3.006	3.05%	300	309.2	3.07%
4	15	20	3.333	3.620	8.61%	600	651.2	8.53%
5	15	20	4.444	5.153	15.95%	800	927.6	15.95%
8	15	25	3.472	3.833	10.40%	500	552.0	10.40%
9	15	25	4.167	4.673	12.14%	600	673.1	12.18%
10	15	25	4.861	5.527	13.70%	700	787.2	12.46%
13	15	30	3.333	3.907	17.22%	400	468.8	17.20%
14	15	30	5.000	5.600	12.00%	600	672.3	12.05%
15	15	30	6.667	6.693	0.39%	800	803.2	0.40%
18 *	15	35	5.833	6.187	6.07%	600	636.5	6.08%
19	15	35	6.806	6.793	-0.19%	700	698.5	-0.21%
20 *	15	35	7.778	7.167	-7.86%	800	736.8	-7.90%
22	15	40	3.333	3.473	4.20%	300	312.3	4.10%
23	15	40	4.444	5.047	13.57%	400	453.9	13.48%
24 **	15	40	5.555	6.187	11.38%	500	557.0	11.40%
25 **	15	40	7.778	6.980	-10.26%	700	628.4	-10.23%
27	15	45	5.000	5.773	15.46%	400	461.7	15.43%
28 ***	15	45	6.250	6.927	10.83%	500	554.0	10.80%
29 ***	15	45	8.750	7.167	-18.09%	700	573.2	-18.11%
30 ***	15	45	10.000	7.080	-29.20%	800	566.2	-29.23%

Note: * = Speed Rate Limit
** = Feed Rate Limit
*** = Feed Rate Limit 620

Table G-8. Percent of Error for Prewetting Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Liquid Discharge, ozs/sec	Test Liquid Discharge, ozs/sec	Percent of Error	Set Prewetting Application Rate, gals/ton	Test Prewetting Discharge Rate, gals/ton	Percent of Error
1	60	20	0.711	0.655	-7.88%	20	17.0	-14.95%
6	60	25	0.667	0.813	21.89%	15	17.1	14.00%
2	45	20	1.778	1.346	-24.30%	25	19.2	-23.16%
11	45	30	1.599	1.731	8.26%	30	30.1	0.37%
26	35	45	0.800	1.005	25.63%	10	11.7	16.60%
3	25	20	1.422	1.389	-2.32%	10	9.8	-2.00%
7	25	25	1.333	1.421	6.60%	10	10.7	7.00%
16	25	35	0.622	0.997	60.29%	5	7.8	55.60%
21	22	40	2.844	2.879	1.23%	20	19.6	-2.25%
12	20	30	0.800	0.891	11.38%	5	5.5	10.00%
17	18	35	4.667	4.532	-2.89%	25	23.6	-5.80%
4	15	20	3.200	2.706	-15.44%	15	11.7	-22.00%
5	15	20	8.533	6.505	-23.77%	30	19.7	-34.33%
8	15	25	4.444	4.018	-9.59%	20	16.4	-18.00%
9	15	25	1.333	1.360	2.03%	5	4.6	-8.00%
10	15	25	7.778	6.526	-16.10%	25	18.5	-26.12%
13	15	30	4.266	3.822	-10.41%	20	15.4	-23.00%
14	15	30	8.000	7.404	-7.45%	25	20.7	-17.20%
15	15	30	4.267	4.142	-2.93%	10	9.7	-3.30%
18	15	35	11.199	9.899	-11.61%	30	25.0	-16.67%
19	15	35	4.356	4.390	0.78%	10	10.1	1.00%
20	15	35	7.467	6.829	-8.54%	15	14.9	-0.67%
22	15	40	3.200	3.104	-3.00%	15	14.0	-6.80%
23	15	40	1.422	1.594	12.10%	5	4.9	-1.20%
24	15	40	8.889	8.212	-7.62%	25	20.7	-17.08%
25	15	40	14.933	12.773	-14.46%	30	28.6	-4.73%
27	15	45	9.600	8.509	-11.36%	30	23.0	-23.20%
28	15	45	2.000	2.214	10.70%	5	5.0	-0.20%
29	15	45	8.400	7.810	-7.02%	15	17.0	13.53%
30 *	15	45	12.800	11.665	-8.87%	20	25.8	28.75%

Note: * = Feed/Liquid Limit 620

Table G-9. Theoretical and Test Solid Discharges as a Function of Increasing Theoretical Solid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Theoretical Solid Discharge, lbs/sec.	Test Solid Discharge, lbs/sec
1	20	100	20	60	0.556	0.602
6	25	100	15	60	0.694	0.742
11	30	100	30	45	0.833	0.900
2	20	200	25	45	1.111	1.093
26	45	100	10	35	1.250	1.394
16	35	200	5	25	1.944	2.036
7	25	300	10	25	2.083	2.072
3	20	400	10	25	2.222	2.228
21	40	200	20	22	2.222	2.323
12	30	300	5	20	2.500	2.515
17	35	300	25	18	2.917	3.006
4	20	600	15	15	3.333	3.620
13	30	400	20	15	3.333	3.907
22	40	300	15	15	3.333	3.473
8	25	500	20	15	3.472	3.833
9	25	600	5	15	4.167	4.673
5	20	800	30	15	4.444	5.153
23	40	400	5	15	4.444	5.047
10	25	700	25	15	4.861	5.527
14	30	600	25	15	5.000	5.600
27	45	400	30	15	5.000	5.773
24	40	500	25	15	5.555	6.187
18	35	600	30	15	5.833	6.187
28	45	500	5	15	6.250	6.927
15	30	800	10	15	6.667	6.693
19	35	700	10	15	6.806	6.793
20	35	800	15	15	7.778	7.167
25	40	700	30	15	7.778	6.980
29	45	700	15	15	8.750	7.167
30	45	800	20	15	10.000	7.080

Table G-10. Theoretical and Test Liquid Discharges as a Function of Increasing Theoretical Liquid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Theoretical Liquid Discharge, ozs/sec	Test Liquid Discharge, ozs/sec
16	35	200	5	25	0.622	0.997
6	25	100	15	60	0.667	0.813
1	20	100	20	60	0.711	0.655
12	30	300	5	20	0.800	0.891
26	45	100	10	35	0.800	1.005
7	25	300	10	25	1.333	1.421
9	25	600	5	15	1.333	1.360
3	20	400	10	25	1.422	1.389
23	40	400	5	15	1.422	1.594
11	30	100	30	45	1.599	1.731
2	20	200	25	45	1.778	1.346
28	45	500	5	15	2.000	2.214
21	40	200	20	22	2.844	2.879
4	20	600	15	15	3.200	2.706
22	40	300	15	15	3.200	3.104
13	30	400	20	15	4.266	3.822
15	30	800	10	15	4.267	4.142
19	35	700	10	15	4.356	4.390
8	25	500	20	15	4.444	4.018
17	35	300	25	18	4.667	4.532
20	35	800	15	15	7.467	6.829
10	25	700	25	15	7.778	6.526
14	30	600	25	15	8.000	7.404
29	45	700	15	15	8.400	7.810
5	20	800	30	15	8.533	6.505
24	40	500	25	15	8.889	8.212
27	45	400	30	15	9.600	8.509
18	35	600	30	15	11.199	9.899
30	45	800	20	15	12.800	11.665
25	40	700	30	15	14.933	12.773

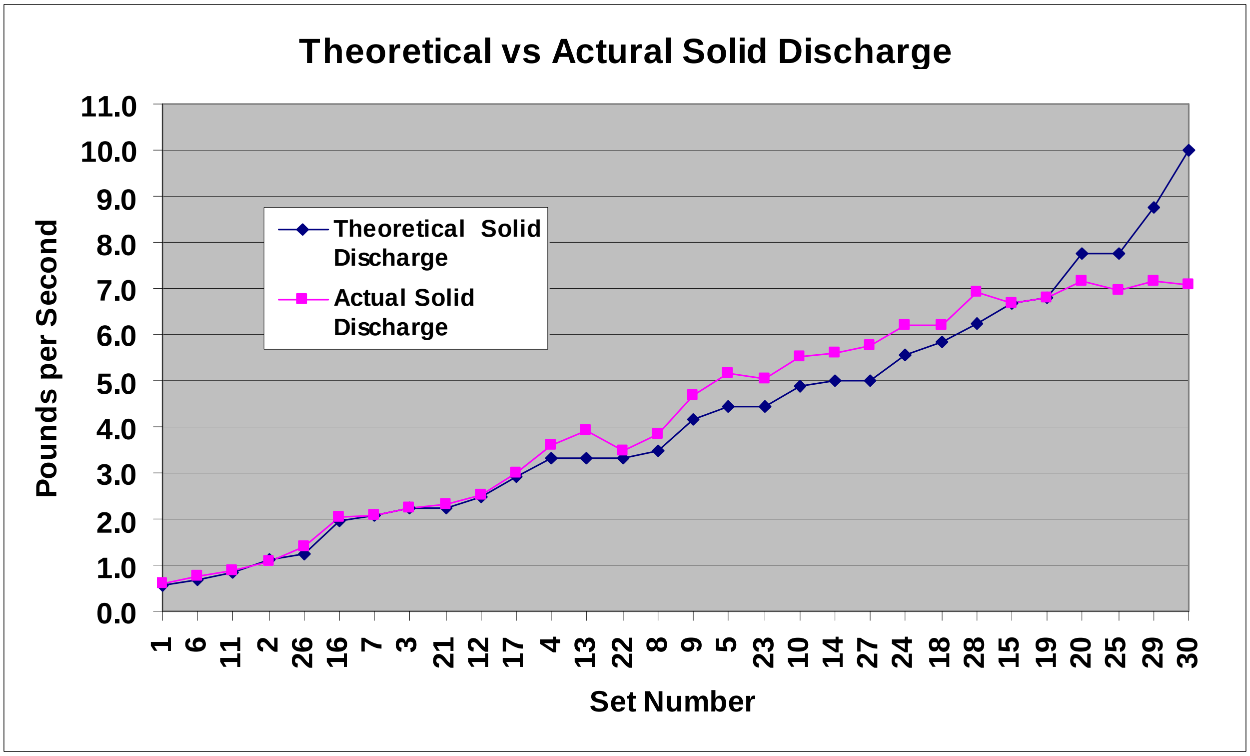

Figure G-1. Theoretical vs Actual Solid Discharge Rate

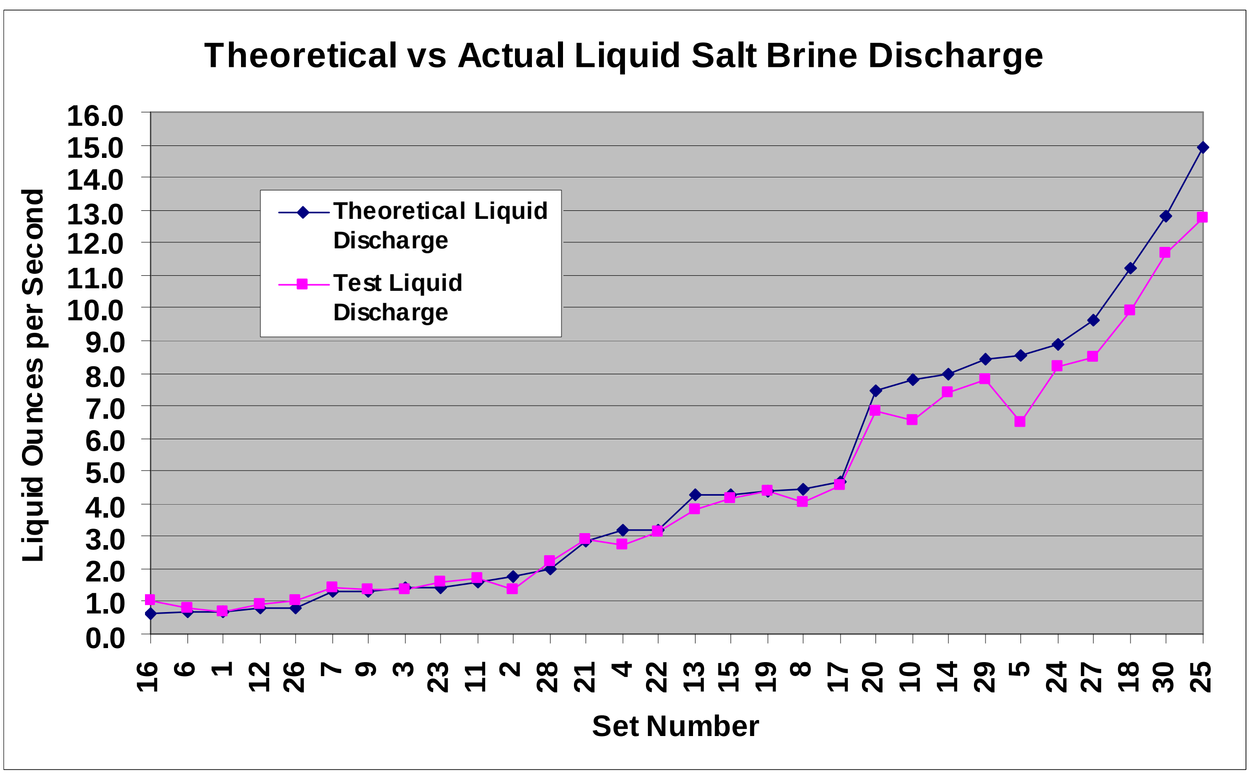

Figure G-2. Theoretical vs Actual Liquid Salt Brine Discharge Rate

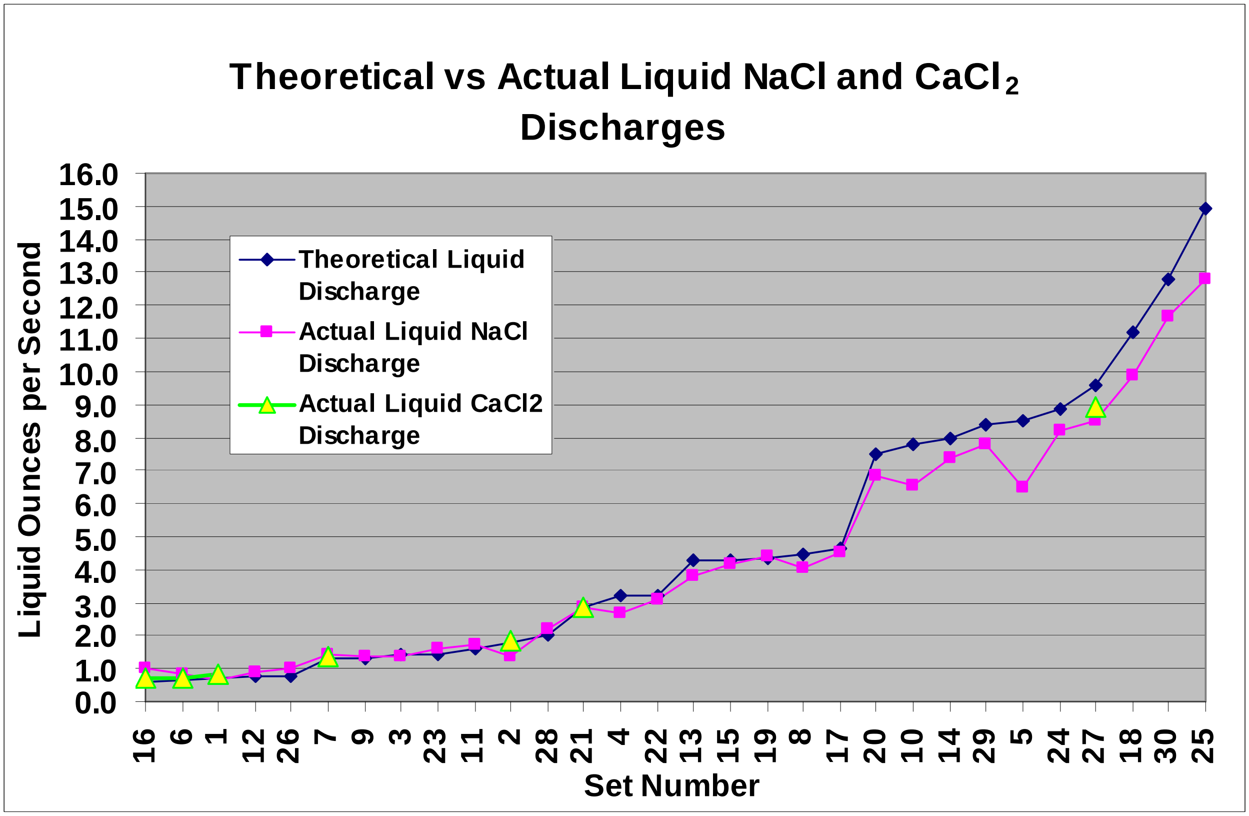

Figure G-3. Theoretical vs Actual Liquid NaCl and $CaCl_2$ Discharge Rates

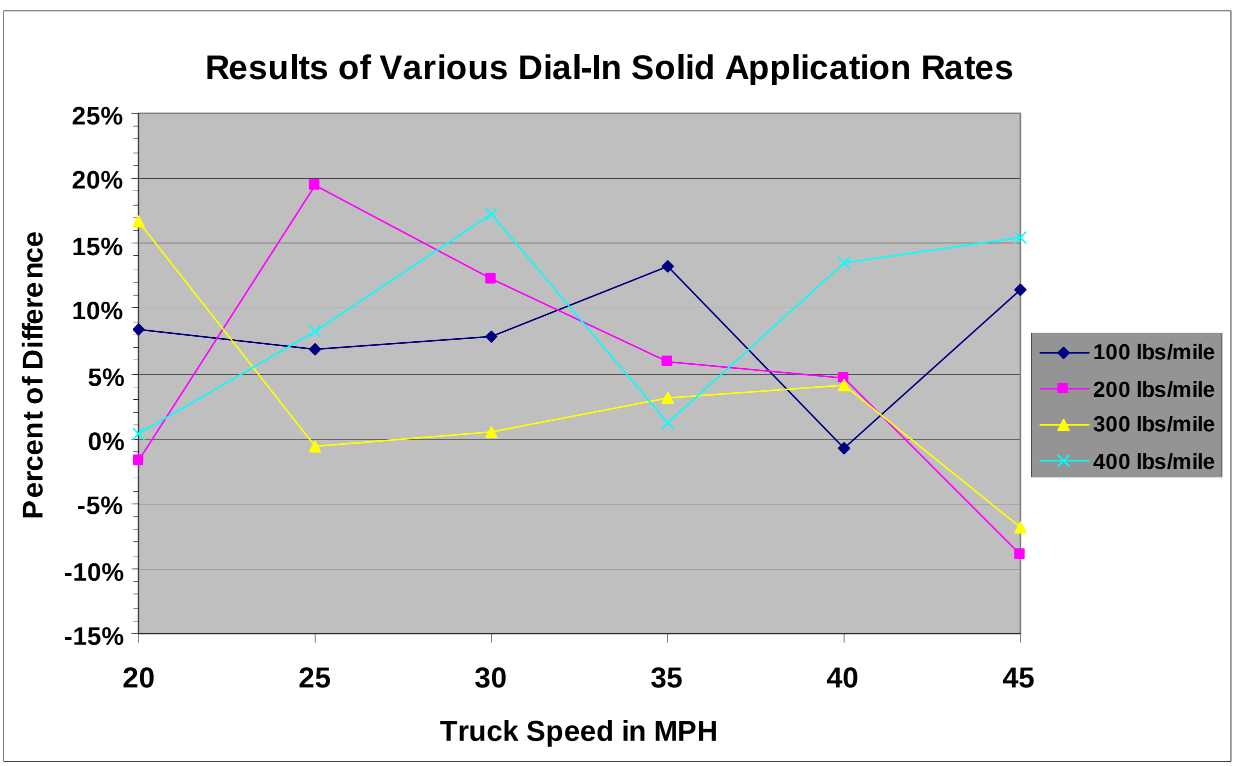

Figure G-4. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

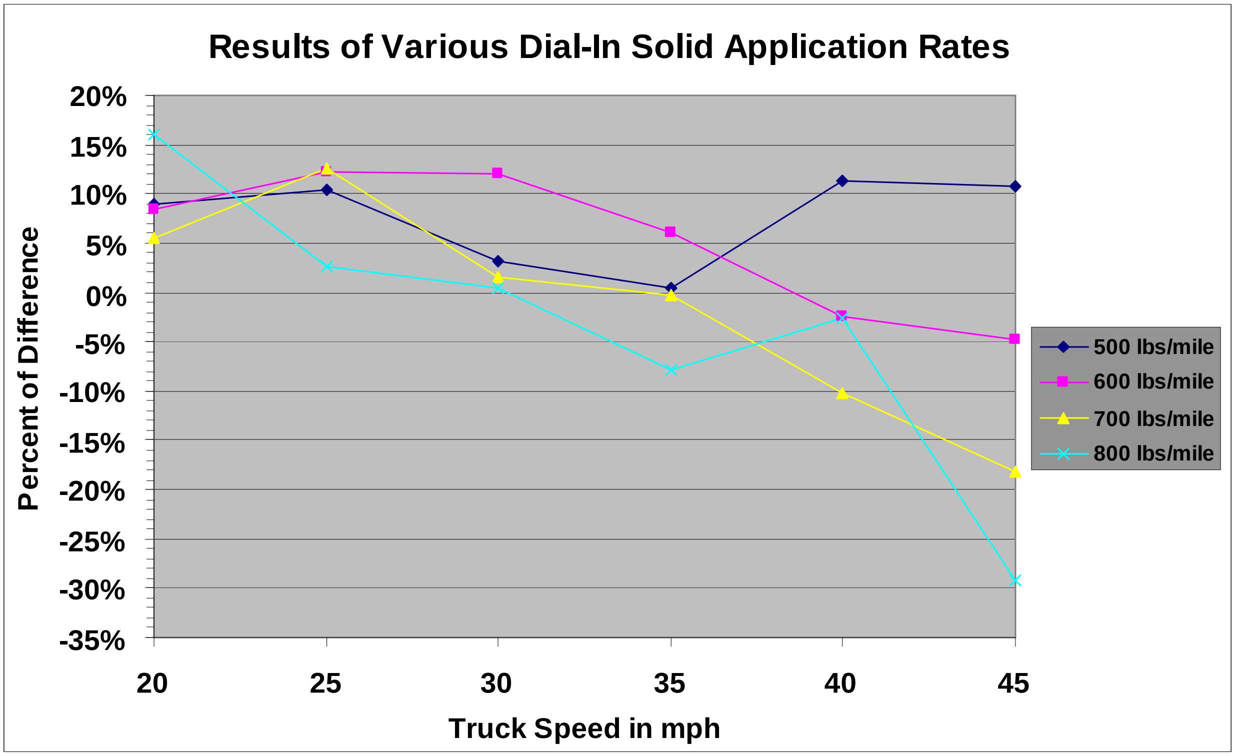

Figure G-5. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

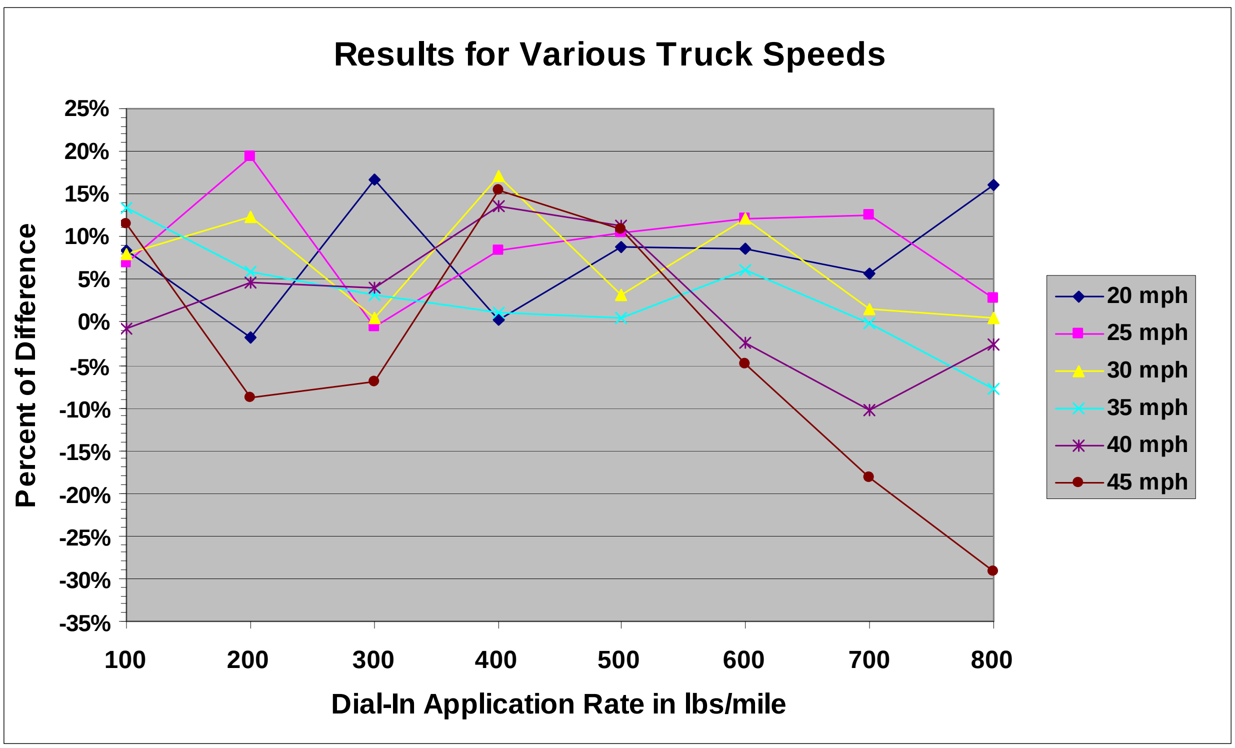

Figure G-6. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Dial-In Solid Application Rate

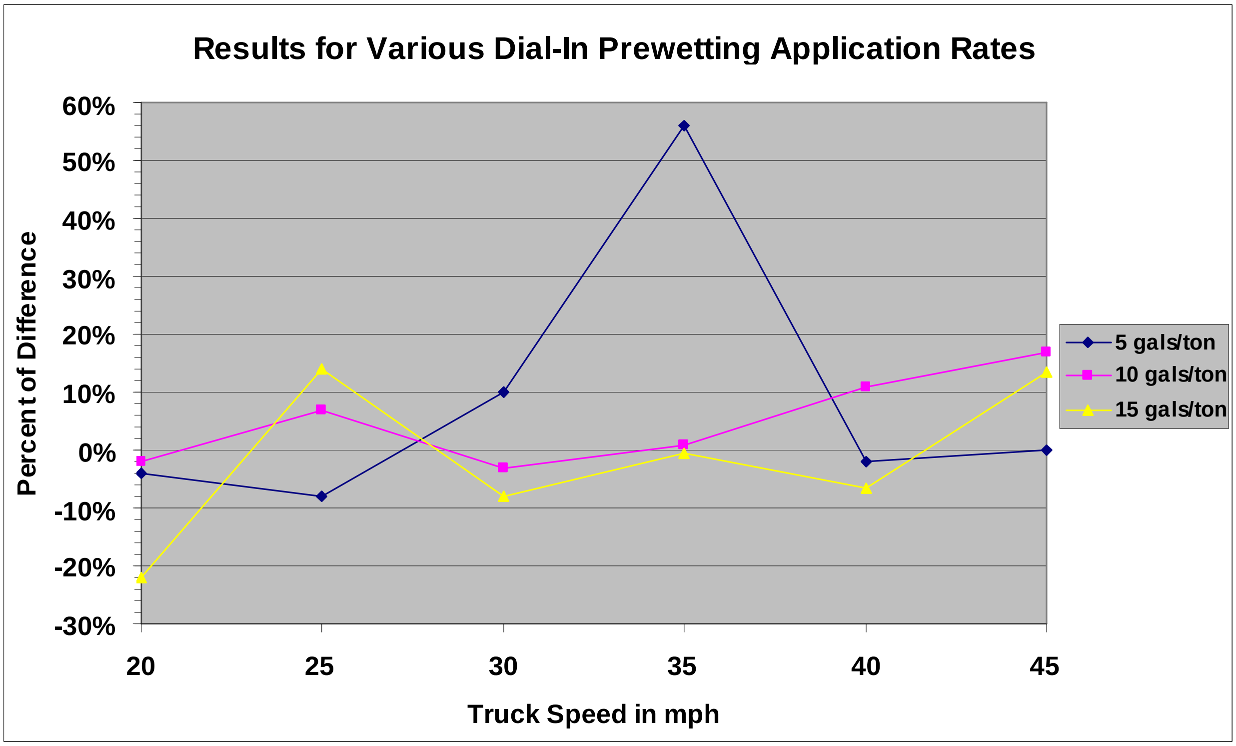

Figure G-7. Percent of Difference between Actual Liquid Discharge Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed

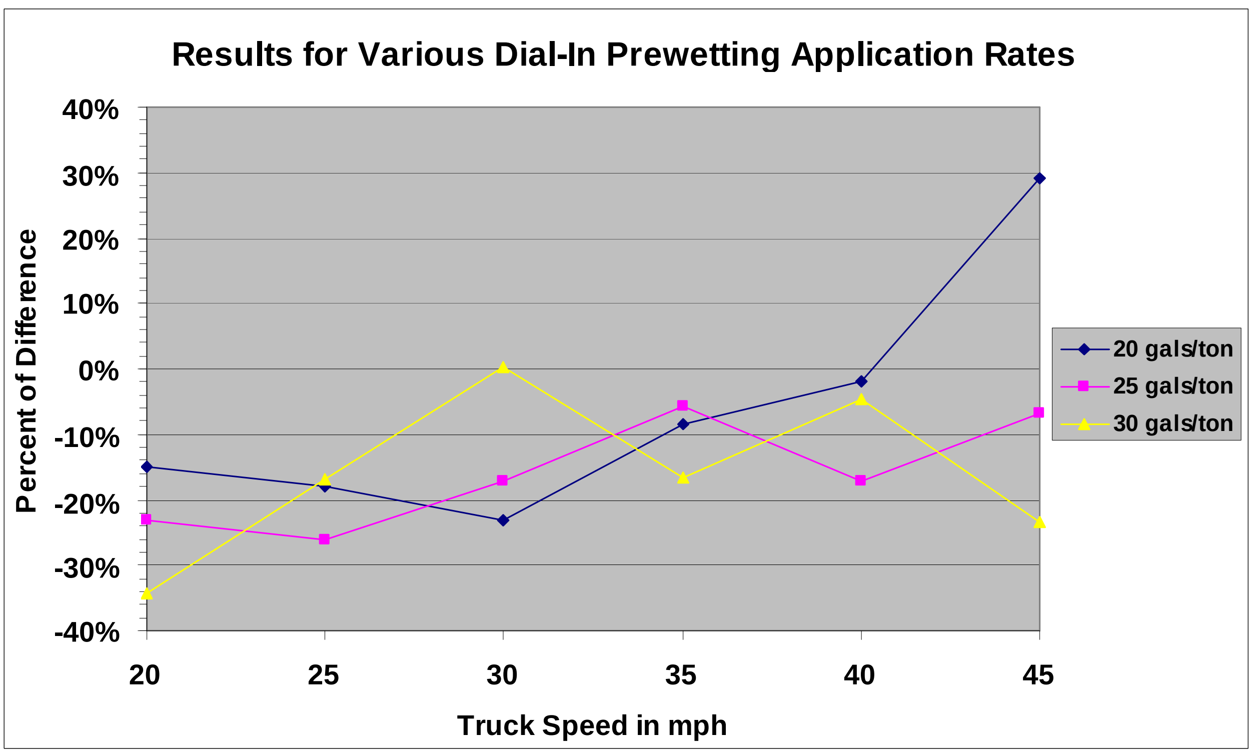

Figure G-8. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed

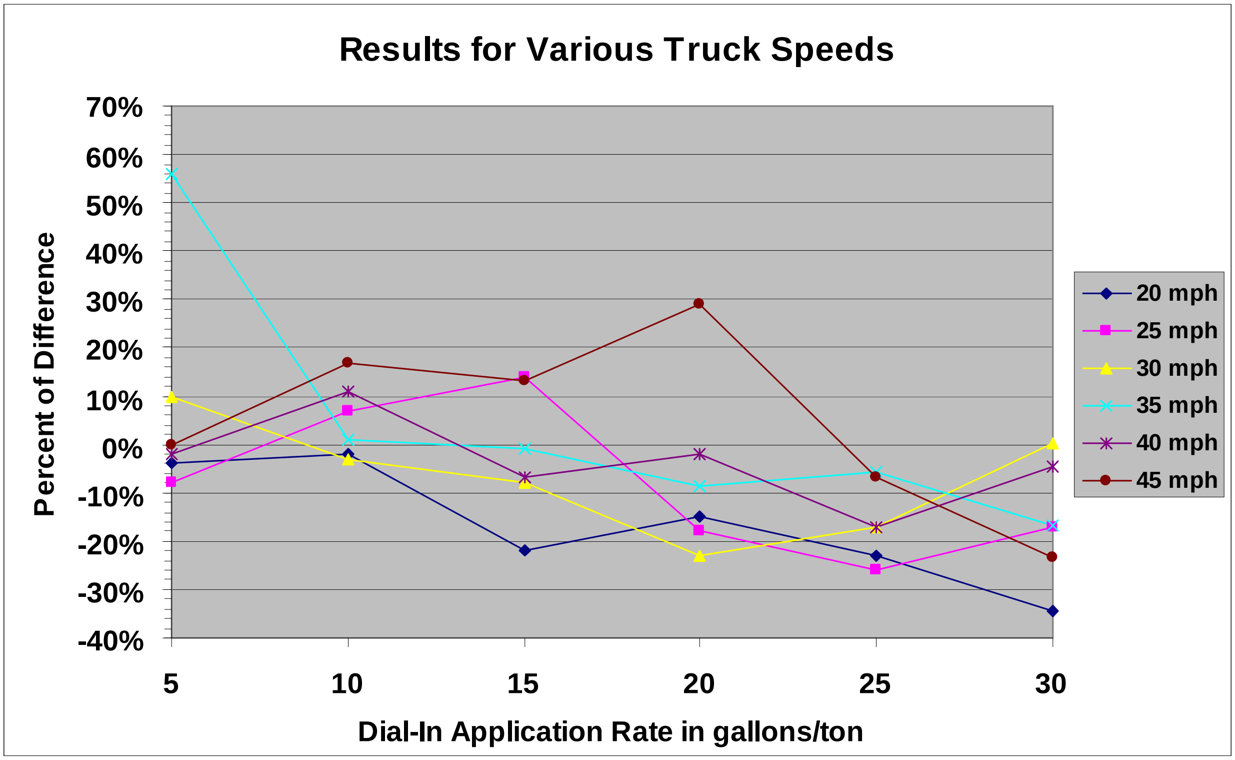

Figure G-9. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Dial-In Prewetting Application Rate

Table G-11. Statistical Analysis Results for Yard Tests

Yard Test Results for Bias, Accuracy, and Precision	
Solid Discharge	
Bias (lbs/mile)	11.9
Accuracy	90.7%
Precision	7.6%
Prewetting Discharge	
Bias (gals/ton)	-1.6
Accuracy	85.3%
Precision	17.3%

Results from Simulated Scenario Testing

Table G-12. Solid Discharges for Closed-loop and Open-loop Modes of Operation from Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (lbs)	Actual Discharge (lbs)	Discharge Amount According to Controller	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	5099.6	4924	5061	-3.44%	-0.76%	2.78%	-2.71%	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	2	5099.6	4887	5058	-4.17%	-0.82%	3.50%	-3.38%	
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	6	5099.6	4920	4581	-3.52%	-10.17%	-6.89%	7.40%	0.30%
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	5	5099.6	5260	4587	3.15%	-10.05%	-12.79%	14.67%	7.23%
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	4950	4795	5006	-3.13%	1.13%	4.40%	-4.21%	
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	4	4950	4796	5003	-3.11%	1.07%	4.32%	-4.14%	
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	7	4950	4660	4540	-5.86%	-8.28%	-2.58%	2.64%	-2.83%
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	8	4950	4540	4537	-8.28%	-8.34%	-0.07%	0.07%	-5.33%

Table G-13. Liquid Discharges for Closed-loop and Open-loop Modes of Operation from Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (gal.)	Actual Discharge (gal.)	Discharge Amount According to Controller (gal.)	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	34.456	35.000	35.3	1.58%	2.45%	0.86%	-0.85%	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	2	34.456	34.675	35.2	0.64%	2.16%	1.51%	-1.49%	
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	6	34.456	NA	NA	NA	NA	NA	NA	NA
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	5	34.456	NA	NA	NA	NA	NA	NA	NA
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	31.500	31.759	32.4	0.82%	2.86%	2.02%	-1.98%	
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	4	31.500	31.675	32.5	0.56%	3.17%	2.60%	-2.54%	
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	7	31.500	NA	NA	NA	NA	NA	NA	NA
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	8	31.500	NA	NA	NA	NA	NA	NA	NA

Note: NA = Firmware 5.6 installed in the truck was not programmed to control the liquid discharge during open-loop mode operations. Thus no liquid discharge was collected during open-loop testing.

Table G-14. Solid Discharge Comparison for Freeway and Highway Scenarios in both Closed-loop and Open-loop Modes of Operation

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Closed-loop	-3.81%	-0.77%
Open-loop	-0.19%	-10.11%
Highway:		
Closed-loop	-3.12%	1.10%
Open-loop	-7.07%	-8.32%

Table G-15. Solid Discharge Comparison of Open-loop to Closed-loop Modes of Operation for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	3.76%
Controller Display Discharge	-9.42%
Highway:	
Actual Discharge	-4.08%
Controller Display Discharge	-9.31%

Table G-16. Prewetting Discharge Comparison for Freeway and Highway Scenarios in Both Closed-loop and Open-loop Operations

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Closed-loop	1.11%	2.31%
Open-loop	No Data	No Data
Highway:		
Closed-loop	0.69%	3.02%
Open-loop	No Data	No Data

Table G-17. Prewetting Discharge Comparison of Open-loop to Closed-loop Operations for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	No Data
Controller Display Discharge	No Data
Highway:	
Actual Discharge	No Data
Controller Display Discharge	No Data

Table G-18. Comparison of Closed-loop and Manual Modes of Operation

Scenario	Test Set No.	Theoretical Discharge (lbs)	Actual Discharge (lbs)	Revolution Count	Output from Controller Weight in lbs	Computed Discharge[A] (lbs)	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Computed Discharge Compared to Theoretical Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference Between Manual and Closed Loop Using Actual Discharge
Freeway Scenario - Closed Loop Mode Test Parameter:200 lbs/mile Drive:20 MPH and 30 MPH	1*	2,700.4	2,715	60.80	2,704	2,736.0	0.54%	0.13%	0.41%	1.32%	0.41%	
Freeway Scenario - Closed Loop Mode Test Parameter:200 lbs/mile Drive:20 MPH and 30 MPH	5	2,700.4	2,740	61.13	2,721	2,750.9	1.47%	0.76%	0.70%	1.87%	0.70%	
Freeway Scenario - Closed Loop Mode Test Parameter:400 lbs/mile Drive:20 MPH and 30 MPH	2	5,399.5	5,400	121.45	5,409	5,465.3	0.01%	0.18%	-0.17%	1.22%	-0.17%	
Highway Scenario - Closed Loop Mode Test Parameter:200 lbs/mile Drive:20 MPH and 30 MPH	3	2,116.9	2,120	47.72	2,122	2,147.4	0.15%	0.24%	-0.09%	1.44%	-0.09%	
Highway Scenario - Closed Loop Mode Test Parameter:400 lbs/mile Drive:20 MPH and 30 MPH	4	4,233.1	4,220	94.40	4,211	4,248.0	-0.31%	-0.52%	0.21%	0.35%	0.21%	
Freeway Scenario - Manual Mode Test Parameter:200 lbs/mile for 30MPH Drive:20 MPH and 30 MPH	10	3,000.6	3,060	66.88	3,021	3,009.6	1.98%	0.68%	1.29%	0.30%	1.29%	11.68%
Freeway Scenario - Manual Mode Test Parameter:200 lbs/mile for 30MPH Drive:20 MPH and 30 MPH	11	3,000.6	2,940	66.18	2,906	2,978.1	-2.02%	-3.15%	1.17%	-0.75%	1.17%	7.30%
Highway Scenario - Manual Mode Test Parameter:200 lbs/mile for 30MPH Drive:20, 25, and 30 MPH	12	2,500.6	2,460	55.00	2,446	2,475.0	-1.62%	-2.18%	0.57%	-1.02%	0.57%	16.04%
Highway Scenario - Manual Mode Test Parameter:200 lbs/mile for 30MPH Drive:20, 25, and 30 MPH	13	2,500.6	2,620	58.17	2,588	2,617.7	4.77%	3.50%	1.24%	4.68%	1.24%	23.58%
Freeway Scenario - Manual Mode Test Parameter:400 lbs/mile for 30MPH Drive:20 MPH and 30 MPH	6*	5,999.4	6,460	145.03	6,457	6,526.4	7.68%	7.63%	0.05%	8.78%	0.05%	19.63%
Freeway Scenario - Manual Mode Test Parameter:400 lbs/mile for 30MPH Drive:20 MPH and 30 MPH	14	5,999.4	5,900	131.35	5,850	5,910.8	-1.66%	-2.49%	0.85%	-1.48%	0.85%	9.26%
Freeway Scenario - Manual Mode Test Parameter:400 lbs/mile for 30MPH Drive:20 MPH and 30 MPH	7	5,999.4	5,980	136.10	6,055	6,124.5	-0.32%	0.93%	-1.24%	2.09%	-1.24%	10.74%
Highway Scenario - Manual Mode Test Parameter:400 lbs/mile for 30MPH Drive:20, 25, and 30 MPH	8	4,999.4	4,940	110.02	4,889	4,950.9	-1.19%	-2.21%	1.04%	-0.97%	1.04%	17.06%
Highway Scenario - Manual Mode Test Parameter:400 lbs/mile for 30MPH Drive:20, 25, and 30 MPH	9	4,999.4	4,840	107.45	4,777	4,835.3	-3.19%	-4.45%	1.32%	-3.28%	1.32%	14.69%

Note: * = Data for Test Sets 1 and 6 are suspect becaused the hydraulic fluid was not warm enough for the test
A = Multiplied revolution count by a constant of lbs/rev (45 lbs/rev)

APPENDIX H
TEST RESULTS FOR DICKEY-JOHN ISC2000 AND CONTROL POINT

Results from Yard Tests for ISC2000

Table H-1. Values of Truck Speed, Solid Discharge Rate, and Test Run Time for Each Test Set Number Used in Yard Testing

Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Test Run Time, sec.	Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Test Run Time, sec
1	20	107	60	15	45	429	20
2	20	322	60	16	45	537	15
3	20	644	30	17	45	751	15
4	30	107	60	18	45	858	10
5	30	322	45	19	25	107	60
6	30	483	30	20	25	322	30
7	45	107	60	21	25	537	20
8	45	322	30	22	25	644	20
9	20	215	60	23	25	751	18
10	20	429	30	24	35	215	40
11	20	858	20	25	35	322	30
12	30	429	20	26	35	644	15
13	30	644	20	27	35	751	10
14	30	858	15	28	35	858	10

Summary Tabulations of Solid Discharge Rates

Table H-2. Actual and Estimated Solid Discharge Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	107	215	322	429	537	644	751	858
20	107.8	233.5	326.8	459.5	**574.3**	661.0	**781.0**	926.3
25	110.2	**244.1**	325.2	**450.8**	589.2	658.2	793.3	**865.2**
30	101.8	**224.9**	316.0	425.5	**536.0**	635.0	**742.7**	838.7
35	**101.4**	232.9	360.3	**412.5**	**516.8**	689.1	838.3	894.9
40	**82.3**	**186.6**	**290.0**	**393.3**	**497.7**	**601.0**	**704.4**	**807.8**
45	100.1	**167.5**	309.1	418.3	516.9	**581.9**	542.2	597.3

Note: Red entries are for 1.5 inch gate opening
Black entries are for 3.0 inch gate opening
The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table H-3. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in MPH	Dial-In Application Rate in lbs/mile							
	107	215	322	429	537	644	751	858
20	0.7%	8.6%	1.5%	7.1%	**6.3%**	2.6%	**3.4%**	8.0%
25	3.0%	**12.9%**	1.0%	**4.5%**	9.7%	2.2%	5.6%	**0.2%**
30	-4.9%	**4.0%**	-1.9%	-0.8%	**-0.8%**	-1.4%	**-1.7%**	-2.2%
35	**-5.8%**	11.6%	11.9%	**-4.5%**	**-4.4%**	7.0%	11.6%	4.3%
40	**-23.7%**	**-13.8%**	**-10.6%**	**-8.9%**	**-7.9%**	**-7.3%**	**-6.8%**	**-6.5%**
45	-6.4%	**-22.7%**	-4.0%	-2.5%	-3.7%	**-10.2%**	-27.8%	-30.4%

Note: Red entries are for 1.5 inch gate opening

Black entries are for 3.0 inch gate opening

The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table H-4. Regression Coefficients for Determination of Missing Test Discharge Values

Material	Rate Coefficient	Speed Coefficient	Intercept	R - squared
	A1	A2	B	(As percent)
Solid	0.966	-3.830	132.124	93.3%

Table H-5. Percent of Error for Actual Solid Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Solid Discharge, lbs/sec	Test Solid Discharge, lbs/sec	Percent of Error	Set (Dial-In) Solid Discharge Rate, lbs/mile	Test Solid Discharge Rate, lbs/mile	Percent of Error
1	60	20	0.594	0.598	0.67%	107	107.8	0.75%
2	60	20	1.789	1.815	1.45%	322	326.8	1.49%
4	60	30	0.892	0.848	-4.93%	107	101.8	-4.86%
7	60	45	1.338	1.252	-6.43%	107	100.1	-6.45%
9	60	20	1.194	1.297	8.63%	215	233.5	8.60%
19	60	25	0.743	0.765	2.96%	107	110.2	2.99%
5	45	30	2.683	2.633	-1.86%	322	316.0	-1.86%
24	40	35	2.090	2.265	8.37%	215	232.9	8.33%
3	30	20	3.578	3.673	2.66%	644	661.0	2.64%
6	30	30	3.575	3.893	8.90%	429	467.0	8.86%
8	30	45	4.025	3.863	-4.02%	322	309.1	-4.01%
10	30	20	2.383	2.553	7.13%	429	459.5	7.11%
20	30	25	2.236	2.260	1.07%	322	325.2	0.99%
25	30	35	3.131	3.503	11.88%	322	360.3	11.89%
11	20	20	4.767	5.145	7.93%	858	926.3	7.96%
12	20	30	3.575	3.545	-0.84%	429	425.5	-0.82%
13	20	30	5.367	5.290	-1.43%	644	635.0	-1.40%
15	20	45	5.363	5.230	-2.48%	429	418.3	-2.49%
21	20	25	3.729	4.090	9.68%	537	589.2	9.72%
22	20	25	4.472	4.570	2.19%	644	658.2	2.20%
23	18	25	5.215	5.511	5.68%	751	793.3	5.63%
14	15	30	7.150	6.987	-2.28%	858	838.7	-2.25%
16	15	45	6.713	6.460	-3.77%	537	516.9	-3.74%
17	15	45	9.388	6.780	-27.78%	751	542.2	-27.80%
26	15	35	6.261	6.700	7.01%	644	689.1	7.00%
18	10	45	10.725	7.470	-30.35%	858	597.3	-30.38%
27	10	35	7.301	8.150	11.63%	751	838.3	11.62%
28	10	35	8.342	8.700	4.29%	858	894.9	4.30%

Table H-6. Theoretical and Test Solid Discharges as a Function of Increasing Theoretical Solid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Test Run Time, sec	Theoretical Solid Discharge, lbs/sec	Test Solid Discharge, lbs/sec
1	20	107	60	0.594	0.598
19	25	107	60	0.743	0.765
4	30	107	60	0.892	0.848
9	20	215	60	1.194	1.297
7	45	107	60	1.338	1.252
2	20	322	60	1.789	1.815
24	35	215	40	2.090	2.265
20	25	322	30	2.236	2.260
10	20	429	30	2.383	2.553
5	30	322	45	2.683	2.633
25	35	322	30	3.131	3.503
6	30	429	30	3.575	3.893
12	30	429	20	3.575	3.545
3	20	644	30	3.578	3.673
21	25	537	20	3.729	4.090
8	45	322	30	4.025	3.863
22	25	644	20	4.472	4.570
11	20	858	20	4.767	5.145
23	25	751	18	5.215	5.511
15	45	429	20	5.363	5.230
13	30	644	20	5.367	5.290
26	35	644	15	6.261	6.700
16	45	537	15	6.713	6.460
14	30	858	15	7.150	6.987
27	35	751	10	7.301	8.150
28	35	858	10	8.342	8.700
17	45	751	15	9.388	6.780
18	45	858	10	10.725	7.470

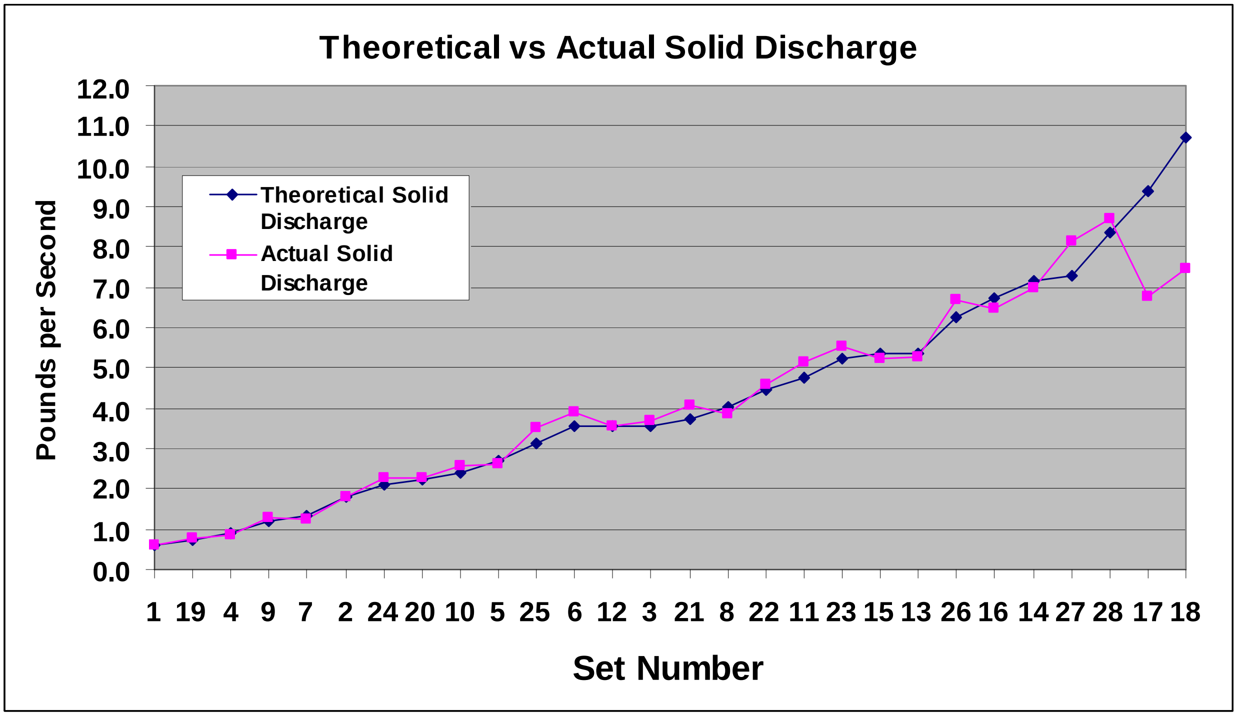

Figure H-1. Theoretical vs Actual Solid Discharge Rate

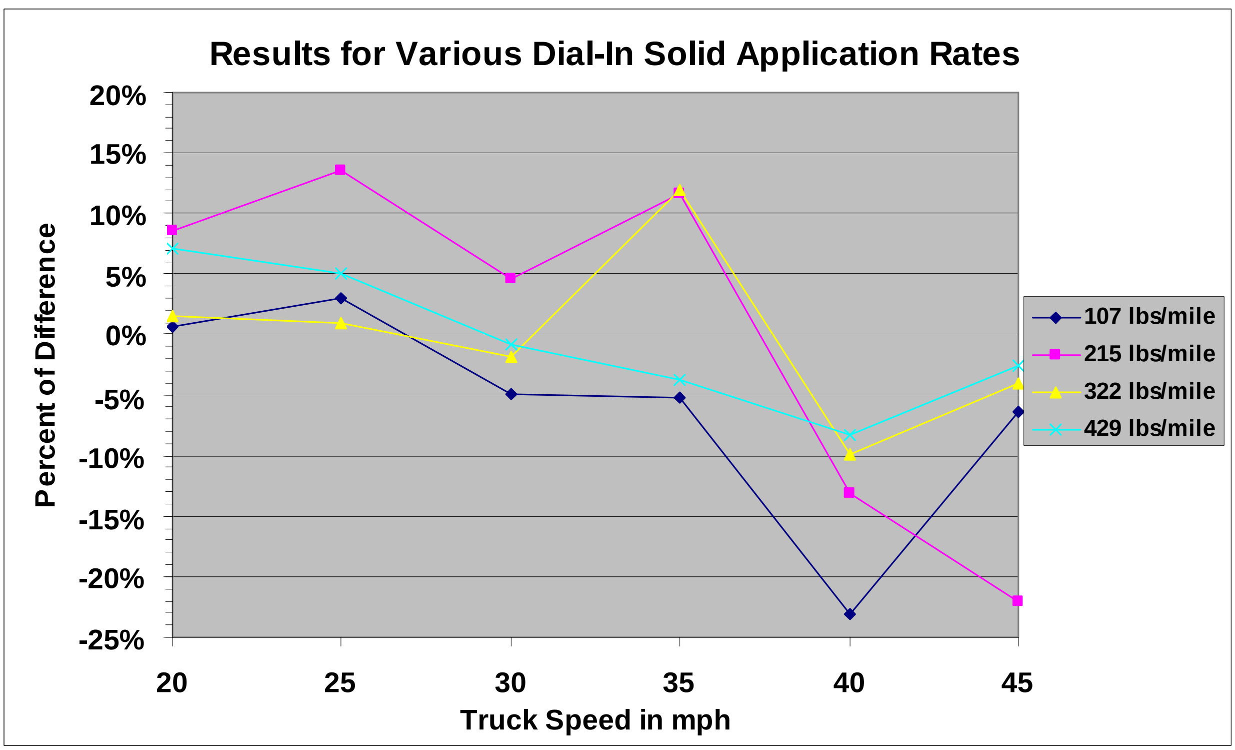

Figure H-3. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

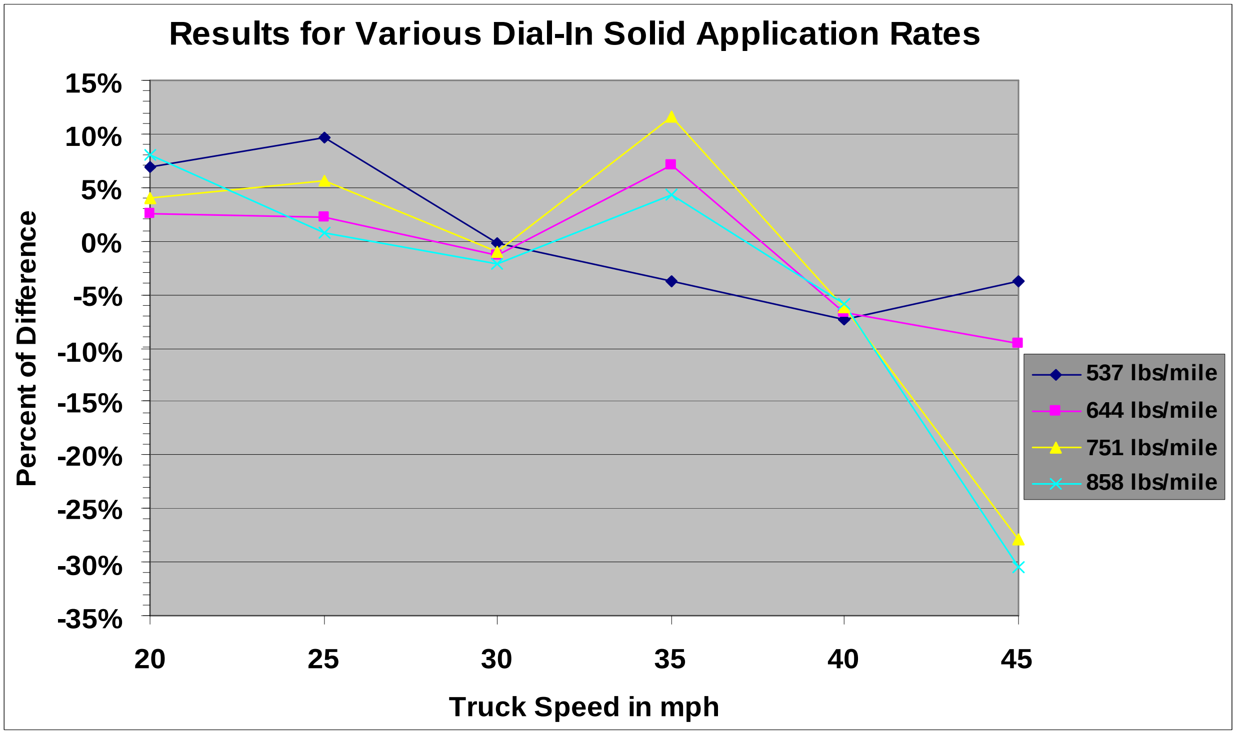

Figure H-4. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

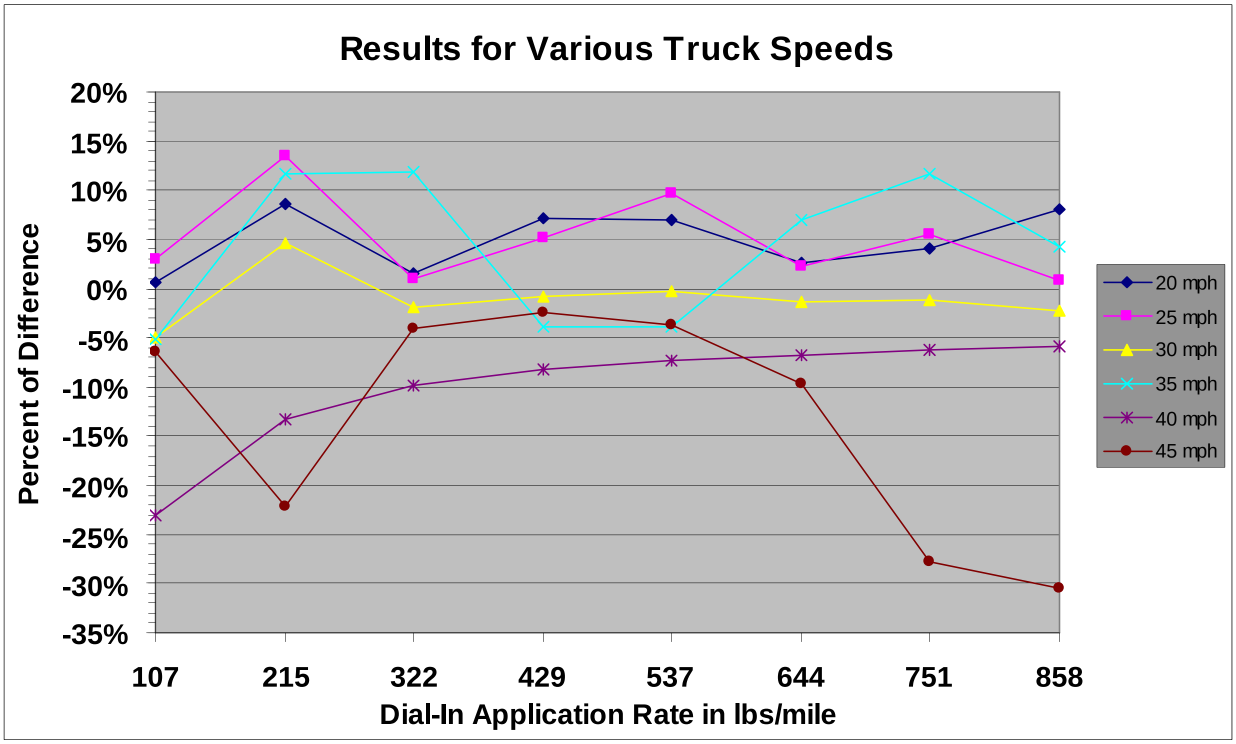

Figure H-5. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Dial-In Solid Application Rate

Table H-7. Statistical Analysis Results for Yard Tests

Yard Test Results for Bias, Accuracy, and Precision	
Solid Discharge	
Bias (lbs/mile)	-3.5
Accuracy	93.0%
Precision	8.0%
Prewetting Discharge	
Bias (gals/ton)	N/A
Accuracy	N/A
Precision	N/A

Note: N/A = Prewetting not available with this spreader/controller

Results from Yard Tests for Control Point

Table H-8. Values of Truck Speed, Solid Discharge Rate, Prewetting Rate, and Test Run Time for Each Test Set Number Used in Yard Testing

Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec
1	20	100	20	90	16	35	200	5	50
2	20	200	25	45	17	35	300	25	17
3	20	400	10	40	18	35	600	30	15
4	20	600	15	15	19	35	700	10	15
5	20	800	30	15	20	35	800	15	15
6	25	100	15	72	21	40	200	20	22
7	25	300	10	24	22	40	300	15	15
8	25	500	20	15	23	40	400	5	15
9	25	600	5	15	24	40	500	25	15
10	25	700	25	15	25	40	700	30	15
11	30	100	30	60	26	45	100	10	40
12	30	300	5	20	27	45	400	30	15
13	30	400	20	15	28	45	500	5	15
14	30	600	25	15	29	45	700	15	15
15	30	800	10	15	30	45	800	20	12

Summary Tabulations of Solid and Liquid Discharge Rates

Table H-9. Actual and Estimated Solid Discharge Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	99.0	201.7	**304.0**	407.6	**520.6**	625.0	**737.2**	851.0
25	97.3	**202.9**	316.0	**419.3**	531.2	637.6	739.2	**852.5**
30	97.5	**209.7**	315.0	426.7	**534.6**	648.7	**751.2**	836.0
35	**108.4**	212.7	323.7	**433.3**	**541.6**	642.9	750.3	854.3
40	**115.4**	222.6	332.0	442.0	545.5	**656.9**	789.0	**873.5**
45	110.3	**230.7**	**339.0**	443.6	556.0	**663.9**	781.3	894.4

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table H-10. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	-1.0%	0.8%	**1.3%**	1.9%	**4.1%**	4.2%	**5.3%**	6.4%
25	-2.7%	**1.3%**	5.3%	**4.8%**	6.2%	6.3%	7.0%	**6.6%**
30	-2.5%	**4.8%**	5.0%	6.7%	**6 .9%**	8.5%	**7.3%**	4.5%
35	**8.4%**	6.3%	7.9%	**8.3%**	**8.3%**	7.2%	7.2%	6.8%
40	**15.4%**	11.3%	10.7%	10.5%	9.1%	**9.5%**	12.7%	**9.2%**
45	10.3%	**15.4%**	**13.0%**	10.9%	11.2%	**10.7%**	11.6%	11.8%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table H-11. Actual Prewetting Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rates in gallons/ton					
	5	10	15	20	25	30
20	**NE**	9.5	9.0	2.1	10.5	7.0
25	4.6	8.9	10.6	8.2	6.9	**NE**
30	4.1	5.8	**NE**	8.9	6.5	11.1
35	5.1	5.6	5.4	**NE**	10.1	6.1
40	4.4	**NE**	8.8	9.6	6.1	5.0
45	4.4	3.3	5.1	5.1	**NE**	6.7

Note: **NE** = Not estimated

Table H-12. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	NE	-5.0%	-40.0%	-89.5%	-58.0%	-76.7%
25	-8.0%	-11.0%	-29.3%	-59.0%	-72.4%	NE
30	-18.0%	-42.0%	NE	-55.5%	-74.0%	-63.0%
35	2.0%	-44.0%	-64.0%	NE	-59.6%	-79.7%
40	-12.0%	NE	-41.3%	-52.0%	-75.6%	-83.3%
45	-12.0%	-67.0%	-66.0%	-74.5%	NE	-77.7%

Note: **NE** = Not estimated

Table H-13. Regression Coefficients for Determination of Missing Test Discharge Values

Material	Rate Coefficient	Speed Coefficient	Intercept	R - squared
	A1	A2	B	(as percent)
Solid	1.083	1.397	-48.804	99.8%
Liquid	No determination was made of missing test discharge values			

Table H-14. Percent of Error for Actual Solid Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Solid Discharge, lbs/sec	Test Solid Discharge, lbs/sec	Percent of Error	Set (Dial-In) Solid Discharge Rate, lbs/mile	Test Solid Discharge Rate, lbs/mile	Percent of Error
1	90	20	0.556	0.550	-1.08%	100	99.0	-1.00%
6	72	25	0.694	0.676	-2.59%	100	97.3	-2.70%
11	60	30	0.833	0.813	-2.40%	100	97.5	-2.50%
16	50	35	1.944	2.068	6.38%	200	212.7	6.35%
2	45	20	1.111	1.120	0.81%	200	201.7	0.85%
3	40	20	2.222	2.263	1.85%	400	407.6	1.90%
26	40	45	1.250	1.380	10.40%	100	110.3	10.30%
7	24	25	2.083	2.196	5.42%	300	316.0	5.33%
21	22	40	2.222	2.473	11.30%	200	222.6	11.30%
12	20	30	2.500	2.625	5.00%	300	315.0	5.00%
17	17	35	2.917	3.147	7.88%	300	323.7	7.90%
4	15	20	3.333	3.473	4.20%	600	625.0	4.17%
5	15	20	4.444	4.727	6.37%	800	851.0	6.38%
8	15	25	3.472	3.687	6.19%	500	531.2	6.24%
9	15	25	4.167	4.427	6.24%	600	637.6	6.27%
10	15	25	4.861	5.133	5.60%	700	739.2	5.60%
13	15	30	3.333	3.553	6.60%	400	426.7	6.68%
14	15	30	5.000	5.407	8.14%	600	648.7	8.12%
15	15	30	6.667	6.967	4.50%	800	836.0	4.50%
18	15	35	5.833	6.253	7.20%	600	642.9	7.15%
19	15	35	6.806	7.293	7.16%	700	750.3	7.19%
20	15	35	7.778	8.307	6.80%	800	854.3	6.79%
22	15	40	3.333	3.687	10.62%	300	332.0	10.67%
23	15	40	4.444	4.913	10.55%	400	442.0	10.50%
24	15	40	5.555	6.060	9.09%	500	545.5	9.10%
25	15	40	7.778	8.767	12.72%	700	789.0	12.71%
27	15	45	5.000	5.547	10.94%	400	443.6	10.90%
28	15	45	6.250	6.953	11.25%	500	556.0	11.20%
29	15	45	8.750	9.767	11.62%	700	781.3	11.61%
30	12	45	10.000	11.183	11.83%	800	894.4	11.80%

Table H-15. Percent of Error for Actual Liquid Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Liquid Discharge, ozs/sec.	Test Liquid Discharge, ozs/sec	Percent of Error	Set (Dial-In) Liquid Discharge Rate, gals/ton	Test Liquid Discharge Rate, gals/ton	Percent of Error
1	90	20	0.711	0.074	-89.59%	20	2.1	-89.50%
6	72	25	0.667	0.457	-31.48%	15	10.6	-29.33%
11	60	30	1.599	0.567	-64.54%	30	11.1	-63.00%
16	50	35	0.622	0.670	7.72%	5	5.1	2.00%
2	45	20	1.778	0.751	-57.76%	25	10.5	-58.00%
3	40	20	1.422	1.375	-3.31%	10	9.5	-5.00%
7	24	25	1.333	1.267	-4.95%	10	8.9	-11.00%
21	22	40	2.844	1.509	-46.94%	20	9.6	-52.00%
12	20	30	0.800	0.685	-14.38%	5	4.1	-18.00%
17	17	35	4.667	2.018	-56.76%	25	10.1	-59.60%
4	15	20	3.200	1.980	-38.13%	15	9.0	-40.00%
5	15	20	8.533	2.113	-75.24%	30	7.0	-76.67%
8	15	25	4.444	1.927	-56.64%	20	8.2	-59.00%
9	15	25	1.333	1.293	-3.00%	5	4.6	-8.00%
10	15	25	7.778	2.240	-71.20%	25	6.9	-72.40%
13	15	30	4.266	2.047	-52.02%	20	8.9	-55.50%
14	15	30	8.000	2.287	-71.41%	25	6.5	-74.00%
15	15	30	4.267	2.527	-40.78%	10	5.8	-42.00%
18	15	35	11.199	2.440	-78.21%	30	6.1	-79.67%
19	15	35	4.356	2.600	-40.31%	10	5.6	-44.00%
20	15	35	7.467	2.840	-61.97%	15	5.4	-64.00%
22	15	40	3.200	2.107	-34.16%	15	8.8	-41.33%
23	15	40	1.422	1.347	-5.27%	5	4.4	-12.00%
24	15	40	8.889	2.440	-72.55%	25	6.1	-75.60%
25	15	40	14.933	2.813	-81.16%	30	5.0	-83.33%
26	15	45	0.800	0.290	-63.75%	10	3.3	-67.00%
27	15	45	9.600	2.353	-75.49%	30	6.7	-77.67%
28	15	45	2.000	1.933	-3.35%	5	4.4	-12.00%
29	15	45	8.400	3.167	-62.30%	15	5.1	-66.00%
30	12	45	12.800	3.667	-71.35%	20	5.1	-74.50%

Table H-16. Theoretical and Test Solid Discharges as a Function of Increasing Theoretical Solid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Theoretical Solid Discharge, lbs/sec	Test Solid Discharge, lbs/sec
1	20	100	20	90	0.556	0.550
6	25	100	15	72	0.694	0.676
11	30	100	30	60	0.833	0.813
2	20	200	25	45	1.111	1.120
26	45	100	10	40	1.250	1.380
16	35	200	5	50	1.944	2.068
7	25	300	10	24	2.083	2.196
3	20	400	10	40	2.222	2.263
21	40	200	20	22	2.222	2.473
12	30	300	5	20	2.500	2.625
17	35	300	25	17	2.917	3.147
4	20	600	15	15	3.333	3.473
13	30	400	20	15	3.333	3.553
22	40	300	15	15	3.333	3.687
8	25	500	20	15	3.472	3.687
9	25	600	5	15	4.167	4.427
5	20	800	30	15	4.444	4.727
23	40	400	5	15	4.444	4.913
10	25	700	25	15	4.861	5.133
14	30	600	25	15	5.000	5.407
27	45	400	30	15	5.000	5.547
24	40	500	25	15	5.555	6.060
18	35	600	30	15	5.833	6.253
28	45	500	5	15	6.250	6.953
15	30	800	10	15	6.667	6.967
19	35	700	10	15	6.806	7.293
20	35	800	15	15	7.778	8.307
25	40	700	30	15	7.778	8.767
29	45	700	15	15	8.750	9.767
30	45	800	20	12	10.000	11.183

Table H-17. Theoretical and Test Liquid Discharges as a Function of Increasing Theoretical Liquid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run time, sec	Theoretical Liquid Discharge, ozs/sec	Test Liquid Discharge, ozs/sec
16	35	200	5	50	0.622	0.670
6	25	100	15	72	0.667	0.457
1	20	100	20	90	0.711	0.074
12	30	300	5	20	0.800	0.685
26	45	100	10	40	0.800	0.290
7	25	300	10	24	1.333	1.267
9	25	600	5	15	1.333	1.293
3	20	400	10	40	1.422	1.375
23	40	400	5	15	1.422	1.347
11	30	100	30	60	1.599	0.567
2	20	200	25	45	1.778	0.751
28	45	500	5	15	2.000	1.933
21	40	200	20	22	2.844	1.509
4	20	600	15	15	3.200	1.980
22	40	300	15	15	3.200	2.107
13	30	400	20	15	4.266	2.047
15	30	800	10	15	4.267	2.527
19	35	700	10	15	4.356	2.600
8	25	500	20	15	4.444	1.927
17	35	300	25	17	4.667	2.018
20	35	800	15	15	7.467	2.840
10	25	700	25	15	7.778	2.240
14	30	600	25	15	8.000	2.287
29	45	700	15	15	8.400	3.167
5	20	800	30	15	8.533	2.113
24	40	500	25	15	8.889	2.440
27	45	400	30	15	9.600	2.353
18	35	600	30	15	11.199	2.440
30	45	800	20	12	12.800	3.667
25	40	700	30	15	14.933	2.813

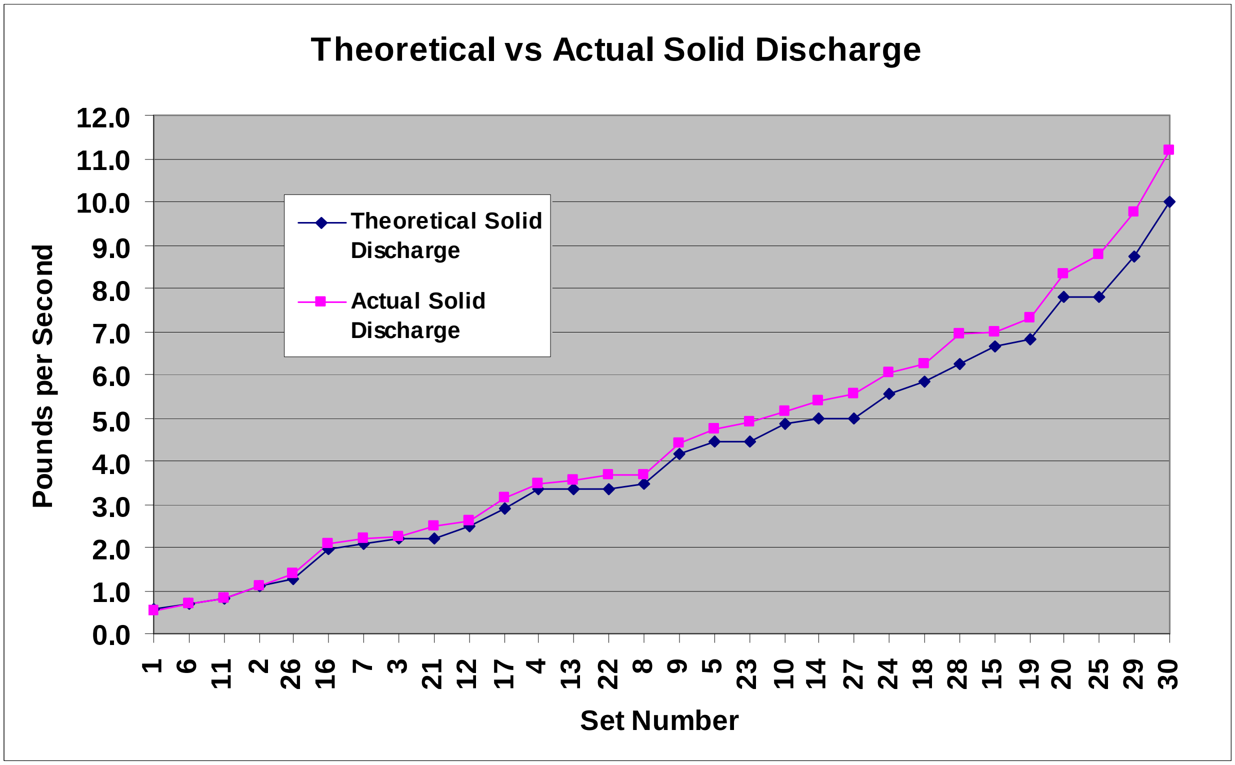

Figure H-6. Theoretical vs Actual Solid Discharge Rate

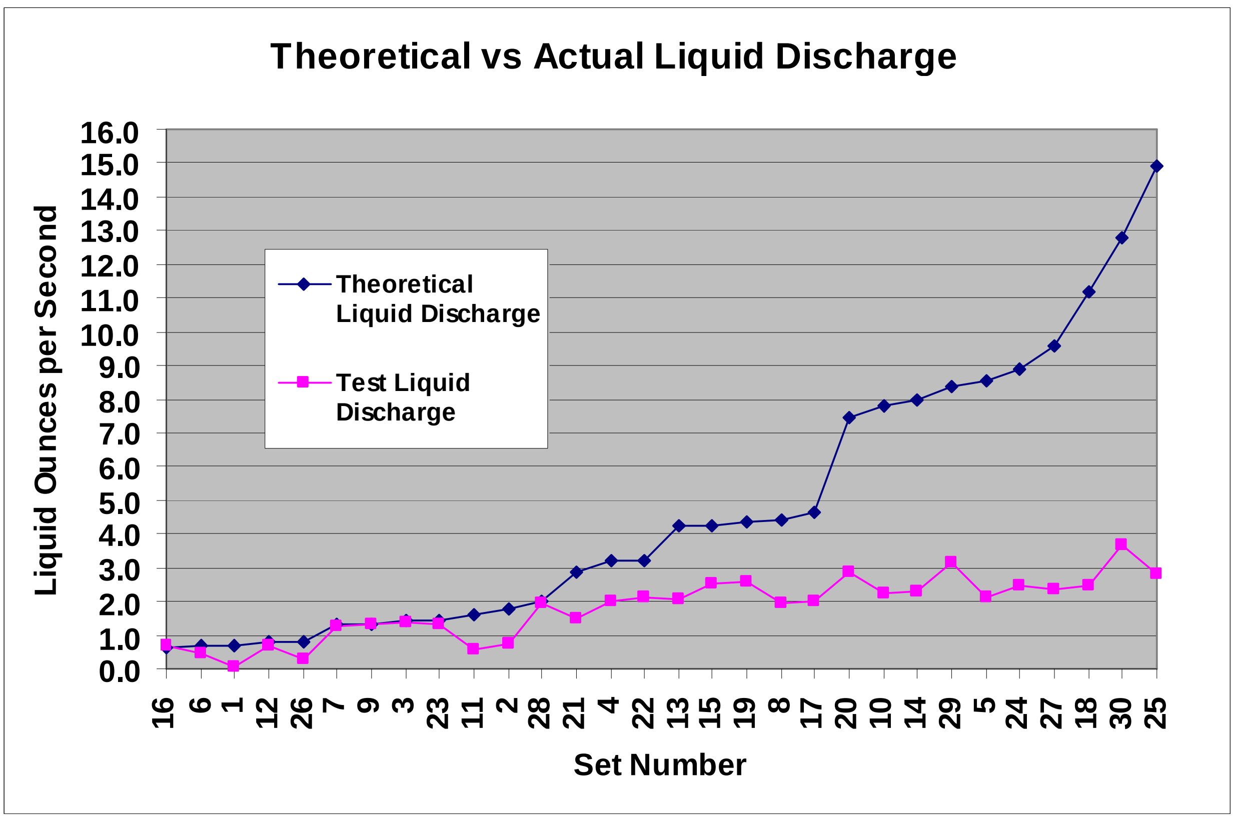

Figure H-7. Theoretical vs Actual Liquid Carbohydrate Enhanced Calcium Chloride Discharge Rate

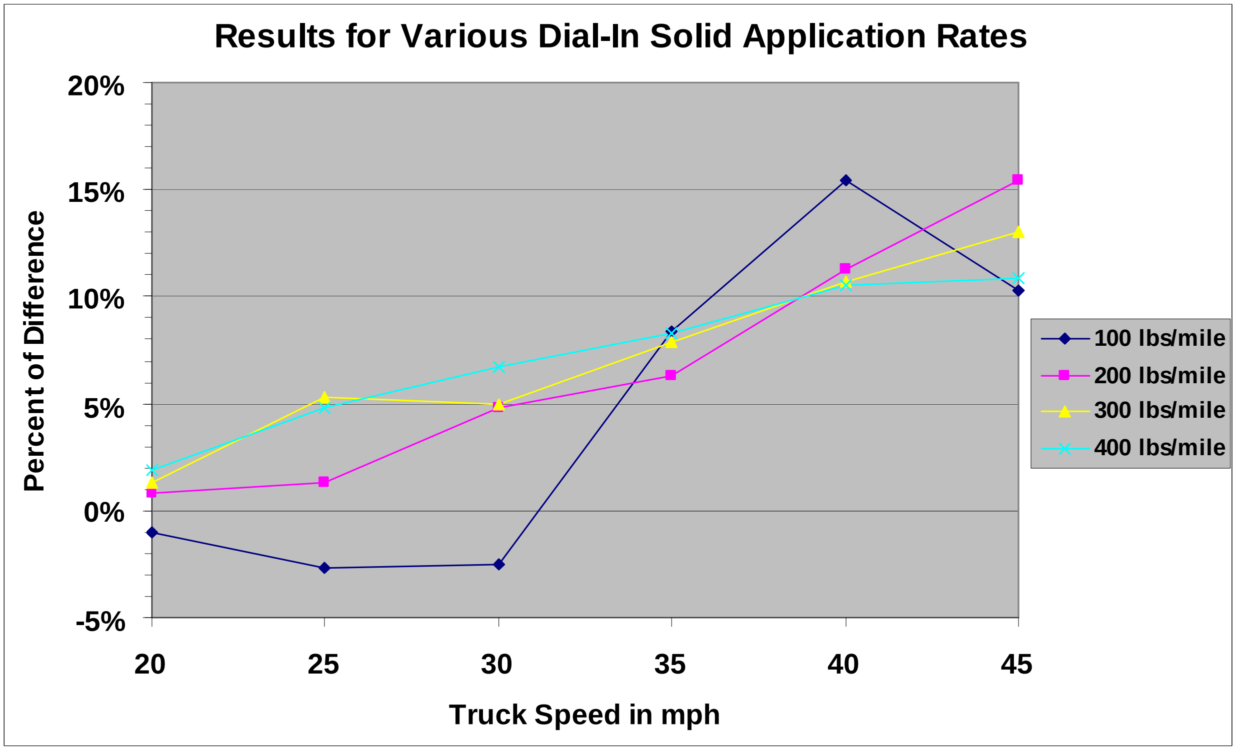

Figure H-8. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

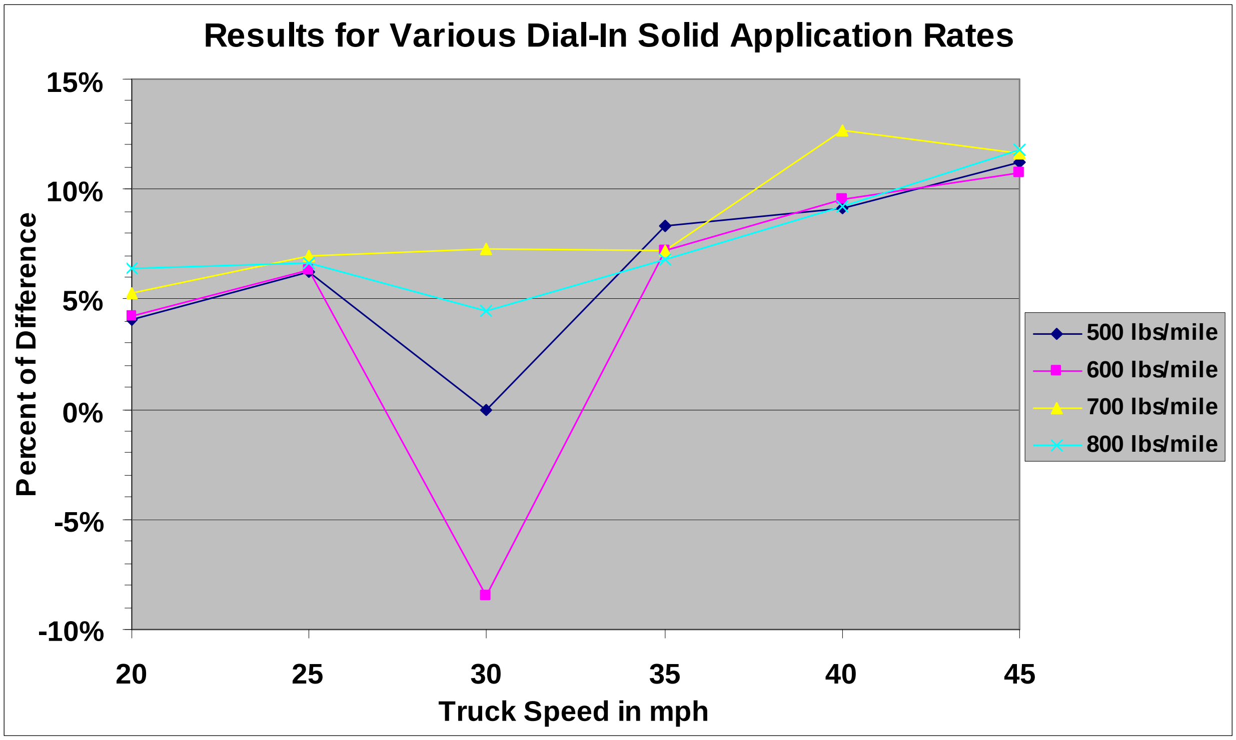

Figure H-9. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

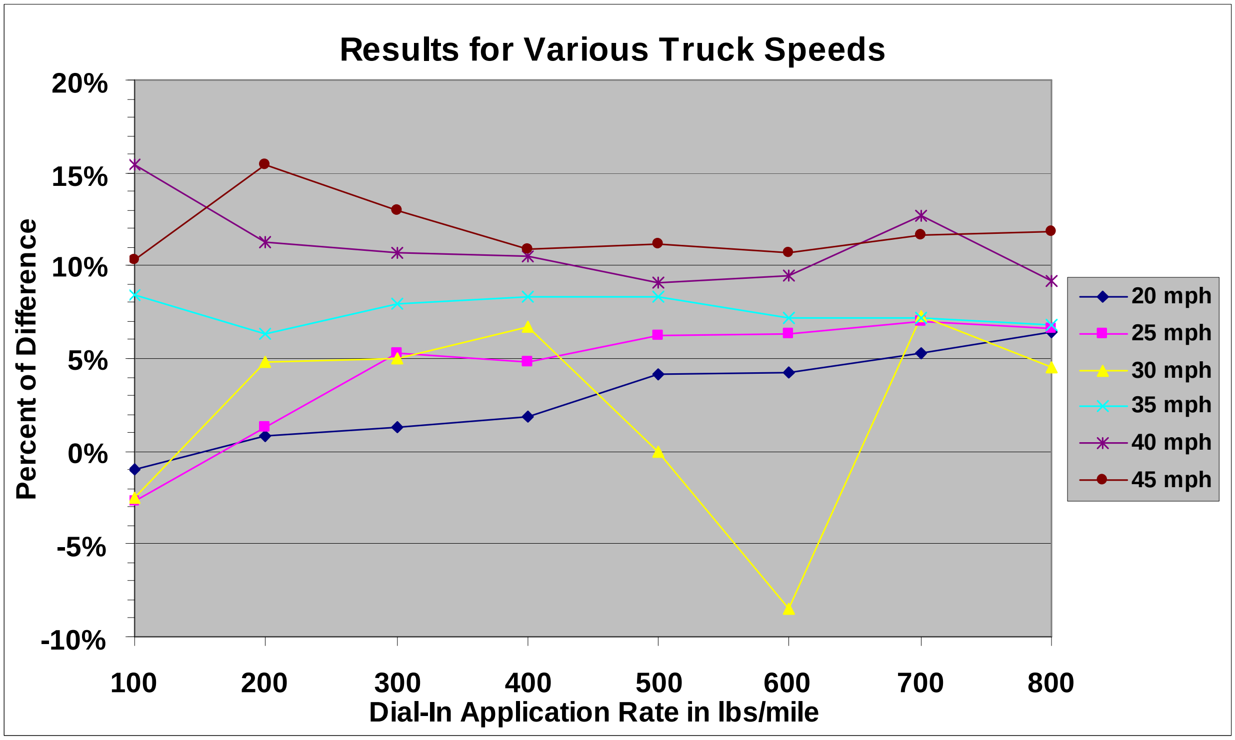

Figure H-10. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Dial-In Solid Application Rate

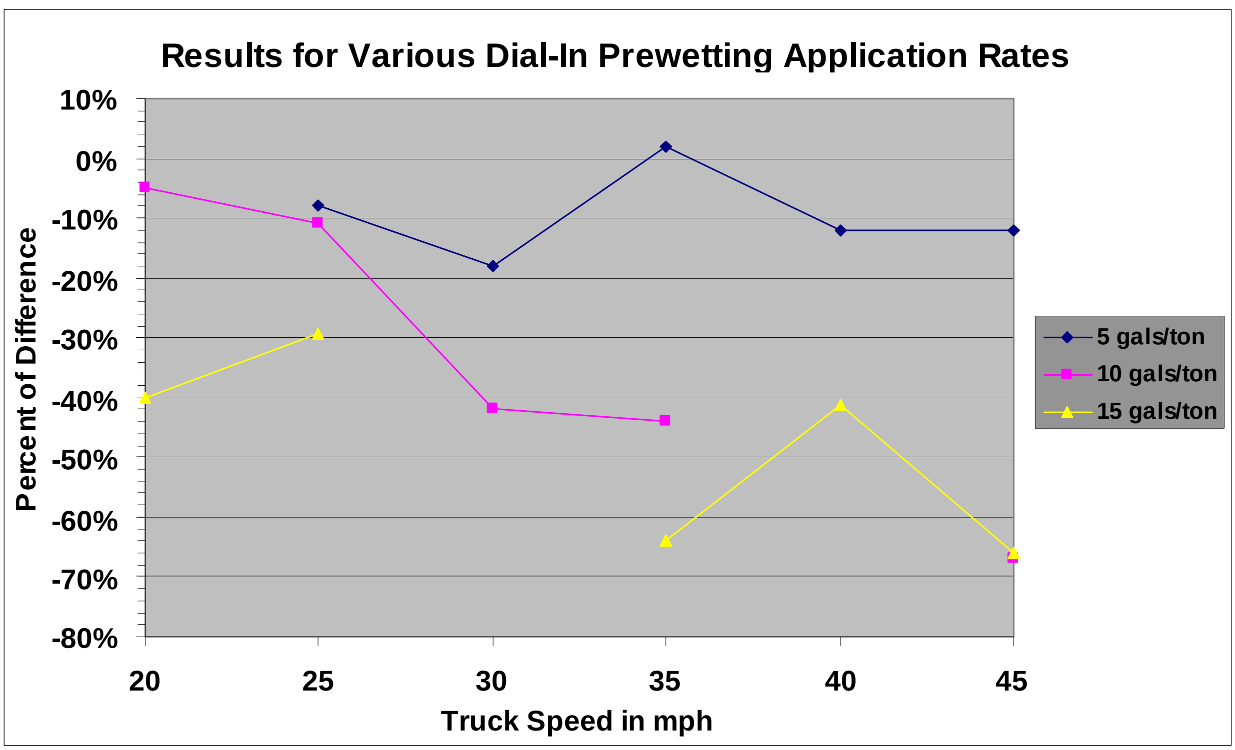

Figure H-11. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed

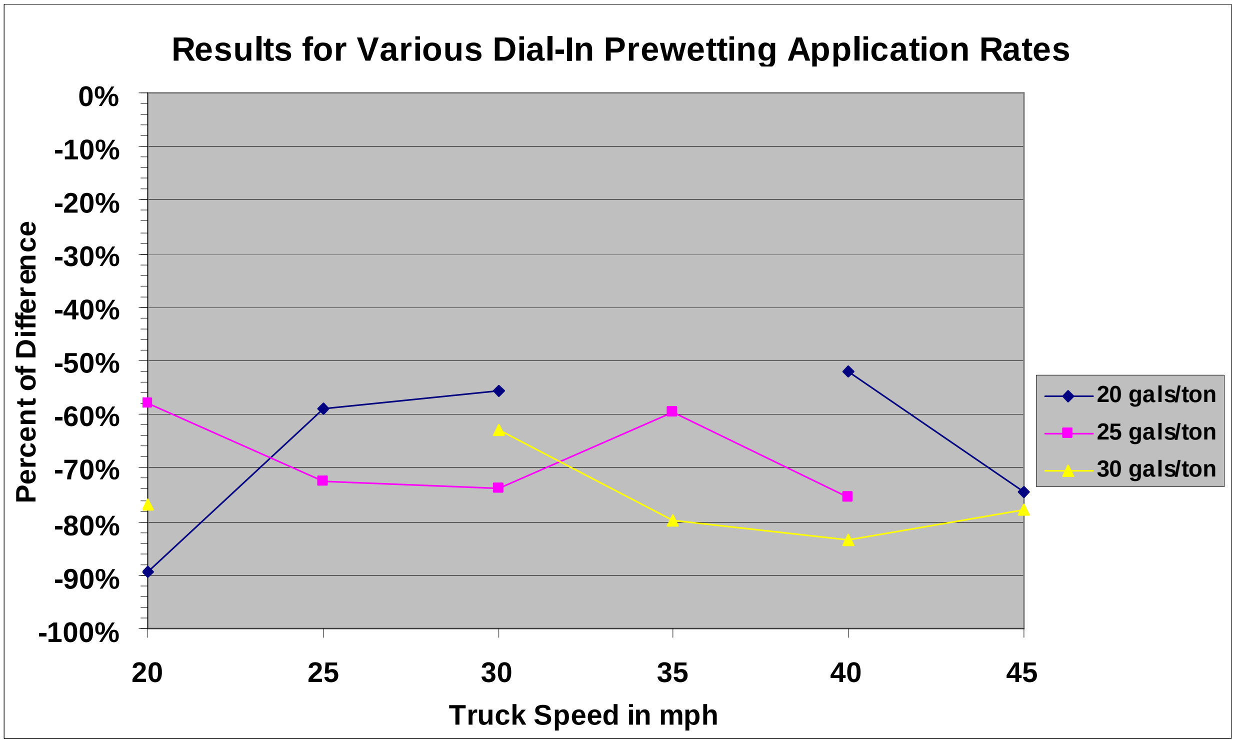

Figure H-12. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed

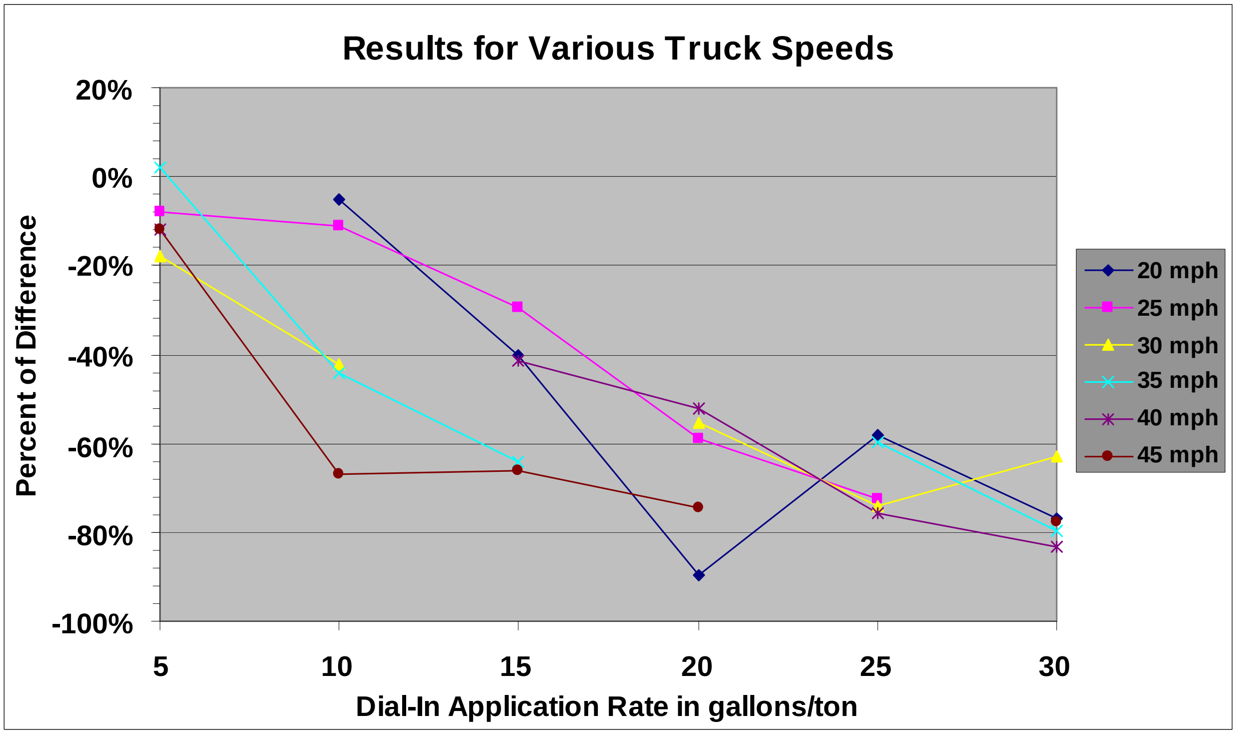

Figure H-13. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Dial-In Prewetting Rate

Table H-18. Statistical Analysis Results for Yard Tests

Yard Test Results for Bias, Accuracy, and Precision	
Solid Discharge	
Bias (lbs/mile)	34.3
Accuracy	92.9%
Precision	4.1%
Prewetting Discharge	
Bias (gals/ton)	Data too Erratic to made determination
Accuracy	Data too Erratic to made determination
Precision	Data too Erratic to made determination

Results from Simulated Scenario Testing for Control Point

Table H-19. Solid Discharges for Closed-loop and Open-loop Modes from Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (lbs)	Actual Discharge (lbs)	Discharge Amount According to Controller	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	5,109	4,550	5,100	-10.94%	-0.18%	12.09%	-10.78%	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	2	5,117	5,000	5,108	-2.29%	-0.18%	2.16%	-2.11%	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	5	5,110	5,325	5,144	4.20%	0.66%	-3.40%	3.52%	
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	7	4,700	2,635	*	-43.93%	NA	NA	NA	-46.9%
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	5,000	5,425	4,986	8.49%	-0.29%	-8.09%	8.80%	
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	4	4,909	6,485	4,929	32.11%	0.41%	-23.99%	31.57%	
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	6	4,972	5,375	4,863	8.11%	-2.19%	-9.53%	10.53%	
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	8	4,725	3,125	*	-33.86%	NA	NA	NA	-45.8%

Note: * = Data not available from the controller.

NA = Could not be computed because data were not available from the controller.

Table H-20. Solid Discharge Comparison for Freeway and Highway Scenarios in Both Closed-loop and Open-loop Operations

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Closed-loop	3.01%	0.10%
Open-loop	-43.93%	No Data
Highway:		
Closed-loop	16.16%	0.69%
Open-loop	-33.86%	No Data

Table H-21. Solid Discharge Comparison of Open-loop to Closed-loop Operations for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	-46.85%
Controller Display Discharge	No Data
Highway:	
Actual Discharge	-45.77%
Controller Display Discharge	No Data

APPENDIX I
TEST RESULTS FOR FORCE AMERICA 2100

Results from Yard Tests

Table I-1. Values of Truck Speed, Test Time, and Solid Discharge for each Test Set Number used in Yard Testing

Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Test Run Time, sec.	Set No.	Truck Speed, mph	Set Solid Discharge Rate lbs/mile	Test Run Time, sec.
1	20	117.6	N/T	14	40	268.8	20
2	20	420.0	45	15	40	525.0	15
3	20	798.0	30	16	45	117.6	40
4	25	268.8	40	17	45	420.0	10
5	25	525.0	20	18	45	798.0	10
6	25	700	N/T	19	20	1008	20
7	30	117.6	N/T	20	30	1008	10
8	30	420.0	20	21	45	1008	5
9	30	798.0	15	22	30	205.8	30
10	35	205.8	45	23	30	340.2	20
11	35	600	N/T	24	30	525.0	15
12	35	700	N/T	25	25	340.2	20
13	40	205.8	30	26	40	340.2	20

Note: N/T = No Test

Summary Tabulations of Solid Discharge Rates

Table I-2. Actual and Estimated Solid Discharge Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile								
	117.6	205.8	268.8	340.2	420.0	525.0	798.0	966.0	1008.0
20	ANT	**-24.6**	**83.3**	**184.0**	300.4	**346.9**	443.6	**673.1**	684.6
25	NE	**46.2**	218.3	326.6	**322.1**	456.7	**556.9**	**743.9**	**945.3**
30	ANT	204.4	**224.9**	341.0	370.8	498.7	611.5	**814.7**	1129.8
35	NE	149.3	**295.7**	**396.4**	**463.6**	**559.2**	**698.4**	**885.5**	**1086.8**
40	NE	169.4	264.5	307.4	**534.4**	683.2	**769.2**	**956.2**	**1157.6**
45	99.2	**329.3**	**437.2**	**537.9**	604.3	**700.8**	1009.3	**1027.0**	1209.1

Note: ANT = Auger would not turn

NE = Not estimated

The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table I-3. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile								
	117.5	205.8	268.8	340.2	420.0	525.0	798.0	966.0	1008.0
20	ANT	NE	**-69.0%**	**-45.9%**	-28.5%	**-33.9%**	-44.4%	**-30.3%**	-32.1%
25	NE	**-77.6%**	-18.8%	-4.0%	**-23.3%**	-13.0%	**-30.2%**	**-23.0%**	**-6.2%**
30	ANT	0.7%	**-16.3%**	0.2%	-11.7%	-5.0%	-23.4%	**-15.7%**	12.1%
35	NE	-27.5%	**10.0%**	**16.5%**	**10.4%**	**6.5%**	**-12.5%**	**-8.3%**	**7.8%**
40	NE	-17.7%	-1.6%	-9.6%	**27.2%**	30.1%	**-3.6%**	**-1.0%**	**14.8%**
45	-15.6%	**60.0%**	**60.0%**	**58.1%**	43.9%	**33.5%**	26.5%	**6.3%**	20.0%

Note: ANT = Auger would not turn

NE = Not Estimated

The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table I-4. Regression Coefficients for Determination of Missing Test Discharge Values

Material	Rate Coefficient	Speed Coefficient	Intercept	R - squared
	A1	A2	B	(As percent)
Solid	1.370	14.156	-473.107	90.6%

Table I-5. Percent of Error for Actual Solid Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Solid Discharge, lbs/sec.	Test Solid Discharge, lbs/sec	Percent of Error	Set Solid Discharge Rate, lbs/mile	Test solid Discharge Rate, lbs/mile	Percent of Error
2	45	20	2.333	1.669	-28.46%	420.0	300.4	-28.48%
10	45	35	2.001	1.451	-27.49%	205.8	149.3	-27.45%
4	40	25	1.867	1.515	-18.85%	268.8	218.3	-18.79%
16	40	40	1.469	1.240	-15.59%	117.6	99.2	-15.65%
3	30	20	4.433	2.463	-44.44%	798.0	443.6	-44.41%
13	30	40	2.287	1.883	-17.67%	205.8	169.4	-17.69%
22	30	30	1.715	1.703	-0.70%	205.8	204.4	-0.68%
5	20	25	3.646	3.170	-13.06%	525.0	456.7	-13.01%
8	20	30	3.500	3.060	-12.57%	420.0	370.8	-11.71%
14	20	40	2.987	2.940	-1.57%	268.8	264.5	-1.60%
19	20	20	5.600	3.835	-31.52%	1008.0	684.6	-32.08%
23	20	30	2.835	2.840	0.18%	340.2	341.0	0.24%
25	20	25	2.363	2.270	-3.94%	340.2	326.6	-4.00%
26	20	40	3.780	3.415	-9.66%	340.2	307.4	-9.64%
9	15	30	6.650	5.093	-23.41%	798.0	611.5	-23.37%
15	15	40	5.833	7.593	30.17%	525.0	683.2	30.13%
24	15	30	4.375	4.153	-5.07%	525.0	498.7	-5.01%
17	10	45	5.250	7.550	43.81%	420.0	604.3	43.88%
18	10	45	9.975	12.620	26.52%	798.0	1009.3	26.48%
20	10	30	8.400	9.440	12.38%	1008.0	1129.8	12.08%
21	5	45	12.600	15.120	20.00%	1008.0	1209.1	19.95%

Table I-6. Theoretical and Test Solid Discharges as a Function of Increasing Theoretical Solid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Test Run Time, sec	Theoretical Solid Discharge Rate, lbs/sec.	Test Solid Discharge Rate, lbs/sec
16	40	117.6	40	1.469	1.240
22	30	205.8	30	1.715	1.703
4	25	268.8	40	1.867	1.515
10	35	205.8	45	2.001	1.451
13	40	205.8	30	2.287	1.883
2	20	420.0	45	2.333	1.669
25	25	340.2	20	2.363	2.270
23	30	340.2	20	2.835	2.840
14	40	268.8	20	2.987	2.940
8	30	420.0	20	3.500	3.060
5	25	525.0	20	3.646	3.170
26	40	340.2	20	3.780	3.415
24	30	525.0	15	4.375	4.153
3	20	798.0	30	4.433	2.463
17	45	420.0	10	5.250	7.550
19	20	1008.0	20	5.600	3.835
15	40	525.0	15	5.833	7.593
9	30	798.0	15	6.650	5.093
20	30	1008.0	10	8.400	9.440
18	45	798.0	10	9.975	12.620
21	45	1008.0	5	12.600	15.120

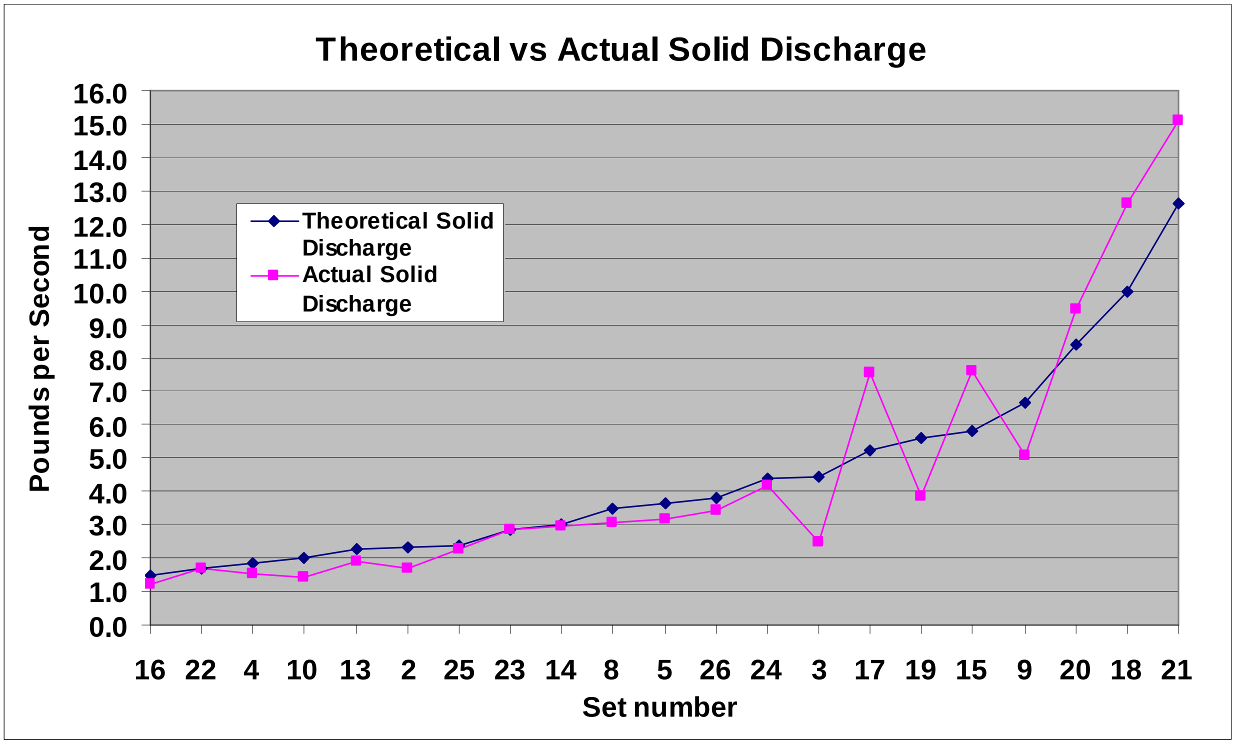

Figure I-1. Theoretical vs Actual Solid Discharge Rate

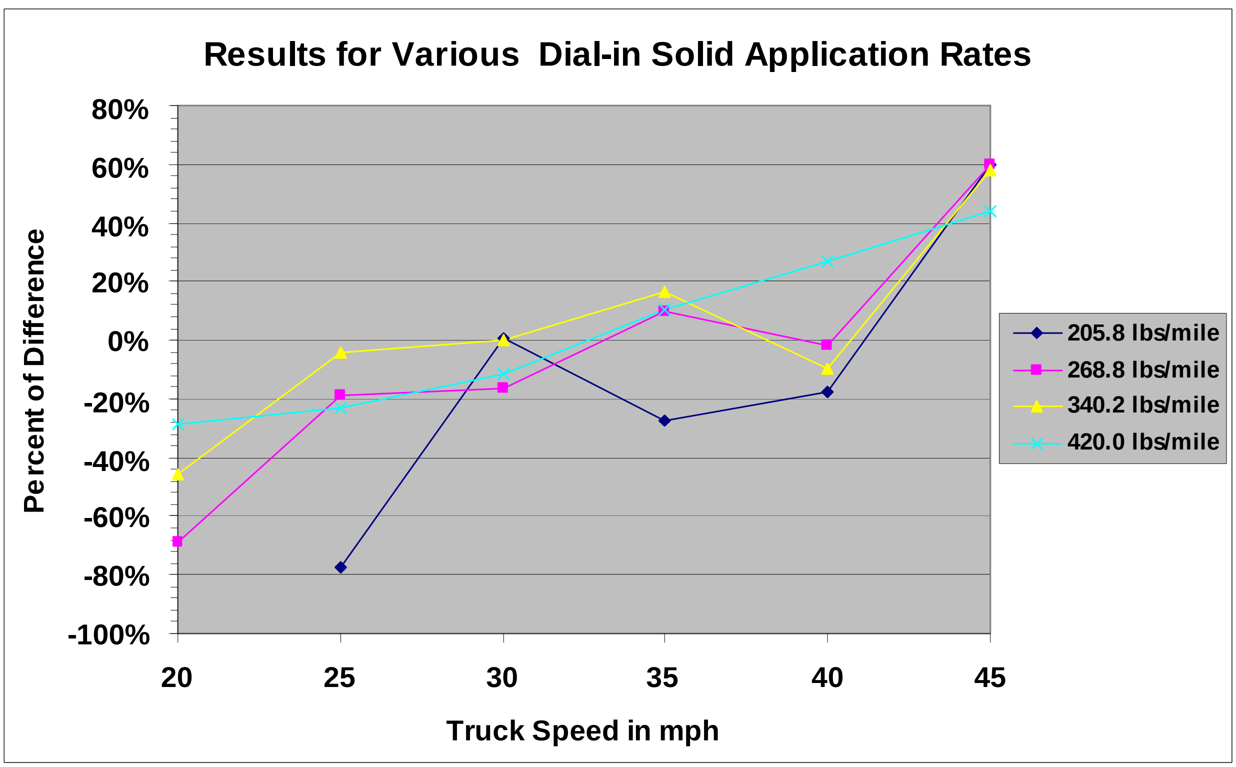

Figure I-2 Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

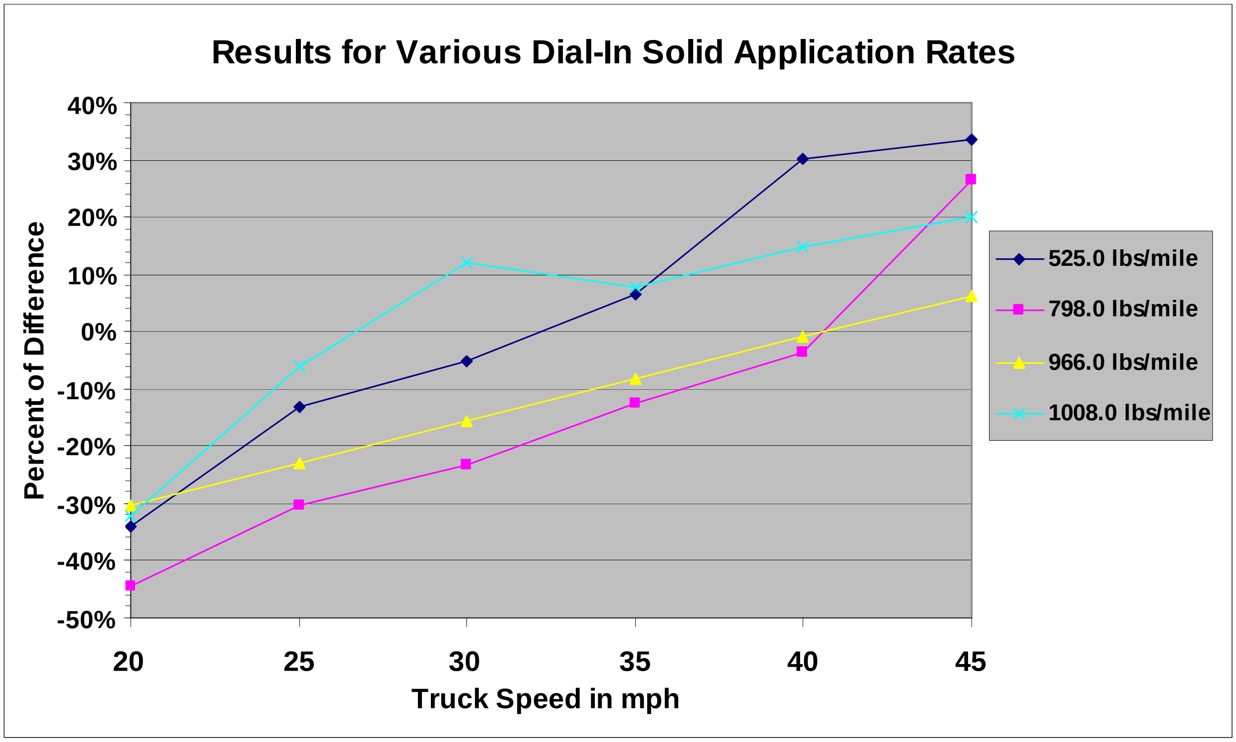

Figure I-3. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

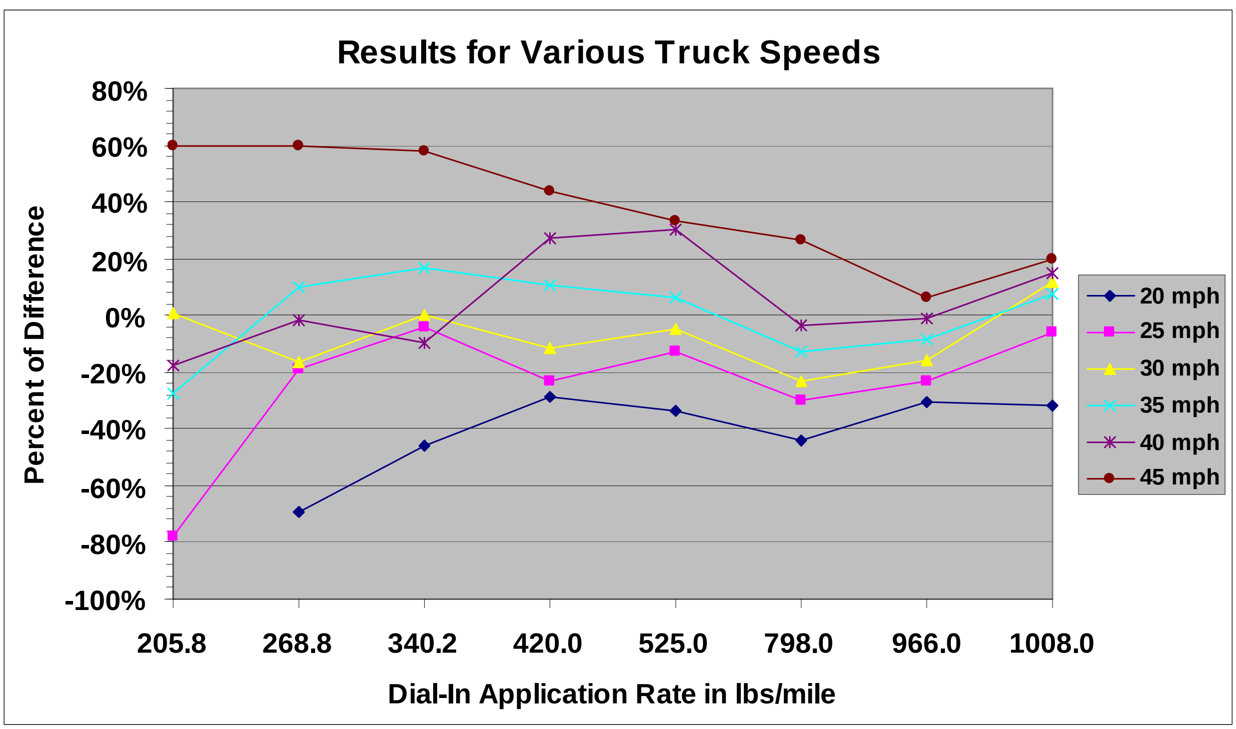

Figure I-4. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Dial-In Solid Application Rate

Table I-7. Statistical Analysis Results for Yard Tests

Yard Test Results for Bias, Accuracy, and Precision	
Solid Discharge	
Bias (lbs/mile)	121.4
Accuracy	64.7%
Precision	44.5%

Results from Simulated Scenario Testing

Table I-8. Solid Discharge for Open-loop Mode for Freeway and Highway Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (lbs)	Actual Discharge (lbs)	Percent of Difference of Actual Compared to Theoretical Discharge
Freeway Scenario - Open-Loop Mode Test Parameter 242.84 and 512.68 lbs/mile Driven: 15, 17, 22, 30, & 35 mph	1	6,632	4,920	-25.82%
Freeway Scenario - Open-Loop Mode Test Parameter 242.84 and 512.68 lbs/mile Driven: 15, 17, 22, 30, & 35 mph	2	4,946	4,280	-13.46%
Freeway Scenario - Open-Loop Mode Test Parameter 242.84 and 512.68 lbs/mile Driven: 15, 22, 30, & 35 mph	5	5,985	3,840	-35.84%
Highway Scenario - Open-Loop Mode Test Parameter 380.22 and 583.81 lbs/mile Driven: 15, 22, 25, 30, & 35 mph	3	6,489	5,280	-18.63%
Highway Scenario - Open-Loop Mode Test Parameter 380.22 and 5583.82 lbs/mile Driven: 15, 20, 22, 25, 30, & 35 mph	4	6,489	4,520	-30.34%

Table I-9. Solid Discharge Comparison for Freeway and Highway Scenarios in Both Closed-loop and Open-loop Operations

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Closed-loop	Does not operate in this mode	Does not operate in this mode
Open-loop	-25.75%	No Data
Highway:		
Closed-loop	Does not operate in this mode	Does not operate in this mode
Open-loop	-24.49%	No Data

Table I-10. Solid Discharge Comparison of Open-loop to Closed-loop Operations for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	Does not operate in Closed-loop mode
Controller Display Discharge	Does not operate in Closed-loop mode
Highway:	
Actual Discharge	Does not operate in Closed-loop mode
Controller Display Discharge	Does not operate in Closed-loop mode

APPENDIX J
TEST RESULTS FOR FORCE AMERICA MODEL 5100

Results from Yard Tests

Table J-1. Values of Truck Speed, Test Run Time, Solid Discharge, and Prewetting for each Test Set Number used in Yard Testing

Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetted Application Rate, gals/ton	Test Run Time, sec	Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetted Application Rate, gals/ton	Test Run Time, sec
1	20	100	20	60	16	35	200	5	25
2	20	200	25	45	17	35	300	25	18
3	20	400	10	25	18	35	600	30	9
4	20	600	15	15	19	35	700	10	7
5	20	800	30	10	20	35	800	15	5
6	25	100	15	60	21	40	200	20	22
7	25	300	10	25	22	40	300	15	15
8	25	500	20	15	23	40	400	5	10
9	25	600	5	10	24	40	500	25	8
10	25	700	25	10	25	40	700	30	6
11	30	100	30	45	26	45	100	10	35
12	30	300	5	20	27	45	400	30	10
13	30	400	20	15	28	45	500	5	8
14	30	600	25	10	29	45	700	15	5
15	30	800	10	7	30	45	800	20	5

Summary Tabulations of Solid and Liquid Discharge Rates

Table J-2. Actual and Estimated Solid Discharge Rates for Various Dial-In Application Rates as Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	103.7	207.3	**325.0**	423.8	**545.8**	645.2	**766.6**	865.2
25	106.0	**215.0**	321.6	**435.8**	546.6	667.7	769.0	**877.4**
30	109.4	**215.4**	324.6	441.1	**546.6**	665.5	**767.4**	890.9
35	**105.4**	217.4	331.6	**436.6**	**547.0**	661.3	786.6	889.4
40	**105.8**	218.5	320.1	435.0	559.1	**657.8**	759.9	**878.6**
45	107.8	**216.6**	**327.0**	435.0	543.7	**658.2**	762.3	857.8

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table J-3. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	3.7%	3.7%	**8.3%**	6.0%	**9.2%**	7.5%	**9.5%**	8.2%
25	6.0%	**7.5%**	7.2%	**9.0%**	9.3%	11.3%	9.9%	**9.7%**
30	9.4%	**7.7%**	8.2%	10.3%	**9.3%**	10.9%	**9.6%**	11.4%
35	**5.4%**	8.7%.	10.5%	**9.2%**	**9.4%**	10.2%	12.4%	11.2%
40	**5.8%**	9.3%	6.7%	8.8%	11.8%	**9.6%**	8.6%	**9.8%**
45	7.8%	**8.3%**	**9.0%**	8.8%	8.7%	**9.7%**	8.9%	7.2%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table J-4. Actual and Estimated Discharge Prewetting Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dialed –In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**9.5**	10.1	14.5	20.8	25.4	20.5
25	4.9	9.6	14.9	18.5	18.7	**23.1**
30	4.6	9.4	**13.1**	18.7	17.9	30.1
35	5.4	9.4	11.4	**14.9**	23.3	15.8
40	4.9	**7.8**	14.3	19.4	15.5	11.6
45	4.9	8.8	9.9	9.1	**15.5**	17.6

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table J-5. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed.

Speed in mph	Dial –In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**90.0%**	1.0%	-3.3%	4.0%	1.6%	-31.7%
25	-2.0%	-4.0%	-0.7%	-7.5%	-25.2%	**-23.0%**
30	-8.0%	-6.0%	**-12.7%**	-6.5%	-28.4%	0.3%
35	8.0%	-6.0%	-24.0%	**-25.5%**	-6.8%	-47.3%
40	-2.0%	**-22.0%**	-4.7%	-3.0%	-38.0%	-61.3%
45	-2.0%	-12.0%	-34.0%	-54.5%	**-38.0%**	-41.3%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table J-6. Regression Coefficients for Determination of Missing Test Discharge Values

Material	Rate Coefficient	Speed Coefficient	Intercept	R - squared
	A1	A2	B	(as percent)
Solid	1.104	0.082	-7.852	99.6%
Liquid	0.590	-0.230	11.113	71.5%

Table J-7. Percent of Error for Actual Solid Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Solid Discharge, lbs/sec	Test Solid Discharge, lbs/sec	Percent of Error	Set (Dial-In) Solid Discharge Rate, lbs/mile	Test Solid Discharge Rate, lbs/mile	Percent of Error
1	60	20	0.556	0.577	3.78%	100	103.7	3.70%
6	60	25	0.694	0.738	6.34%	100	106.0	6.00%
2	45	20	1.111	1.151	3.60%	200	207.3	3.65%
11	45	30	0.833	0.911	9.36%	100	109.4	9.40%
26 **	35	45	1.250	1.349	7.92%	100	107.8	7.80%
3	25	20	2.222	2.360	6.21%	400	423.8	5.95%
7	25	25	2.083	2.232	7.15%	300	321.6	7.20%
16	25	35	1.944	2.120	9.05%	200	217.4	8.70%
21	22	40	2.222	2.427	9.23%	200	218.5	9.25%
12	20	30	2.500	2.705	8.20%	300	324.6	8.20%
17	18	35	2.917	3.222	10.46%	300	331.6	10.53%
4	15	20	3.333	3.587	7.62%	600	645.2	7.53%
8	15	25	3.472	3.793	9.25%	500	546.6	9.32%
13	15	30	3.333	3.673	10.20%	400	441.1	10.28%
22	15	40	3.333	3.527	5.82%	300	320.1	6.70%
5	10	20	4.444	4.770	7.34%	800	865.2	8.15%
9	10	25	4.167	4.650	11.59%	600	667.7	11.28%
10	10	25	4.861	5.340	9.85%	700	769.0	9.86%
14	10	30	5.000	5.550	11.00%	600	665.5	10.92%
23	10	40	4.444	4.830	8.69%	400	435.0	8.75%
27 **	10	45	5.000	5.440	8.80%	400	435.0	8.75%
18	9	35	5.833	6.433	10.29%	600	661.3	10.22%
24	8	40	5.555	6.213	11.85%	500	559.1	11.82%
28 **	8	45	6.250	6.800	8.80%	500	543.7	8.74%
15	7	30	6.667	7.429	11.43%	800	890.9	11.36%
19	7	35	6.806	7.643	12.30%	700	786.6	12.37%
25	6	40	7.778	8.450	8.64%	700	759.9	8.56%
20	5	35	7.778	8.640	11.08%	800	889.4	11.18%
29 **	5	45	8.750	9.400	7.43%	700	762.3	8.90%
30 **	5	45	10.000	10.600	6.00%	800	857.8	7.22%

Note: ** = Slow Down, Over Speed

Table J-8. Percent of Error for Actual Liquid Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Liquid Discharge, ozs/sec	Test Liquid Discharge, ozs/sec	Percent of Error	Set (Dial-In) Liquid Discharge Rate, gals/ton	Test Liquid Discharge Rate, gals/ton	Percent of Error
1	60	20	0.711	0.543	-23.63%	20	20.8	4.00%
6	60	25	0.667	0.483	-27.59%	15	14.9	-0.67%
2	45	20	1.778	1.333	-25.03%	25	25.4	1.60%
11	45	30	1.599	1.249	-21.89%	30	30.1	0.33%
26 **	35	45	0.800	0.546	-31.75%	10	8.8	-12.00%
3	25	20	1.422	1.116	-21.52%	10	10.1	1.00%
7	25	25	1.333	0.976	-26.78%	10	9.6	-4.00%
16	25	35	0.622	0.480	-22.83%	5	5.4	8.00%
21	25	40	2.844	1.840	-35.30%	20	19.4	-3.00%
12	20	30	0.800	0.565	-29.38%	5	4.6	-8.00%
17	18	35	4.667	3.444	-26.21%	25	23.3	-6.80%
4	15	20	3.200	2.367	-26.03%	15	14.5	-3.33%
8	15	25	4.444	3.187	-28.29%	20	18.5	-7.50%
13	15	30	4.266	3.200	-24.99%	20	18.7	-6.50%
22	15	40	3.200	2.333	-27.09%	15	14.3	-4.67%
5	10	20	8.533	4.650	-45.51%	30	20.5	-31.67%
9	10	25	1.333	1.000	-24.98%	5	4.9	-2.00%
10	10	25	7.778	4.600	-40.86%	25	18.7	-25.20%
14 *	10	30	8.000	4.510	-43.63%	25	17.9	-28.40%
23	10	40	1.422	1.080	-24.05%	5	4.9	-2.00%
27 *&**	10	45	9.600	4.500	-53.13%	30	17.6	-41.33%
18 *	9	35	11.199	4.622	-58.73%	30	15.8	-47.33%
24 *	8	40	8.889	4.375	-50.78%	25	15.5	-38.00%
28 **	8	45	2.000	1.338	-33.10%	5	4.9	-2.00%
15	7	30	4.267	3.186	-25.33%	10	9.4	-6.00%
19	7	35	4.356	3.271	-24.91%	10	9.4	-6.00%
25 *	6	40	14.933	4.450	-70.20%	30	11.6	-61.33%
20	5	35	7.467	4.460	-40.27%	15	11.4	-24.00%
29 *&**	5	45	8.400	4.400	-47.62%	15	9.9	-34.00%
30 *&**	5	45	12.800	4.400	-65.63%	20	9.1	-54.50%

Note: * = Prewetting Range Error
** = Slow Down, Over Speed

Table J-9. Theoretical and Test Solid Discharges as a Function of Increasing Theoretical Solid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetted Application Rate, gals/ton	Test Run Time, sec	Theoretical Solid Discharge, lbs/sec	Test Solid Discharge, lbs/sec
1	20	100	20	60	0.556	0.577
6	25	100	15	60	0.694	0.738
11	30	100	30	45	0.833	0.911
2	20	200	25	45	1.111	1.151
26	45	100	10	35	1.250	1.349
16	35	200	5	25	1.944	2.120
7	25	300	10	25	2.083	2.232
3	20	400	10	25	2.222	2.360
21	40	200	20	22	2.222	2.427
12	30	300	5	20	2.500	2.705
17	35	300	25	18	2.917	3.222
4	20	600	15	15	3.333	3.587
13	30	400	20	15	3.333	3.673
22	40	300	15	15	3.333	3.527
8	25	500	20	15	3.472	3.793
9	25	600	5	10	4.167	4.650
5	20	800	30	10	4.444	4.770
23	40	400	5	10	4.444	4.830
10	25	700	25	10	4.861	5.340
14	30	600	25	10	5.000	5.550
27	45	400	30	10	5.000	5.440
24	40	500	25	8	5.555	6.213
18	35	600	30	9	5.833	6.433
28	45	500	5	8	6.250	6.800
15	30	800	10	7	6.667	7.429
19	35	700	10	7	6.806	7.643
20	35	800	15	5	7.778	8.640
25	40	700	30	6	7.778	8.450
29	45	700	15	5	8.750	9.400
30	45	800	20	5	10.000	10.600

Table J-10. Theoretical and Test Liquid Discharges as a Function of Increasing Theoretical Liquid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Theoretical Liquid Discharge, ozs/sec	Test Liquid Discharge, ozs/sec
16	35	200	5	25	0.622	0.480
6	25	100	15	60	0.667	0.483
1	20	100	20	60	0.711	0.543
12	30	300	5	20	0.800	0.565
26	45	100	10	35	0.800	0.546
7	25	300	10	25	1.333	0.976
9	25	600	5	10	1.333	1.000
3	20	400	10	25	1.422	1.116
23	40	400	5	10	1.422	1.080
11	30	100	30	45	1.599	1.249
2	20	200	25	45	1.778	1.333
28	45	500	5	8	2.000	1.338
21	40	200	20	25	2.844	1.840
4	20	600	15	15	3.200	2.367
22	40	300	15	15	3.200	2.333
13	30	400	20	15	4.266	3.200
15	30	800	10	7	4.267	3.186
19	35	700	10	7	4.356	3.271
8	25	500	20	15	4.444	3.187
17	35	300	25	18	4.667	3.444
20	35	800	15	5	7.467	4.460
10	25	700	25	10	7.778	4.600
14	30	600	25	10	8.000	4.510
29	45	700	15	5	8.400	4.400
5	20	800	10	10	8.533	4.650
24	40	500	25	8	8.889	4.375
27	45	400	30	10	9.600	4.500
18	35	600	30	9	11.199	4.622
30	45	800	20	5	12.800	4.400
25	40	700	30	6	14.933	4.450

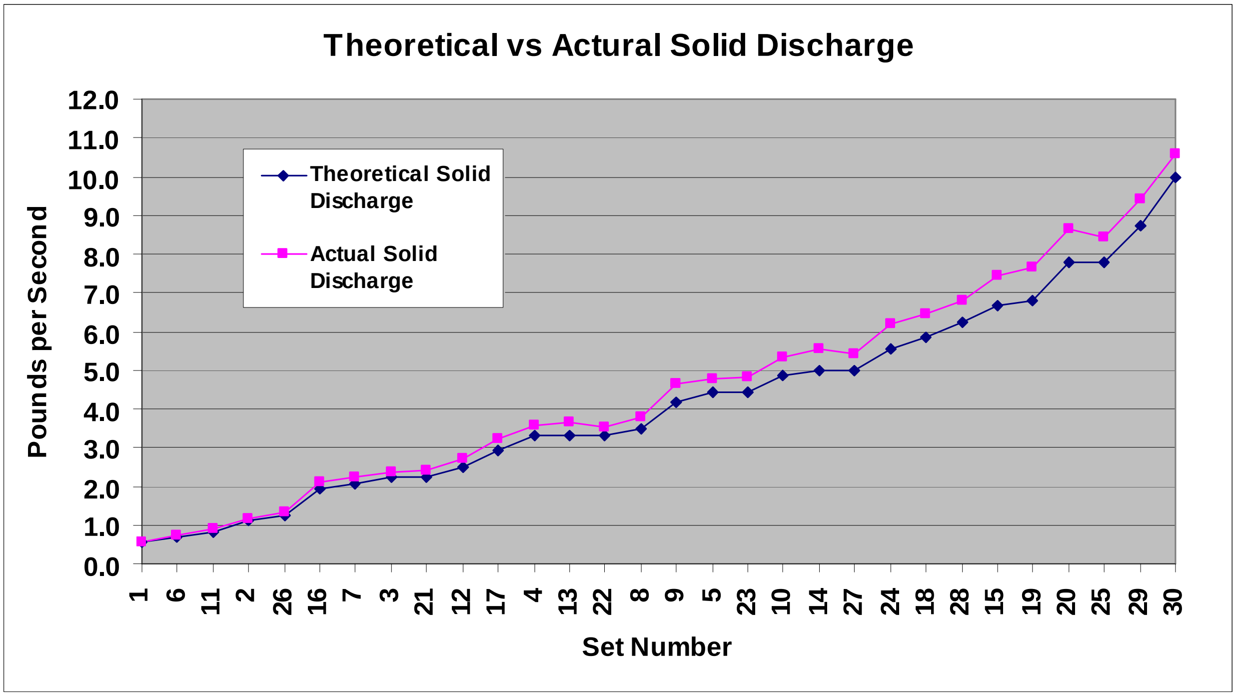

Figure J-1. Theoretical Vs Actual Solid Discharge Rate

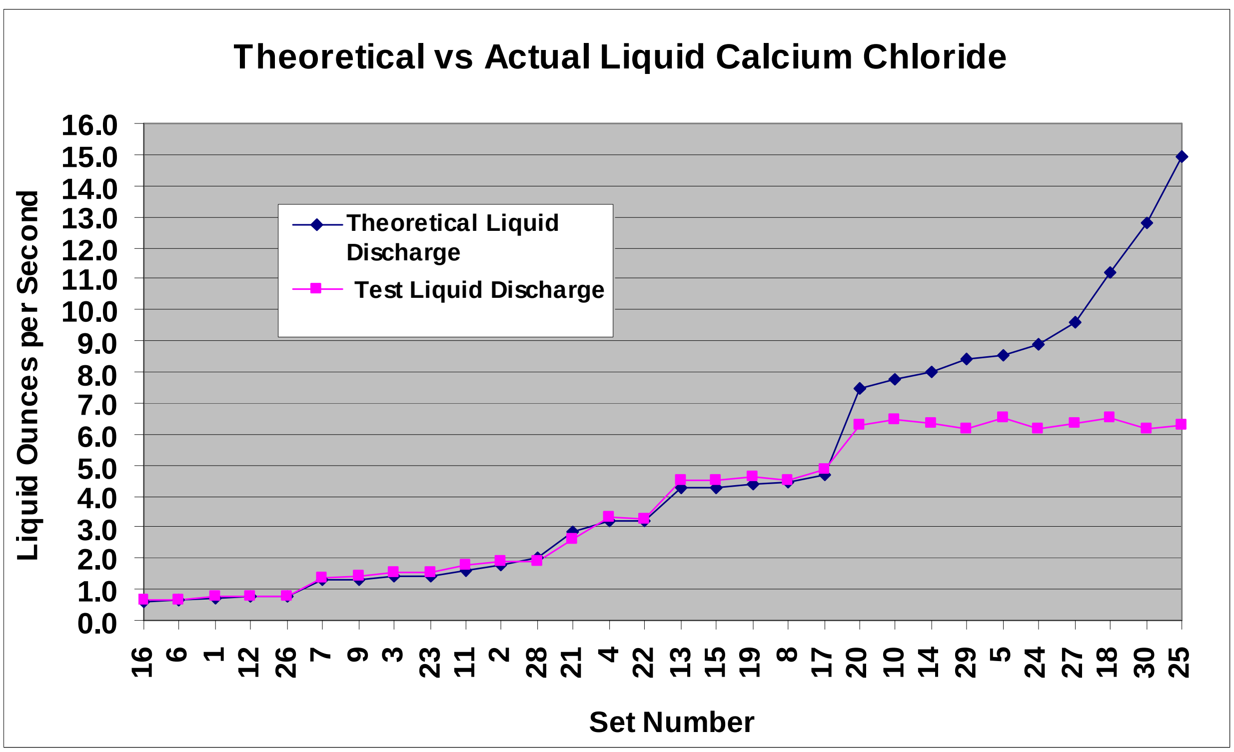

Figure J-2. Theoretical Vs Actual Liquid Calcium Chloride Discharge Rate

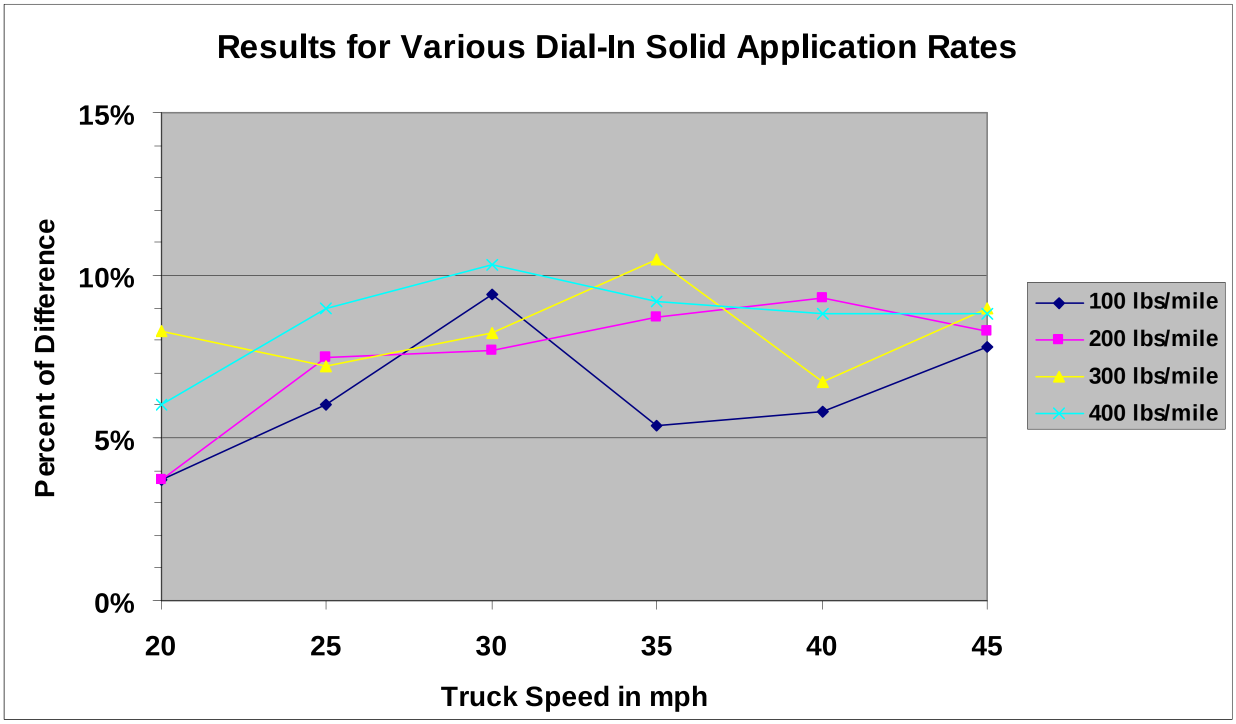

Figure J-3. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

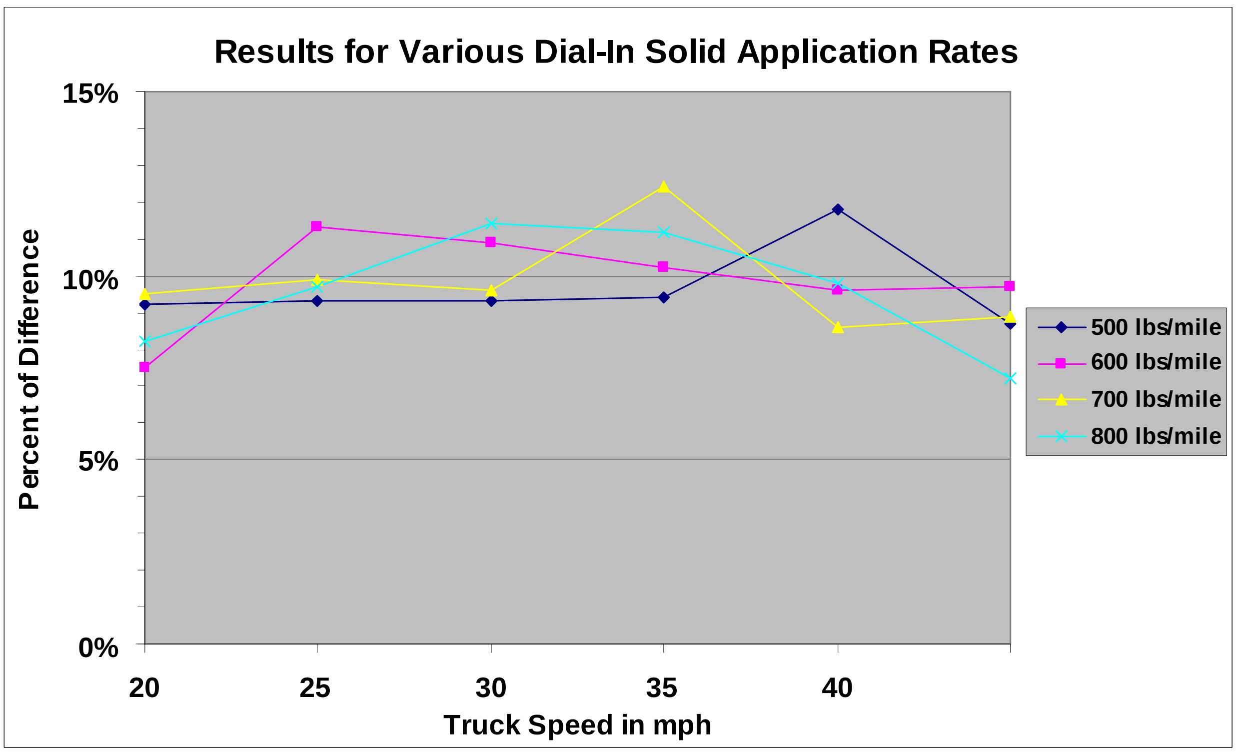

Figure J-4. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

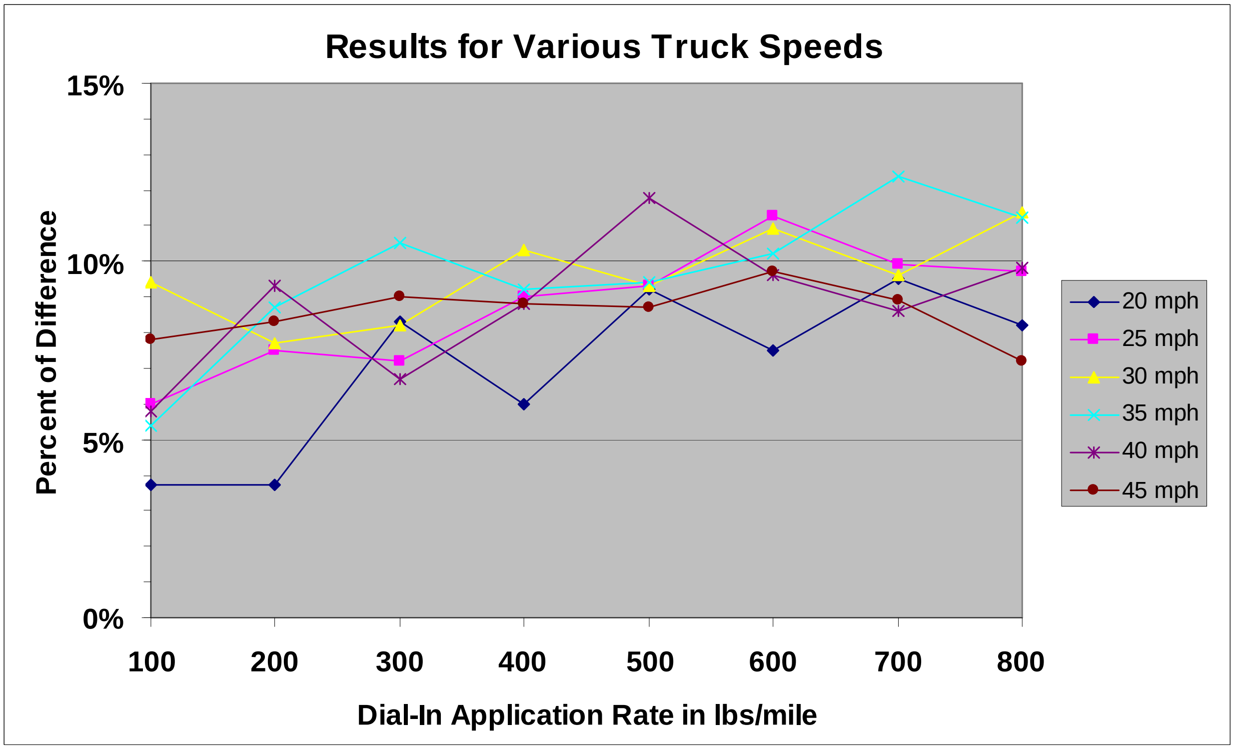

Figure J-5. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Dial-In Solid Application Rate

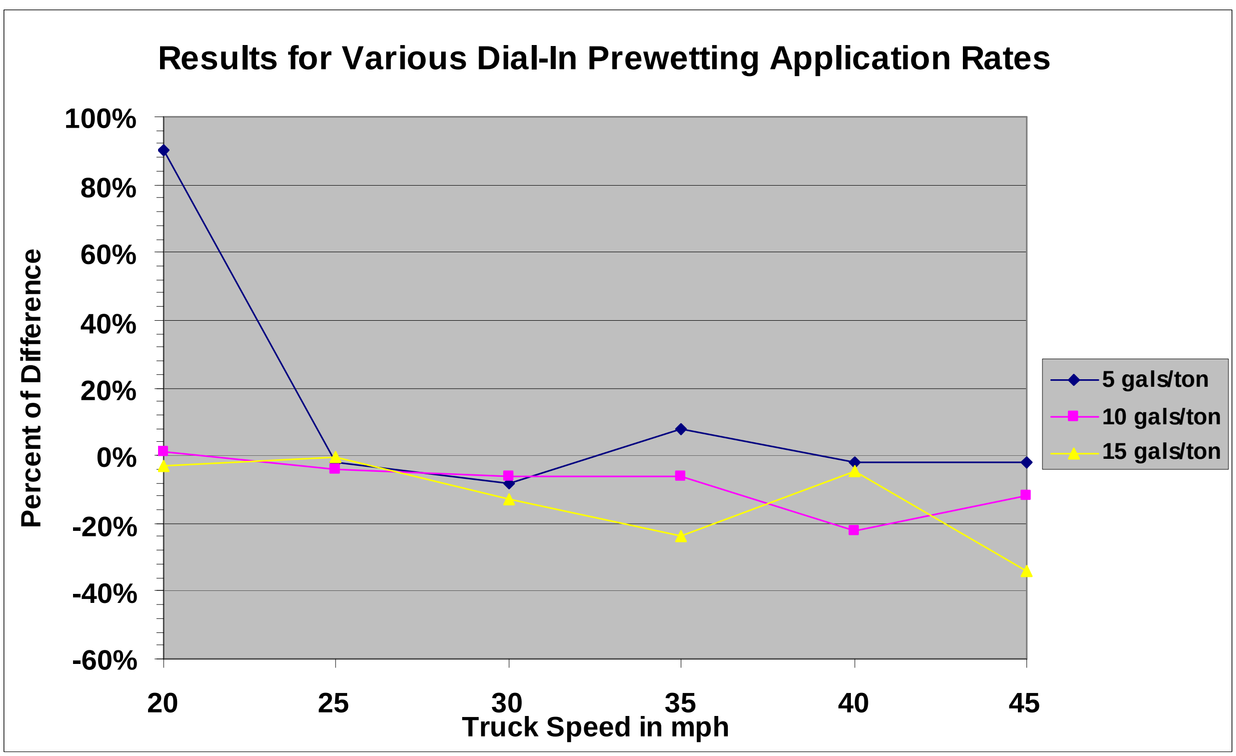

Figure J-**6. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed**

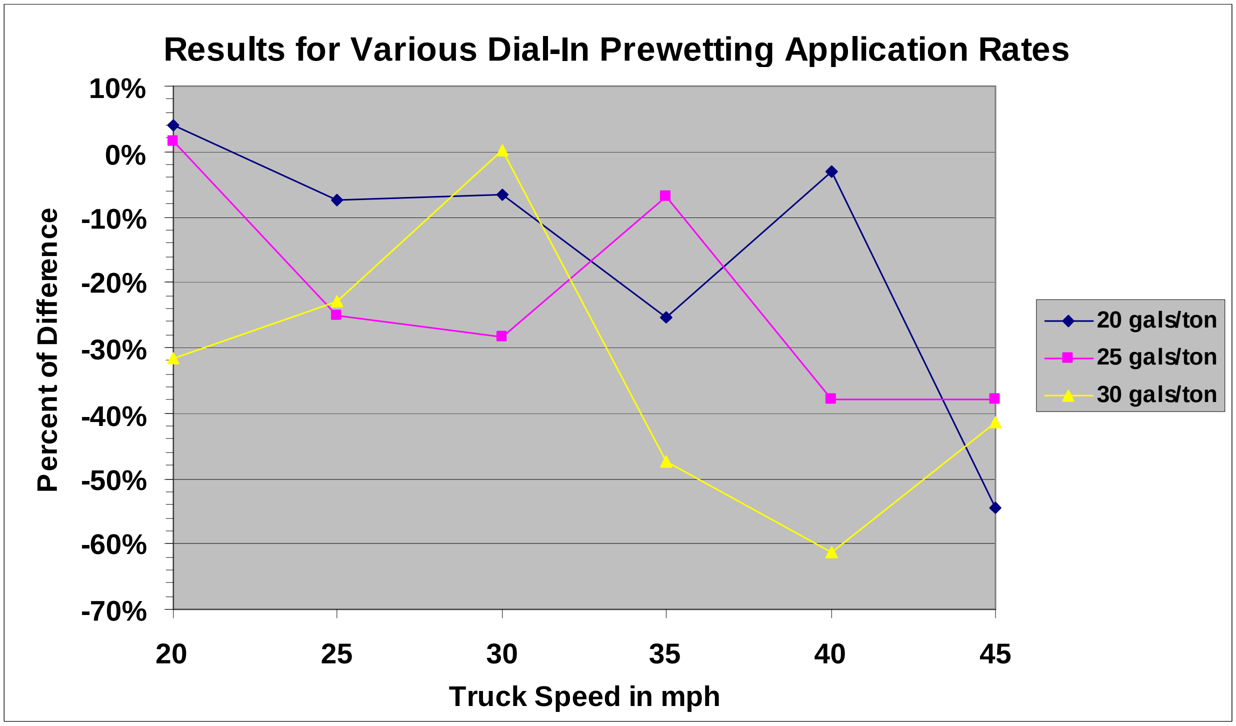

Figure J-7. **Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed**

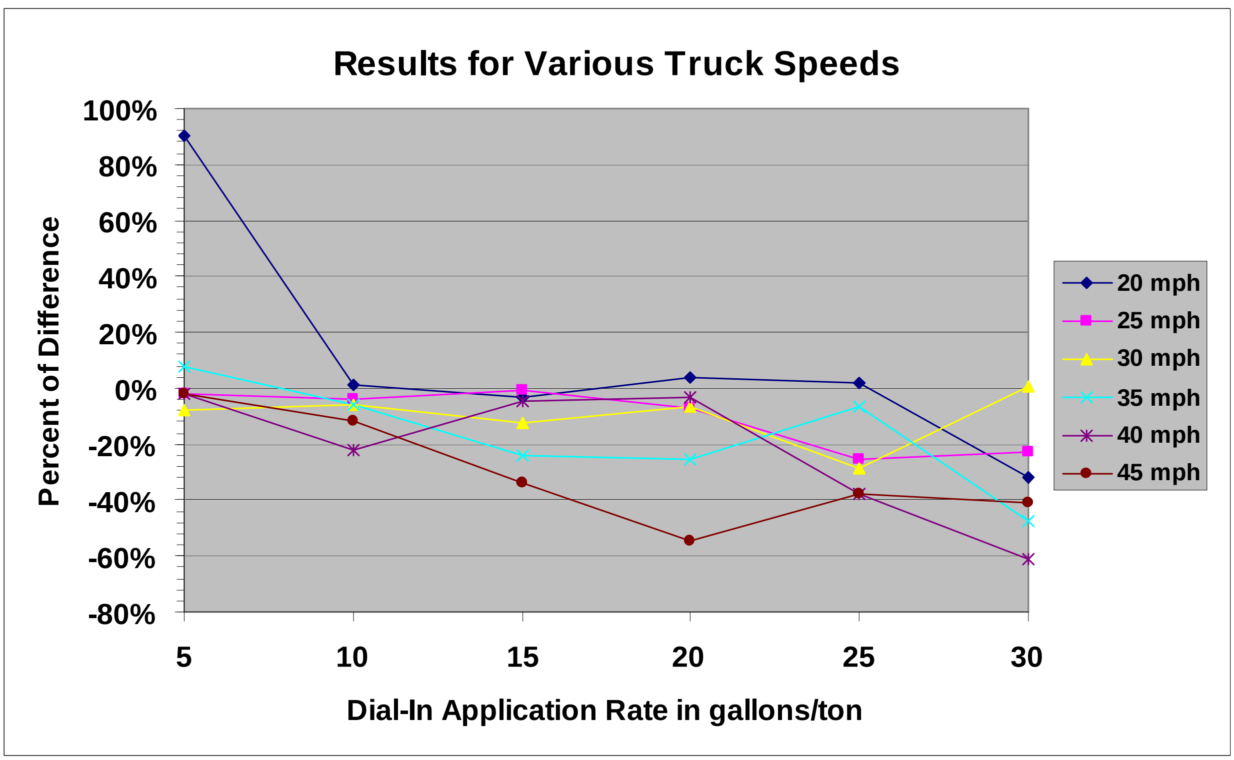

Figure J-8. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Dial-In Prewetting Rate

Table J-11. Statistical Analysis Results for Yard Tests

Yard Test Results for Bias, Accuracy, and Precision	
Solid Discharge	
Bias (lbs/mile)	42.5
Accuracy	91.2%
Precision	3.6%
Prewetting Discharge	
Bias (gals/ton)	-3.6
Accuracy	82.2%
Precision	22.0%

Results from Simulated Scenario Testing

Table J-12. Solid Discharges for Closed-loop and Open-loop Modes from Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (lbs)	Actual Discharge (lbs)	Discharge Amount According to Controller	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	5099.6	5560	*	9.03%	NA	NA	NA	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	2	5099.6	5230	*	2.56%	NA	NA	NA	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	6	5099.6	5000	5100	-1.95%	0.01%	2.00%	-1.96%	
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	7	5100	13900	*	172.55%	NA	NA	NA	164.09%
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	5025	4980	5060	-0.90%	0.69%	1.61%	-1.58%	
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	4	4950	5000	4971	1.01%	0.42%	-0.58%	0.58%	
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	8	5150	15300	*	197.09%	NA	NA	NA	206.61%

Note: * = Data not available from the controller.
NA = Could not be computed because data were not available from the controller.

Table J-13. Liquid Discharges for Closed-loop and Open-loop Modes from Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (gals)	Actual Discharge (gals)	Discharge Amount According to Controller (gals)	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	34.453	36.70	33.0	6.52%	-4.22%	-10.08%	11.21%	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	2	34.453	37.05	33.0	7.54%	-4.22%	-10.93%	12.27%	
Freeway Scenario - Closed Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	6	34.453	37.25	33.0	8.12%	-4.22%	-11.41%	12.88%	
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	7	34.453	61.50	*	78.50%	NA	NA	NA	66.22%
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	31.875	32.75	29.0	2.75%	-9.02%	-11.45%	12.93%	
Highway Scenario - Closed Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	4	31.500	32.55	29.0	3.33%	-7.94%	-10.91%	12.24%	
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	8	32.500	51.00	*	56.92%	NA	NA	NA	56.20%

Note: * = Data not available from the controller.

Table J-14. Solid Discharge Comparison for Freeway and Highway Scenarios in Both Closed-loop and Open-loop Operations

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Closed-loop	3.21%	.01%
Open-loop	172.55%	No Data
Highway:		
Closed-loop	0.05%	0.56%
Open-loop	197.09%	No Data

Table J-15. Solid Discharge Comparison of Open-loop to Closed-loop Operations for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	164.09%
Controller Display Discharge	No Data
Highway:	
Actual Discharge	206.61%
Controller Display Discharge	No Data

Table J-16. Prewetting Discharge Comparison for Freeway and Highway Scenarios in Both Closed-loop and Open-loop Operations

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Closed-loop	7.39%	-4.22%
Open-loop	78.50%	No Data
Highway:		
Closed-loop	3.04%	-8.48%
Open-loop	56.92%	No Data

Table J-17. Prewetting Discharge Comparison of Open-loop to Closed-loop Modes of Operation for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	66.22%
Controller Display Discharge	No Data
Highway:	
Actual Discharge	56.20%
Controller Display Discharge	No Data

APPENDIX K
TEST RESULTS FOR MUNCIE POWER MESP402D SPREADER CONTROLLER

Results from Yard Tests

Table K-1. Values of Truck Speed, Solid Discharge Rate, Prewetting Rate, and Test Run Time for Each Test Set Number Used in Yard Testing

Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetted Application Rate, gals/ton	Test Run Time, sec	Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetted Application Rate, gal/ton	Test Run Time, sec
1	20	107	20	105.00	16	35	215	5	20.22
2	20	215	25	75.00	17	35	322	25	16.01
3	20	429	10	32.59	18	35	644	30	15.25
4	20	644	15	23.52	19	35	751	10	15.16
5	20	858	30	20.29	20	35	858	15	15.35
6	25	107	15	50.28	21	40	215	20	15.21
7	25	322	10	30.19	22	40	322	15	15.24
8	25	537	20	30.09	23	40	429	5	15.35
9	25	644	5	22.06	24	40	537	25	15.32
10	25	751	25	20.24	25	40	751	30	15.22
11	30	107	30	60.01	26	45	107	10	19.41
12	30	322	5	30.06	27	45	429	30	15.25
13	30	429	20	30.14	28	45	537	5	15.27
14	30	644	25	20.33	29	45	751	15	14.36
15	30	858	10	15.49	30	45	858	20	12.09

Summary Tabulations of Solid and Liquid Discharge Rates

Table K-2. Actual and Estimated Solid Discharge Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	107	215	322	429	537	644	751	858
20	82.3	186.7	**327.8**	408.7	**489.5**	633.6	**650.4**	799.3
25	103.3	**253.4**	303.1	**414.4**	514.5	603.2	701.4	**737.0**
30	81.2	**259.5**	285.1	390.7	**501.7**	558.7	**662.6**	726.5
35	**184.4**	195.5	497.8	**426.5**	**507.8**	708.6	660.9	735.8
40	**190.5**	330.7	476.4	634.6	550.3	**594.3**	644.6	**755.2**
45	156.8	**277.8**	**358.2**	561.0	500.2	**600.4**	514.1	532.4

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table K-3. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial-In Application Rate in lbs/mile							
	107	215	322	429	537	644	751	858
20	-23.1%	-13.2%	**1.8%**	-4.7%	**-8.8%**	-1.6%	**-13.4%**	-6.8%
25	-3.5%	**17.9%**	-5.9%	**-3.4%**	-4.2%	-6.3%	-6.6%	**-14.1%**
30	-24.1%	**20.7%**	-11.5%	-8.9%	**-6.6%**	-13.2%	**-11.8%**	-15.3%
35	**72.3%**	-9.1%	54.6%	**-0.6%**	**-5.4%**	10.0%	-12.0%	-14.2%
40	**78.0%**	53.8%	48.0%	47.9%	2.5%	**-7.7%**	-14.2%	**-12.0%**
45	46.5%	29.2%	11.2%	30.8%	-6.9%	**-6.8%**	-31.5%	**-37.9%**

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table K-4. Actual and Estimated Discharge Prewetting Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed in mph	Dial –In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**5.4**	6.2	9.3	12.3	15.9	17.5
25	3.1	6.5	9.5	12.7	15.3	**16.6**
30	3.2	6.2	**9.0**	13.0	15.4	20.4
35	2.9	6.3	8.9	**10.8**	14.7	11.0
40	3.1	**5.6**	8.8	12.2	12.5	10.5
45	3.2	6.3	8.9	10.8	**12.1**	11.3

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table K-5. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed.

Speed in mph	Dial–In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**8.0%**	-38.0%	-38.0%	-38.5%	-36.4%	-41.7%
25	-38.0%	-35.0%	-36.7%	-36.5%	-38.8%	**-44.7%**
30	-36.0%	-38.0%	**-40.0%**	-35.0%	-38.4%	-32.0%
35	-42.0%	-37.0%	-40.7%	**-46.0%**	-41.2%	-63.3%
40	-38.0%	**-44.0%**	-41.3%	-39.0%	-50.0%	-65.0%
45	-36.0%	-37.0%	-40.7%	-46.0%	**-51.6%**	-62.3%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table K-6. Regression Coefficients for Determination of Missing Test Discharge Values

Material	Rate Coefficient	Speed Coefficient	Intercept	R - squared
	A1	A2	B	(as percent)
Solid	0.752	1.217	61.335	80.6%
Liquid	0.471	-0.110	5.269	81.9%

Table K-7. Percent of Error for Actual Solid Discharge as a Function of Time

Set #	Test Time, sec	Truck Speed, mph	Theoretical Solid Discharge, lbs/sec.	Test Solid Discharge, lbs/sec	Percent of Error	Set Solid Discharge Rate, lbs/mile	Test solid Discharge Rate, lbs/mile	Percent of Error
1	105.00	20	0.594	0.460	-22.56%	107	82.3	-23.08%
2	75.00	20	1.194	1.036	-13.23%	215	186.7	-13.16%
11	60.01	30	0.892	0.677	-24.10%	107	81.2	-24.11%
6	50.28	25	0.743	0.726	-2.29%	107	103.3	-3.46%
3	32.59	20	2.383	2.271	-4.70%	429	408.7	-4.73%
7	30.19	25	2.236	2.103	-5.95%	322	303.1	-5.87%
13	30.14	30	3.575	3.258	-8.87%	429	390.7	-8.93%
8	30.09	25	3.729	3.573	-4.18%	537	514.5	-4.19%
12	30.06	30	2.683	2.375	-11.48%	322	285.1	-11.46%
4	23.52	20	3.578	3.516	-1.73%	644	633.6	-1.61%
9	22.06	25	4.472	4.184	-6.44%	644	603.2	-6.34%
14	20.33	30	5.367	4.653	-13.30%	644	558.7	-13.25%
5	20.29	20	4.767	4.441	-6.84%	858	799.3	-6.84%
10	20.24	25	5.215	4.872	-6.58%	751	701.4	-6.60%
16	20.22	35	2.090	1.899	-9.14%	215	195.5	-9.07%
26	19.41	45	1.338	1.958	46.34%	107	156.8	46.54%
17	16.01	35	3.131	4.847	54.81%	322	497.8	54.60%
15	15.49	30	7.150	6.056	-15.30%	858	726.5	-15.33%
20	15.35	35	8.342	7.153	-14.25%	858	735.8	-14.24%
23	15.35	40	4.767	7.049	47.87%	429	634.6	47.93%
24	15.32	40	5.967	6.116	2.50%	537	550.3	2.48%
28	15.27	45	6.713	6.254	-6.84%	537	500.2	-6.85%
18	15.25	35	6.261	6.892	10.08%	644	708.6	10.03%
27	15.25	45	5.363	7.010	30.71%	429	561.0	30.77%
22	15.24	40	3.578	5.289	47.82%	322	476.4	47.95%
25	15.22	40	8.344	7.162	-14.17%	751	644.6	-14.17%
21	15.21	40	2.389	3.675	53.83%	215	330.7	53.81%
19	15.16	35	7.301	6.425	-12.00%	751	660.9	-12.00%
29	14.36	45	9.388	6.435	-31.46%	751	514.1	-31.54%
30	12.09	45	10.725	6.650	-38.00%	858	532.4	-37.95%

Table K-8. Percent of Error for Prewetting Discharge as a Function of Time

Set #	Test Time, sec	Truck Speed, mph	Theoretical Liquid Discharge, ozs/sec	Test Liquid Discharge, ozs/sec	Percent of Error	Set Prewetting Application Rate, gals/ton	Test Prewetting Discharge Rate, gals/ton	Percent of Error
1	105.00	20	0.761	0.357	-53.09%	20	12.3	-38.50%
2	75.00	20	1.911	1.052	-44.95%	25	15.9	-36.40%
11	60.01	30	1.712	0.883	-48.42%	30	20.4	-32.00%
6	50.28	25	0.713	0.44	-38.29%	15	9.5	-36.67%
3	32.59	20	1.525	0.899	-41.05%	10	6.2	-38.00%
7	30.19	25	1.431	0.878	-38.64%	10	6.5	-35.00%
13	30.14	30	4.576	2.707	-40.84%	20	13.0	-35.00%
8	30.09	25	4.773	2.915	-38.93%	20	12.7	-36.50%
12	30.06	30	0.859	0.489	-43.07%	5	3.2	-36.00%
4	23.52	20	3.435	2.096	-38.98%	15	9.3	-38.00%
9	22.06	25	1.431	0.843	-41.09%	5	3.1	-38.00%
14	20.33	30	8.587	4.579	-46.68%	25	15.4	-38.40%
5	20.29	20	9.152	4.973	-45.66%	30	17.5	-41.67%
10	20.24	25	8.344	4.748	-43.10%	25	15.3	-38.80%
16	20.22	35	0.669	0.356	-46.79%	5	2.9	-42.00%
26	19.41	45	0.856	0.793	-7.36%	10	6.3	-37.00%
17	16.01	35	5.009	4.528	-9.60%	25	14.7	-41.20%
15	15.49	30	4.576	2.414	-47.25%	10	6.2	-38.00%
20	15.35	35	8.008	4.052	-49.40%	15	8.9	-40.67%
23	15.35	40	1.525	1.414	-7.28%	5	3.1	-38.00%
24	15.32	40	9.547	4.883	-48.85%	25	12.5	-50.00%
28	15.27	45	2.148	1.27	-40.88%	5	3.2	-36.00%
18	15.25	35	12.021	4.846	-59.69%	30	11.0	-63.33%
27	15.25	45	10.296	5.062	-50.84%	30	11.3	-62.33%
22	15.24	40	3.435	2.992	-12.90%	15	8.8	-41.33%
25	15.22	40	16.021	4.823	-69.90%	30	10.5	-65.00%
21	15.21	40	3.058	2.873	-6.05%	20	12.2	-39.00%
19	15.16	35	4.673	2.599	-44.38%	10	6.3	-37.00%
29	14.36	45	9.012	3.649	-59.51%	15	8.9	-40.67%
30	12.09	45	13.728	4.607	-66.44%	20	10.8	-46.00%

Table K-8. Theoretical and Test Solid Discharges as a Function of Increasing Theoretical Solid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Theoretical Solid Discharge, lbs/sec.	Test solid Discharge Rate, lbs/mile
1	20	107	20	105.00	0.594	0.460
6	25	107	15	50.28	0.743	0.726
11	30	107	30	60.01	0.892	0.677
2	20	215	25	75.00	1.194	1.036
26	45	107	10	19.41	1.338	1.958
16	35	215	5	20.22	2.090	1.899
7	25	322	10	30.19	2.236	2.103
3	20	429	10	32.59	2.383	2.271
21	40	215	20	15.21	2.389	3.675
12	30	322	5	30.06	2.683	2.375
17	35	322	25	16.01	3.131	4.847
13	30	429	20	30.14	3.575	3.258
4	20	644	15	23.52	3.578	3.516
22	40	322	15	15.24	3.578	5.289
8	25	537	20	30.09	3.729	3.573
9	25	644	5	22.06	4.472	4.184
5	20	858	30	20.29	4.767	4.441
23	40	429	5	15.35	4.767	7.049
10	25	751	25	20.24	5.215	4.872
27	45	429	30	15.25	5.363	7.010
14	30	644	25	20.33	5.367	4.653
24	40	537	25	15.32	5.967	6.116
18	35	644	30	15.25	6.261	6.892
28	45	537	5	15.27	6.713	6.254
15	30	858	10	15.49	7.150	6.056
19	35	751	10	15.16	7.301	6.425
20	35	858	15	15.35	8.342	7.153
25	40	751	30	15.22	8.344	7.162
29	45	751	15	14.36	9.388	6.435
30	45	858	20	12.09	10.725	6.650

Table K-9. Theoretical and Test Liquid Discharges as a Function of Increasing Theoretical Liquid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Theoretical Liquid Discharge, ozs/sec.	Test Liquid Discharge, ozs/sec
16	35	215	5	20.22	0.669	0.356
6	25	107	15	50.28	0.713	0.440
1	20	107	20	105.00	0.761	0.375
26	45	107	10	19.41	0.856	0.793
12	30	322	5	30.06	0.859	0.489
7	25	322	10	30.19	1.431	0.878
9	25	644	5	22.06	1.431	0.843
3	20	429	10	32.59	1.525	0.899
23	40	429	5	15.35	1.525	1.414
11	30	107	30	60.01	1.712	0.883
2	20	215	25	75.00	1.911	1.052
28	45	537	5	15.27	2.148	1.270
21	40	858	20	15.21	3.058	2.873
4	20	644	15	23.52	3.435	2.096
22	40	322	15	15.24	3.435	2.992
13	30	429	20	30.14	4.576	2.707
15	30	858	10	15.49	4.576	2.414
19	35	751	10	15.16	4.673	2.599
8	25	537	20	30.09	4.773	2.915
17	35	322	25	16.01	5.009	4.528
20	35	800	15	15.35	8.008	4.052
10	25	751	25	20.24	8.344	4.748
14	30	644	25	20.33	8.587	4.579
29	45	751	15	14.36	9.012	3.649
5	20	858	30	20.29	9.152	4.973
24	40	500	25	15.32	9.547	4.883
27	45	429	30	15.25	10.296	5.062
18	35	644	30	15.25	12.021	4.846
30	45	858	20	12.09	13.728	4.607
25	40	537	30	15.22	16.021	4.823

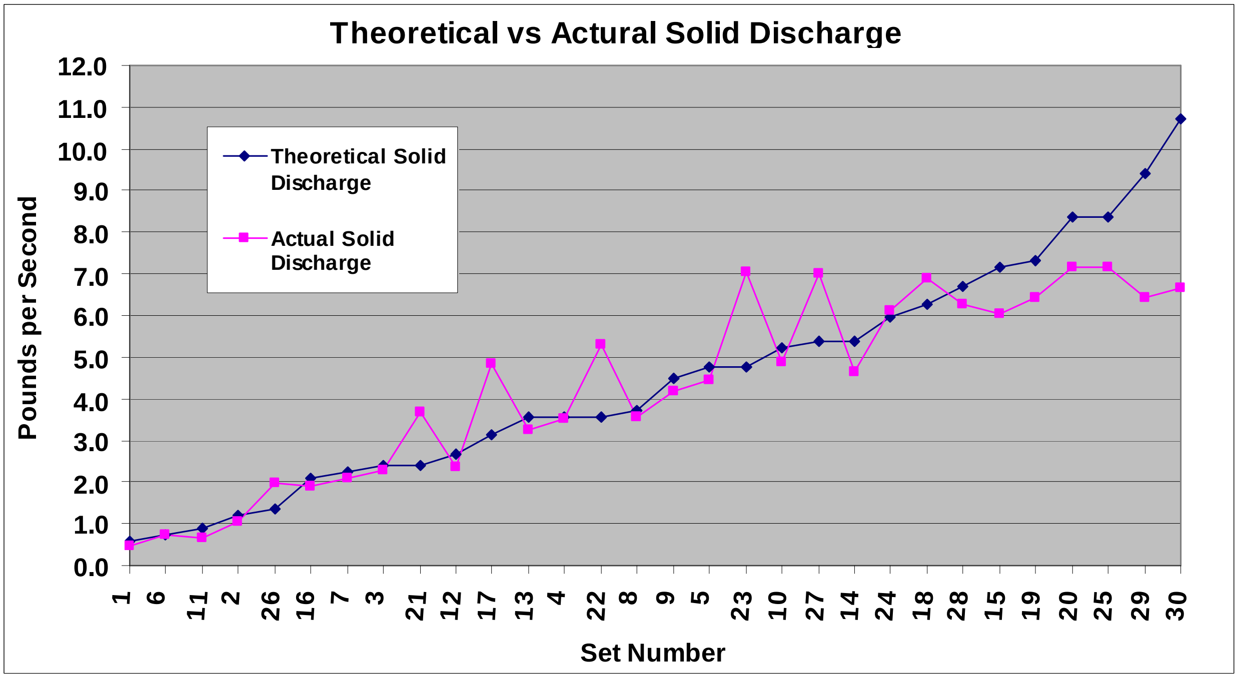

Figure K-1. Theoretical vs Actual Solid Discharge Rate

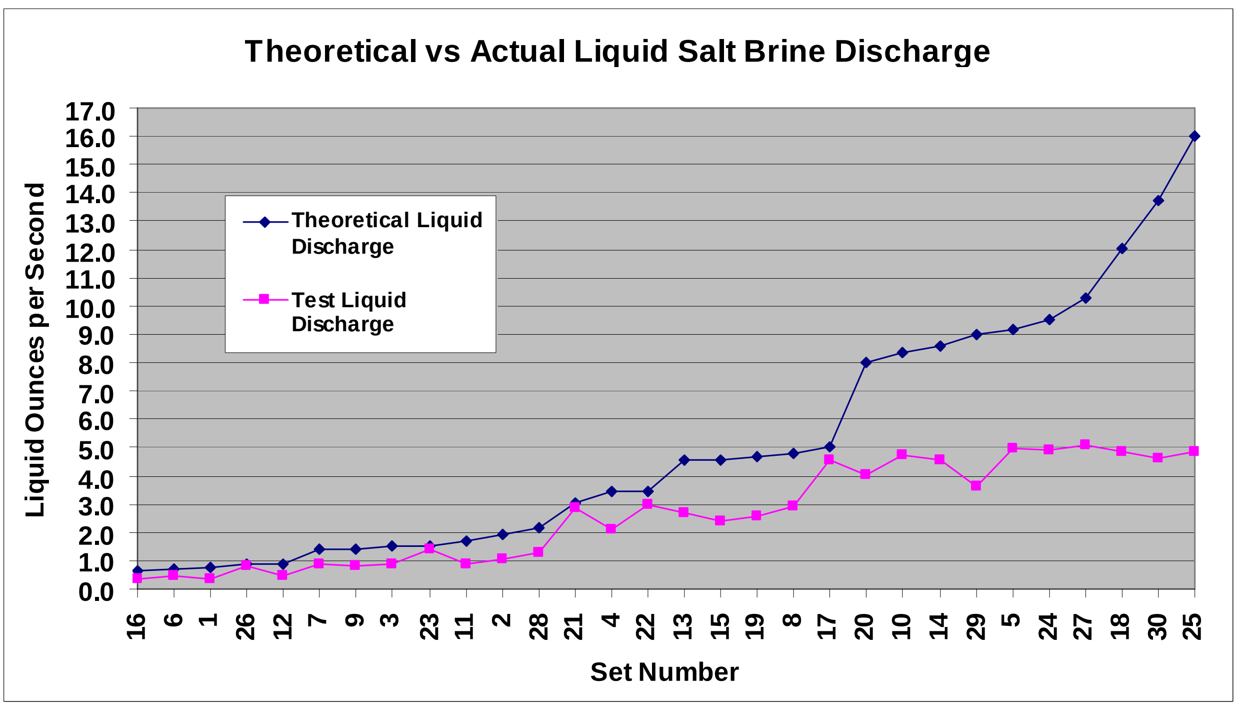

Figure K-2. Theoretical vs Actual Liquid Salt Brine Discharge Rate

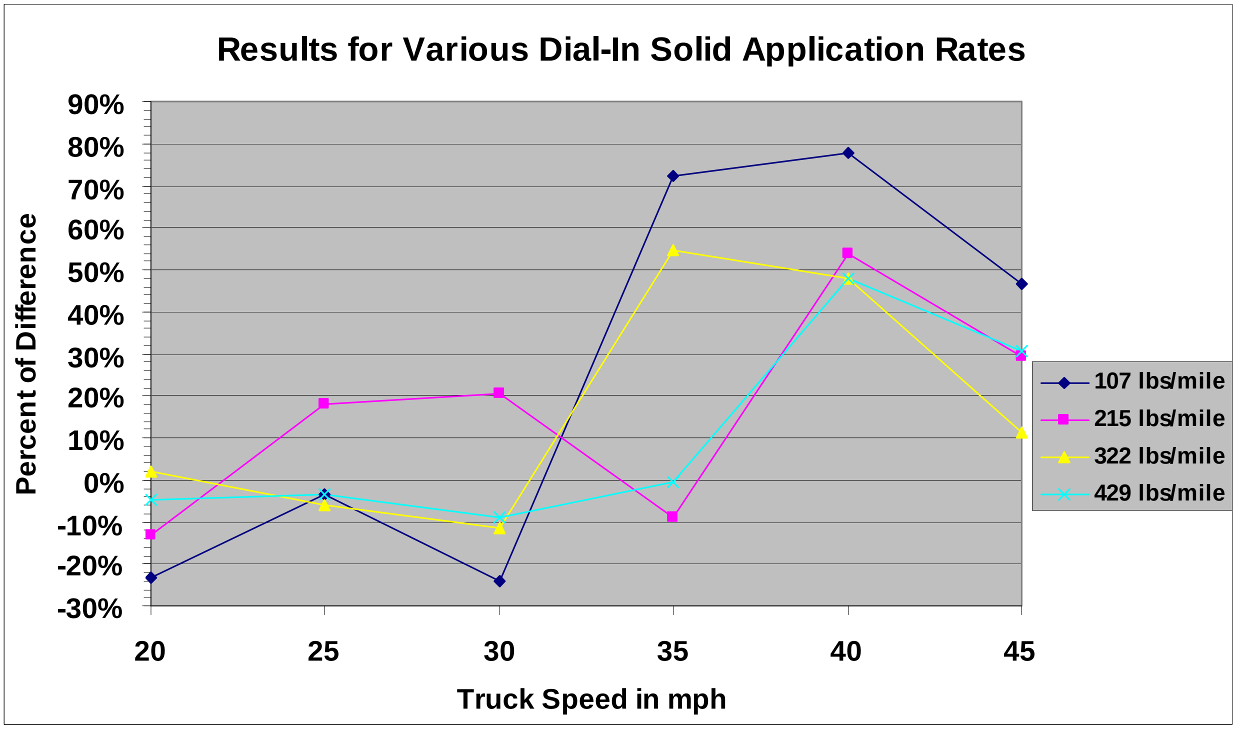

Figure K-3. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

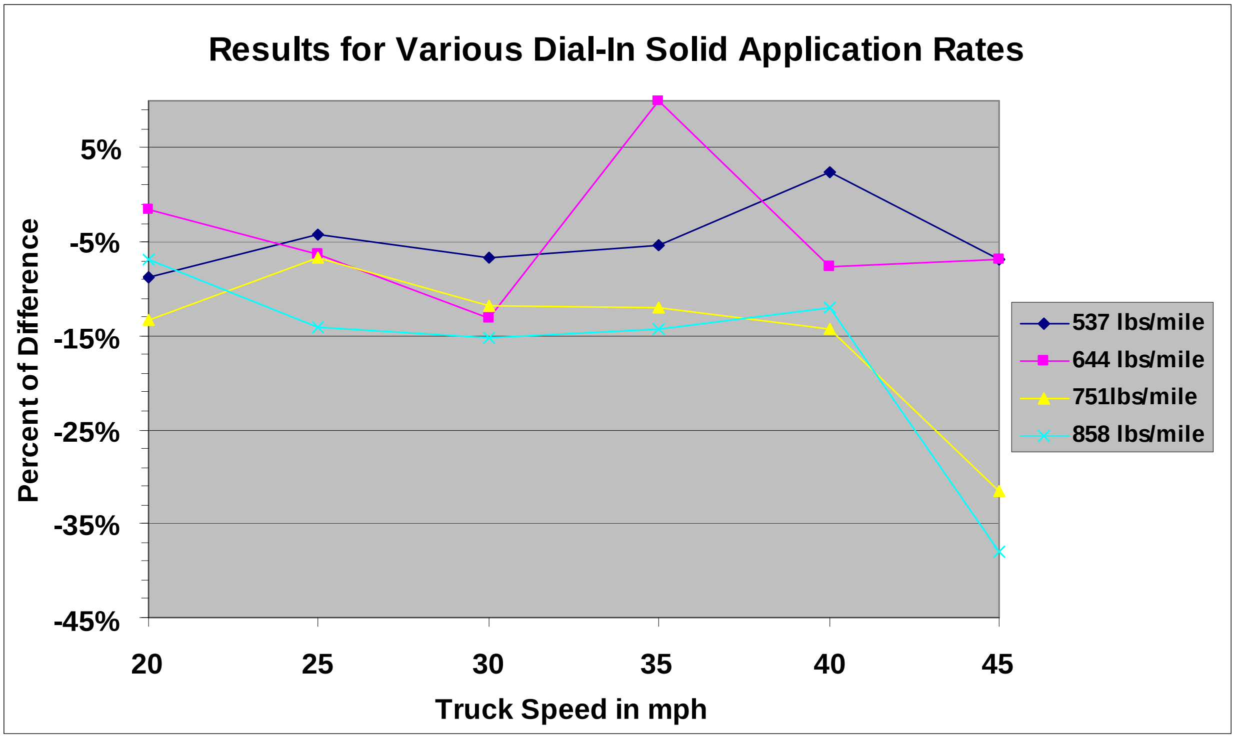

Figure K-4. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

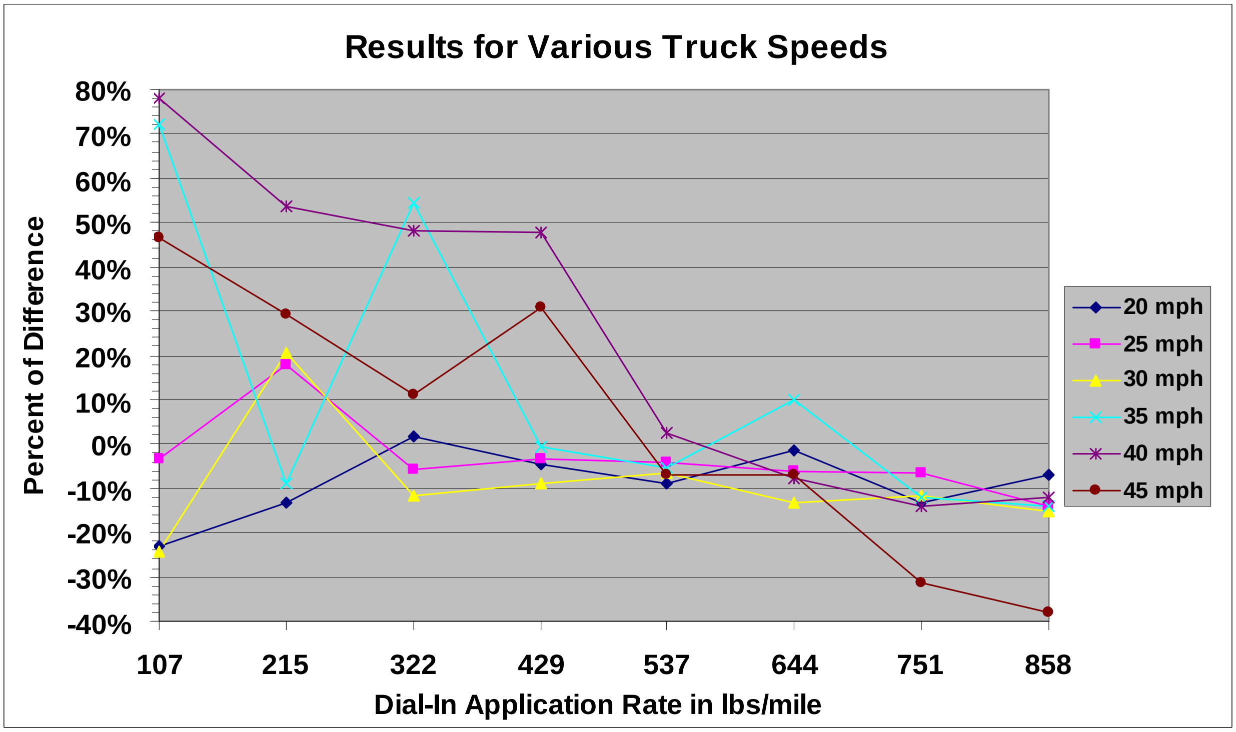

Figure K-5. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Dial-In Solid Application Rate

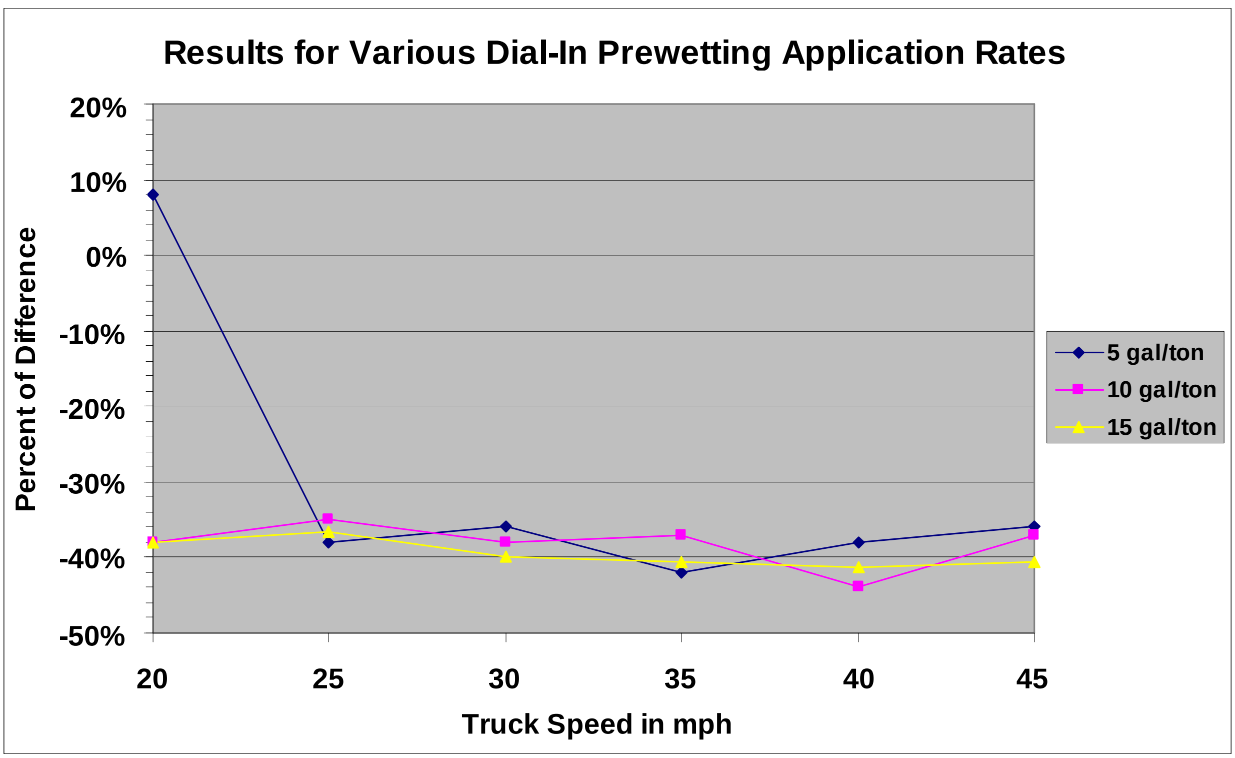

Figure K-6. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed

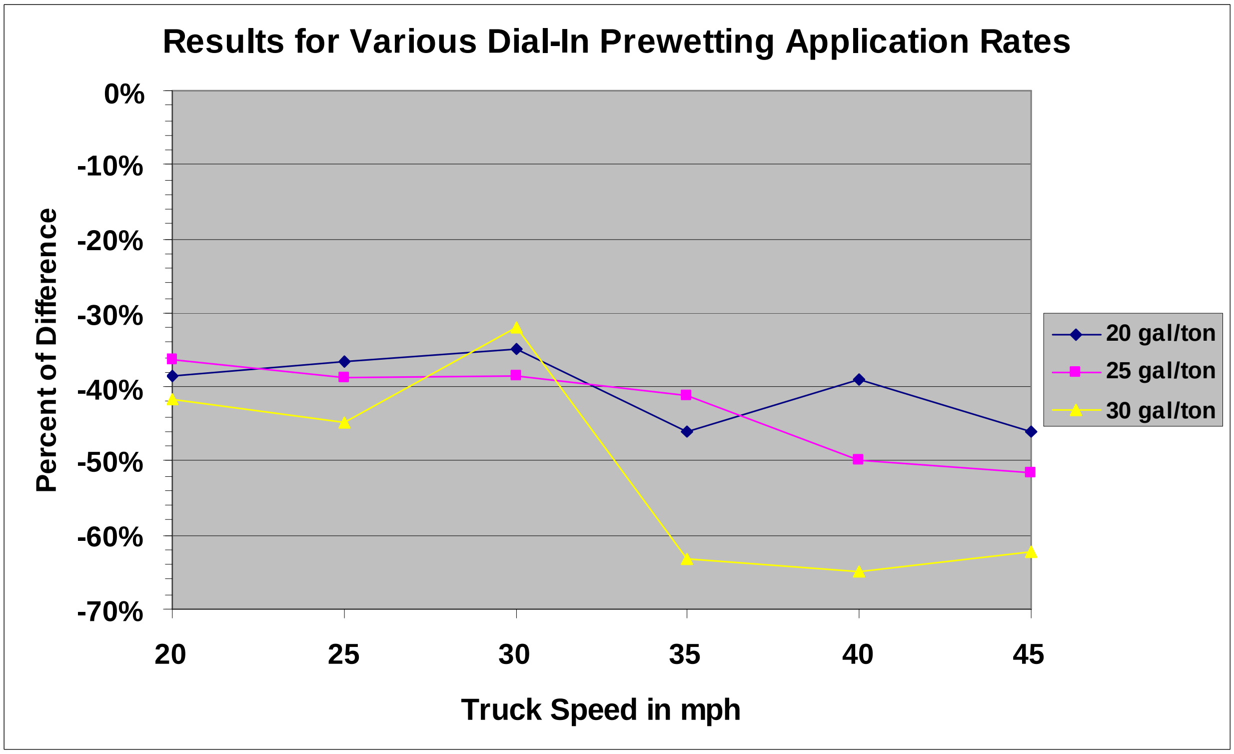

Figure K-7. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed

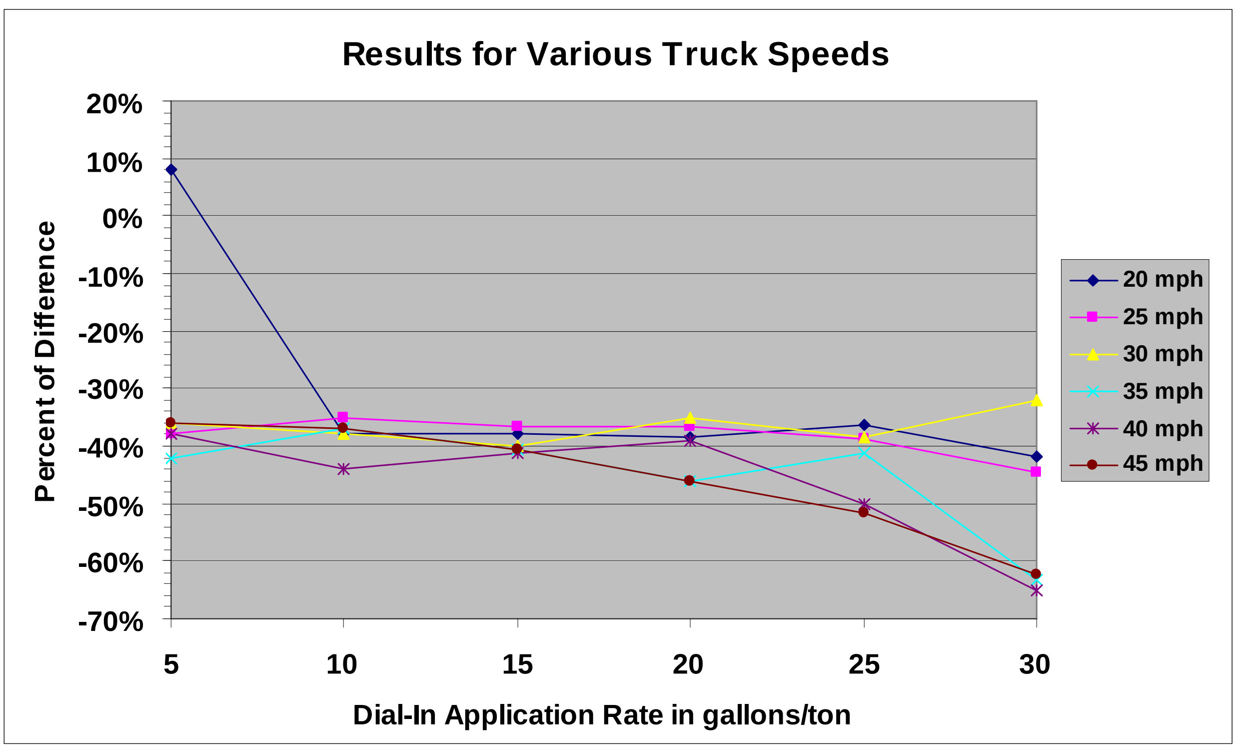

Figure K-8. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Dial-In Prewetting Rate

Table K-8. Statistical Analysis Results for Yard Tests

Yard Test Results for Bias, Accuracy, and Precision	
Solid Discharge	
Bias (lbs/mile)	-20.7
Accuracy	80.7%
Precision	20.8%
Prewetting Discharge	
Bias (gals/ton)	-7.6
Accuracy	58.9%
Precision	15.5%

Results from Simulated Scenario Testing

Table K-9. Solid Discharges for Open-loop Mode from Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (lbs)	Actual Discharge (lbs)	Discharge Amount According to Controller	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	5099.7	4920	*	-3.5%	NA	NA	NA	NA
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	2	5099.7	5120	*	0.4%	NA	NA	NA	NA
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	4950	5120	*	3.4%	NA	NA	NA	NA
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	4	4950	5400	*	9.1%	NA	NA	NA	NA

Note: * = Data not available from the controller.

NA = Could not be computed because data were not available from the controller.

Table K-9a. Solid Discharges for Closed-loop and Open-loop Modes from Various Simulated Scenario Testing

Scenario	Test No.	Theoretical Discharge (lbs)	Actual Weighed Discharge (lbs)	Discharge Amount According to Controller	Percent of Difference between Actual Discharge and Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed-Loop Modes of Operation
Freeway Scenario - Closed-Loop Mode Test Parameter:200 and 500 lbs/mile Drive:15, 20,30, and 35 MPH	1	5099.7	5770	*	13.14%	NA	NA	
Freeway Scenario - Open-Loop Mode Test Parameter:200 and 500 lbs/mile Drive:15, 20,30, and 35 MPH	2	5099.7	5310	*	4.12%	NA	NA	-7.97%
Freeway Scenario - Open-Loop Mode Test Parameter:200 and 500 lbs/mile Drive:15, 20,30, and 35 MPH	3	5099.7	5170	*	1.38%	NA	NA	-7.68%
Freeway Scenario - Closed-Loop Mode Test Parameter:200 and 500 lbs/mile Drive:15, 20,30, and 35 MPH	4	5099.7	5600	*	9.81%	NA	NA	
Highway Scenario - Closed-Loop Mode Test Parameter:300 and 600 lbs/mile Drive:15, 20, 25,30, and 35 MPH	5	4950.0	4370	*	-11.72%	NA	NA	
Highway Scenario - Closed-Loop Mode Test Parameter:300 and 600 lbs/mile Drive:15, 20, 25,30, and 35 MPH	6	4950.0	4220	*	-14.75%	NA	NA	
Highway Scenario - Open-Loop Mode Test Parameter:300 and 600 lbs/mile Drive:15, 20, 25,30, and 35 MPH	7	4950.0	4770	*	-3.64%	NA	NA	9.15%
Highway Scenario - Open-Loop Mode Test Parameter:300 and 600 lbs/mile Drive:15, 20, 25,30, and 35 MPH	8	4950.0	4780	*	-3.43%	NA	NA	13.27%

Note: * = Data not available from the controller.
NA = Could not be computed because data were not available from the controller.

Figure K-10. Liquid Discharges for Open-loop Mode for Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (gals)	Actual Discharge (gals)	Discharge Amount According to Controller (gals)	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	34.456	52.0	*	50.9%	NA	NA	NA	CNC
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	2	34.456	52.2	*	51.5%	NA	NA	NA	CNC
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	31.500	42.5	*	34.9%	NA	NA	NA	CNC
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	4	31.500	42.4	*	34.6%	NA	NA	NA	CNC

Note: * = Data not available from the controller.
NA = Could not be computed because data were not available from the controller.
CNC = Could not compute the value because closed-loop information was not available.

Table K-10a. Liquid Discharges for Closed-loop and Open-loop Modes from Various Simulated Scenario Testing

Scenario	Test No.	Theoretical Liquid Discharge (gals)	Actual Liquid Discharge (gals)	Discharge Amount According to Controller	Percent of Difference between Actual Discharge and Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed-Loop Modes of Operation
Freeway Scenario - Closed-Loop Mode Test Parameter:200 and 500 lbs/mile Drive:15, 20,30, and 35 MPH	1	34.46	43.3	*	25.65%	NA	NA	
Freeway Scenario - Open-Loop Mode Test Parameter:200 and 500 lbs/mile Drive:15, 20,30, and 35 MPH	2	34.46	41.1	*	19.27%	NA	NA	-5.08%
Freeway Scenario - Open-Loop Mode Test Parameter:200 and 500 lbs/mile Drive:15, 20,30, and 35 MPH	3	34.46	42.9	*	24.49%	NA	NA	10.00%
Freeway Scenario - Closed-Loop Mode Test Parameter:200 and 500 lbs/mile Drive:15, 20,30, and 35 MPH	4	34.46	39.0	*	13.17%	NA	NA	
Highway Scenario - Closed-Loop Mode Test Parameter:300 and 600 lbs/mile Drive:15, 20, 25,30, and 35 MPH	5	31.50	27.9	*	-11.43%	NA	NA	
Highway Scenario - Closed-Loop Mode Test Parameter:300 and 600 lbs/mile Drive:15, 20, 25,30, and 35 MPH	6	31.50	29.6	*	-6.03%	NA	NA	
Highway Scenario - Open-Loop Mode Test Parameter:300 and 600 lbs/mile Drive:15, 20, 25,30, and 35 MPH	7	31.50	33.9	*	7.62%	NA	NA	21.51%
Highway Scenario - Open-Loop Mode Test Parameter:300 and 600 lbs/mile Drive:15, 20, 25,30, and 35 MPH	8	31.50	29.8	*	-5.40%	NA	NA	0.68%

Note: * = Data not available from the controller.
NA = Could not be computed because data were not available from the controller.

Table K-11. Solid Discharge Comparison for Freeway and Highway Scenarios in Both Closed-loop and Open-loop Operations

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Closed-loop	11.48%	No Data
Open-loop	2.75%	No Data
Highway:		
Closed-loop	-13.23%	No Data
Open-loop	-3.54%	No Data

Table K-12. Solid Discharge Comparison of Open-loop to Closed-loop Operations for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	-7.83%
Controller Display Discharge	No Data
Highway:	
Actual Discharge	11.18%
Controller Display Discharge	No Data

Table K-13. Prewetting Discharge Comparison for Freeway and Highway Scenarios in Both Closed-loop and Open-loop Operations

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Closed-loop	19.41%	No Data
Open-loop	21.88%	No Data
Highway:		
Closed-loop	-8.73%	No Data
Open-loop	1.11%	No Data

Table K-14. Prewetting Discharge Comparison of Open-loop to Closed-loop Modes of Operations for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	2.07%
Controller Display Discharge	No Data
Highway:	
Actual Discharge	10.78%
Controller Display Discharge	No Data

APPENDIX L
TEST RESULTS FOR PENGWYN MODEL 485

Results from Yard Tests

Table L-1. Values of Truck Speed, Solid Discharge Rate, Prewetting Rate, and Test Run Time for Each Test Set Number Used in Yard Testing

Set No.	Truck Speed ,mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec.	Set No.	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time , sec.
1	20	100	20	90.3	16	35	200	5	35.0
2	20	200	25	59.9	17	35	300	25	19.9
3	20	400	10	35.1	18	35	600	30	15.1
4	20	600	15	20.1	19	35	700	10	15.1
5	20	800	30	15.2	20	35	800	15	15.0
6	25	100	15	89.9	21	40	200	20	29.9
7	25	300	10	30.1	22	40	300	15	19.9
8	25	500	20	20.1	23	40	400	5	15.0
9	25	600	5	15.3	24	40	500	25	15.1
10	25	700	25	15.4	25	40	700	30	15.0
11	30	100	30	75.1	26	45	100	10	20.0
12	30	300	5	30.0	27	45	400	30	15.1
13	30	400	20	21.8	28	45	500	5	15.0
14	30	600	25	15.1	29	45	700	15	12.1
15	30	800	10	15.1	30	45	800	20	12.1

Summary Tabulations of Solid and Liquid Discharge Rates

Table L-2. Actual and Estimated Solid Discharge Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed, mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	93.0	193.7	**261.0**	308.6	**455.4**	491.8	**649.8**	682.2
25	75.0	**174.4**	252.2	**368.8**	473.7	603.1	767.3	**757.6**
30	62.0	**185.0**	283.7	375.0	**476.6**	559.9	**671.0**	747.2
35	**98.5**	186.2	310.1	**390.1**	**487.3**	650.7	748.6	777.4
40	**109.1**	173.8	284.2	386.4	544.6	**595.1**	697.3	**789.5**
45	95.7	**216.9**	**314.1**	448.6	540.5	**605.7**	687.3	699.2

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table L-3. Percent of Difference between Actual and Estimated Solid Discharge Rates and Dial-In Application Rates as Function of Truck Speed

Speed, mph	Dial-In Application Rate in lbs/mile							
	100	200	300	400	500	600	700	800
20	-7.0%	-3.2%	**-13.0%**	-22.9%	**-8.9%**	-18.0%	**-7.2%**	-14.7%
25	-25.0%	**-12.8%**	-15.9%	**-7.8%**	-5.3%	0.5%	9.6%	**-5.3%**
30	-38.0%	**-7.5%**	-5.4%	-6.3%	**-4.7%**	-6.7%	**-4.1%**	-6.6%
35	**-1.5%**	-6.9%	3.4%	**-2.5%**	**-2.5%**	8.5%	6.9%	-2.8%
40	**9.1%**	-13.1%	-5.3%	-3.4%	8.9%	**-0.8%**	-0.4%	**-1.3%**
45	-4.3%	**8.5%**	**4.7%**	12.2%	8.1%	**1.0%**	-1.8%	-12.6%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table L-4. Actual and Estimated Discharge Prewetting Rates for Various Dial-In Application Rates as a Function of Truck Speed

Speed, mph	Dial-In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**16.8**	18.2	16.4	60.4	28.8	20.1
25	7.3	17.8	31.0	16.9	14.2	**30.1**
30	6.7	8.8	**17.5**	18.3	15.2	60.6
35	8.8	7.8	9.2	**17.8**	18.1	17.2
40	7.2	**8.4**	13.6	23.9	13.1	14.9
45	4.5	13.3	9.0	12.2	**15.2**	15.8

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table L-5. Percent of Difference between Actual and Estimated Prewetting Rates and Dial-In Prewetting Application Rates as a Function of Truck Speed

Speed, mph	Dial-In Application Rate in gallons/ton					
	5	10	15	20	25	30
20	**236.0%**	82.0%	9.3%	202.0%	15.2%	-33.0%
25	46.0%	78.0%	106.7%	-15.5%	-43.2%	**0.3%**
30	34.0%	-12.0%	**16.7%**	-8.5%	-39.2%	102.0%
35	76.0%	-22.0%	-38.7%	**-11.0%**	-27.6%	-42.7%
40	44.0%	**-16.0%**	-9.3%	19.5%	-47.6%	-50.3%
45	-10.0%	33.0%	-40.0%	-39.0%	**-39.2%**	-47.3%

Note: The numbers in bold type are computed from the actual test data using a multiple linear regression model.

Table L-6. Regression Coefficients for Determination of Missing Test Discharge Values

Material	Rate Coefficient	Speed Coefficient	Intercept	R - squared
	A1	A2	B	(as percent)
Solid	0.972	2.124	-73.079	95.8%
Liquid	0.649	-0.581	25.162	33.6%

Table L-7. Percent of Error for Solid Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Solid Discharge, lbs/sec.	Test Solid Discharge, lbs/sec	Percent of Error	Set Solid Discharge Rate, lbs/mile	Test Solid Discharge Rate, lbs/mile	Percent of Error
1	90.3	20	0.556	0.517	-7.01%	100	93.0	-7.00%
6	89.9	25	0.694	0.521	-24.93%	100	75.0	-25.00%
11	75.1	30	0.833	0.517	-37.94%	100	62.0	-38.00%
2	59.9	20	1.111	1.075	-3.24%	200	193.7	-3.15%
3	35.1	20	2.222	1.715	-22.82%	400	308.6	-22.85%
16	35.0	35	1.944	1.809	-6.94%	200	186.2	-6.90%
7	30.1	25	2.083	1.754	-15.79%	300	252.2	-15.93%
12	30.0	30	2.500	2.367	-5.32%	300	283.7	-5.43%
21	29.9	40	2.222	1.933	-13.01%	200	173.8	-13.10%
13	21.8	30	3.333	3.124	-6.27%	400	375.0	-6.25%
4	20.1	20	3.333	2.731	-18.06%	600	491.8	-18.03%
8	20.1	25	3.472	3.294	-5.13%	500	473.7	-5.26%
26	20.0	45	1.250	1.200	-4.00%	100	95.7	-4.30%
17	19.9	35	2.917	3.020	3.53%	300	310.1	3.37%
22	19.9	40	3.333	3.166	-5.01%	300	284.2	-5.27%
10	15.4	25	4.861	5.331	9.67%	700	767.3	9.61%
9	15.3	25	4.167	4.176	0.22%	600	603.1	0.52%
5	15.2	20	4.444	3.789	-14.74%	800	682.2	-14.73%
14	15.1	30	5.000	4.649	-7.02%	600	559.9	-6.68%
15	15.1	30	6.667	6.238	-6.43%	800	747.2	-6.60%
18	15.1	35	5.833	6.325	8.43%	600	650.7	8.45%
19	15.1	35	6.806	7.272	6.85%	700	748.6	6.94%
24	15.1	40	5.555	6.066	9.20%	500	544.6	8.92%
27	15.1	45	5.000	5.603	12.06%	400	448.6	12.15%
20	15.0	35	7.778	7.560	-2.80%	800	777.4	-2.83%
23	15.0	40	4.444	4.293	-3.40%	400	386.4	-3.40%
25	15.0	40	7.778	7.747	-0.40%	700	697.3	-0.39%
28	15.0	45	6.250	6.747	7.95%	500	540.5	8.10%
29	12.1	45	8.750	8.554	-2.24%	700	687.3	-1.81%
30	12.1	45	10.000	8.702	-12.98%	800	699.2	-12.60%

Table L-8. Percent of Error for Actual Liquid Discharge as a Function of Time

Set #	Test Run Time, sec	Truck Speed, mph	Theoretical Liquid Discharge, ozs/sec.	Test Liquid Discharge, ozs/sec	Percent of Error	Set Prewetting Application Rate, gals/ton	Test Prewetting Discharge Rate, gals/ton	Percent of Error
1	90.3	20	0.711	1.996	180.73%	20	60.4	202.00%
6	89.9	25	0.667	1.033	54.87%	15	31.0	106.67%
11	75.1	30	1.599	1.997	24.89%	30	60.6	102.00%
2	59.9	20	1.778	1.983	11.53%	25	28.8	15.20%
3	35.1	20	1.422	2.000	40.65%	10	18.2	82.00%
16	35.0	35	0.622	1.017	63.50%	5	8.8	76.00%
7	30.1	25	1.333	1.997	49.81%	10	17.8	78.00%
12	30.0	30	0.800	1.017	27.13%	5	6.7	34.00%
21	29.9	40	2.844	2.960	4.08%	20	23.9	19.50%
13	21.8	30	4.266	3.651	-14.42%	20	18.3	-8.50%
4	20.1	20	3.200	2.856	-10.75%	15	16.4	9.33%
8	20.1	25	4.444	3.547	-20.18%	20	16.9	-15.50%
26	20.0	45	0.800	1.015	26.88%	10	13.3	33.00%
17	19.9	35	4.667	3.482	-25.39%	25	18.1	-27.60%
22	19.9	40	3.200	2.759	-13.78%	15	13.6	-9.33%
10	15.4	25	7.778	4.844	-37.72%	25	14.2	-43.20%
9	15.3	25	1.333	1.941	45.61%	5	7.3	46.00%
5	15.2	20	8.533	4.855	-43.10%	30	20.1	-33.00%
14	15.1	30	8.000	4.530	-43.38%	25	15.2	-39.20%
15	15.1	30	4.267	3.490	-18.21%	10	8.8	-12.00%
18	15.1	35	11.199	6.954	-37.91%	30	17.2	-42.67%
19	15.1	35	4.356	3.623	-16.83%	10	7.8	-22.00%
24	15.1	40	8.889	5.073	-42.93%	25	13.1	-47.60%
27	15.1	45	9.600	5.649	-41.16%	30	15.8	-47.33%
20	15.0	35	7.467	4.447	-40.44%	15	9.2	-38.67%
23	15.0	40	1.422	1.973	38.75%	5	7.2	44.00%
25	15.0	40	14.933	7.353	-50.76%	30	14.9	-50.33%
28	15.0	45	2.000	1.947	-2.65%	5	4.5	-10.00%
29	12.1	45	8.400	4.917	-41.46%	15	9.0	-40.00%
30	12.1	45	12.800	6.777	-47.05%	20	12.2	-39.00%

Table L-9. Theoretical and Test Solid Discharges as a Function of Increasing Theoretical Solid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Theoretical Solid Discharge, lbs/sec.	Test Solid Discharge, lbs/sec
1	20	100	20	90.3	0.556	0.517
6	25	100	15	89.9	0.694	0.521
11	30	100	30	75.1	0.833	0.517
2	20	200	25	59.9	1.111	1.075
26	45	100	10	20.0	1.250	1.200
16	35	200	5	35.0	1.944	1.809
7	25	300	10	30.1	2.083	1.754
3	20	400	10	35.1	2.222	1.715
21	40	200	20	29.9	2.222	1.933
12	30	300	5	30.0	2.500	2.367
17	35	300	25	19.9	2.917	3.020
4	20	600	15	20.1	3.333	2.731
13	30	400	20	21.8	3.333	3.124
22	40	300	15	19.9	3.333	3.166
8	25	500	20	20.1	3.472	3.294
9	25	600	5	15.3	4.167	4.176
5	20	800	30	15.2	4.444	3.789
23	40	400	5	15.0	4.444	4.293
10	25	700	25	15.4	4.861	5.331
14	30	600	25	15.1	5.000	4.649
27	45	400	30	15.1	5.000	5.603
24	40	500	25	15.1	5.555	6.066
18	35	600	30	15.1	5.833	6.325
28	45	500	5	15.0	6.250	6.747
15	30	800	10	15.1	6.667	6.238
19	35	700	10	15.1	6.806	7.272
20	35	800	15	15.0	7.778	7.560
25	40	700	30	15.0	7.778	7.747
29	45	700	15	12.1	8.750	8.554
30	45	800	20	12.1	10.000	8.702

Table L-10. Theoretical and Test Liquid Discharges as a Function of Increasing Theoretical Liquid Discharge

Set #	Truck Speed, mph	Set Solid Discharge Rate, lbs/mile	Set Prewetting Application Rate, gals/ton	Test Run Time, sec	Theoretical Liquid Discharge, ozs/sec	Test Liquid Discharge, ozs/sec
16	35	200	5	35.0	0.622	1.017
6	25	100	15	89.9	0.667	1.033
1	20	100	20	90.3	0.711	1.996
12	30	300	5	30.0	0.800	1.017
26	45	100	10	20.0	0.800	1.015
7	25	300	10	30.1	1.333	1.997
9	25	600	5	15.3	1.333	1.941
3	20	400	10	35.1	1.422	2.000
23	40	400	5	15.0	1.422	1.973
11	30	100	30	75.1	1.599	1.997
2	20	200	25	59.9	1.778	1.983
28	45	500	5	15.0	2.000	1.947
21	40	200	20	29.9	2.844	2.960
4	20	600	15	20.1	3.200	2.856
22	40	300	15	19.9	3.200	2.759
13	30	400	20	21.8	4.266	3.651
15	30	800	10	15.1	4.267	3.490
19	35	700	10	15.1	4.356	3.623
8	25	500	20	20.1	4.444	3.547
17	35	300	25	19.9	4.667	3.482
20	35	800	15	15.0	7.467	4.447
10	25	700	25	15.4	7.778	4.844
14	30	600	25	15.1	8.000	4.530
29	45	700	15	12.1	8.400	4.917
5	20	800	30	15.2	8.533	4.855
24	40	500	25	15.1	8.889	5.073
27	45	400	30	15.1	9.600	5.649
18	35	600	30	15.1	11.199	6.954
30	45	800	20	12.1	12.800	6.777
25	40	700	30	15.0	14.933	7.353

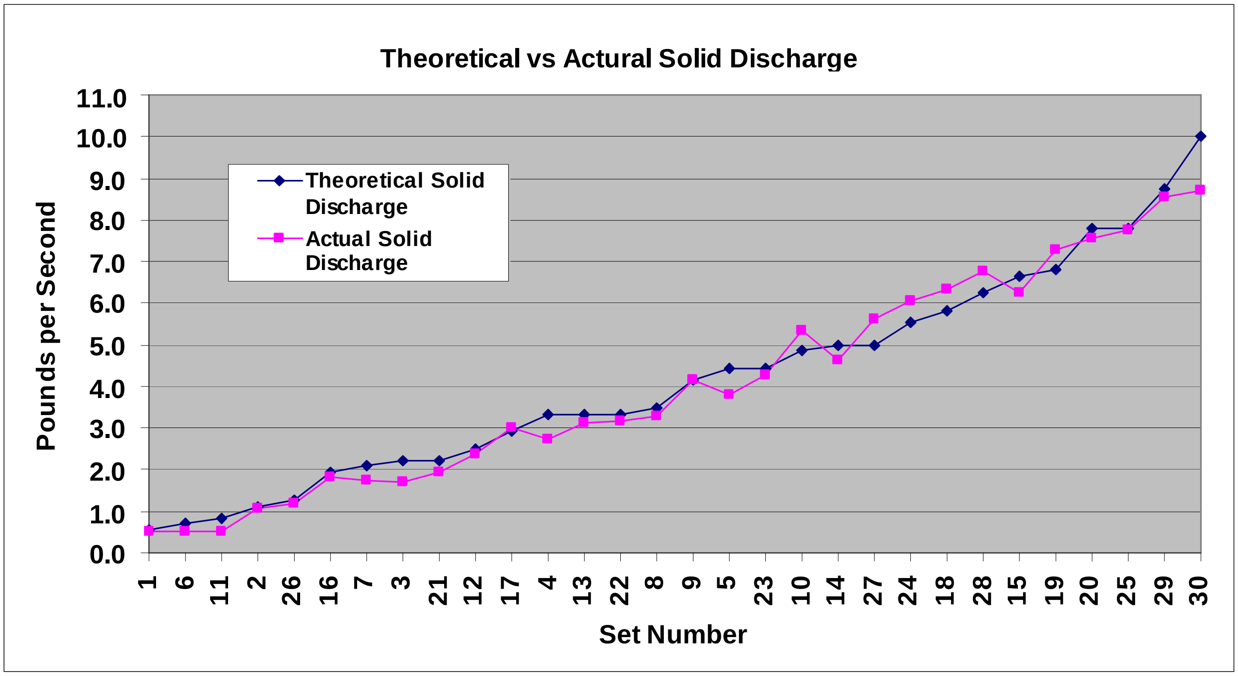

Figure L-1. Theoretical vs Actual Solid Discharge Rate

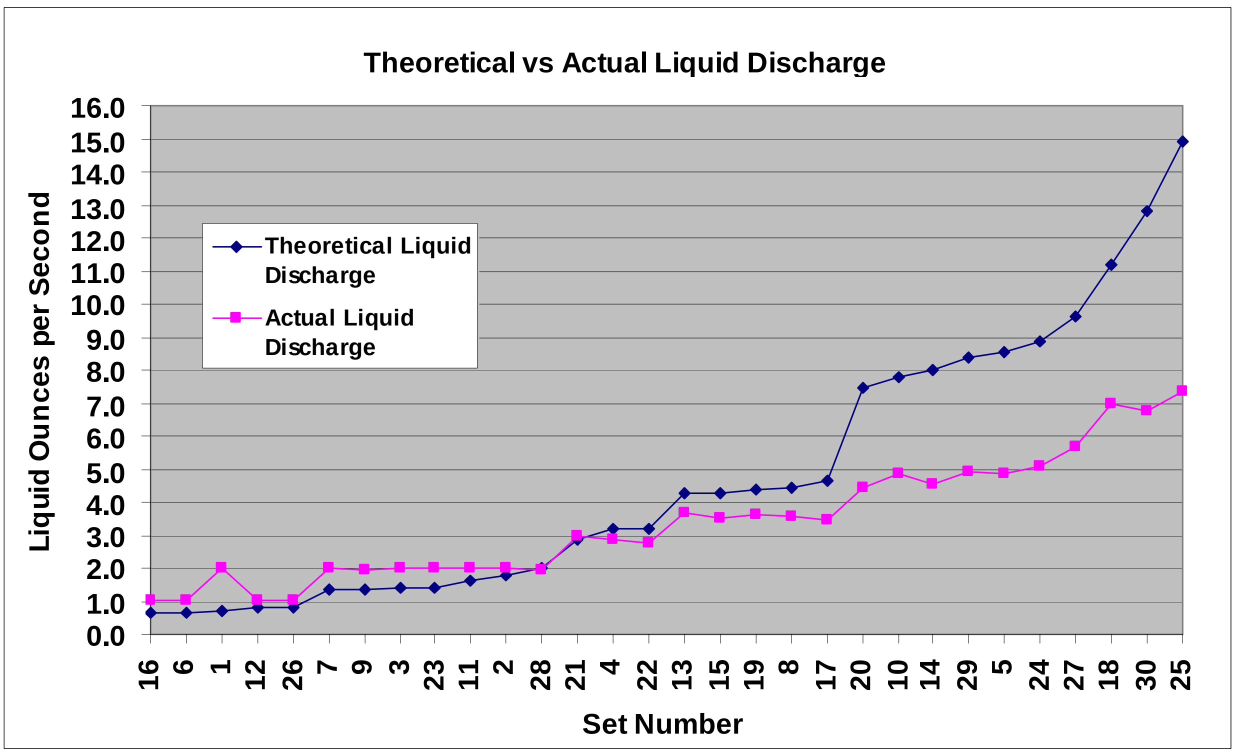

Figure L-2. Theoretical vs Actual Liquid Salt Brine Discharge Rate

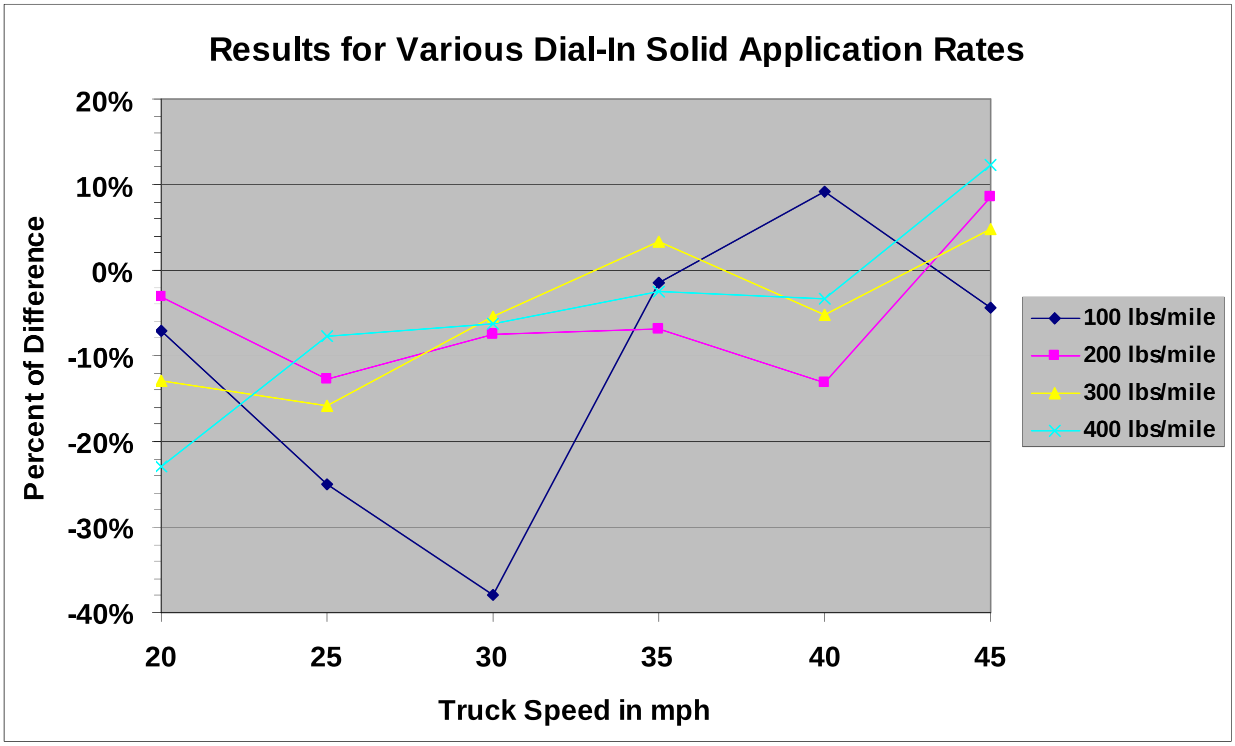

Figure L-3. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

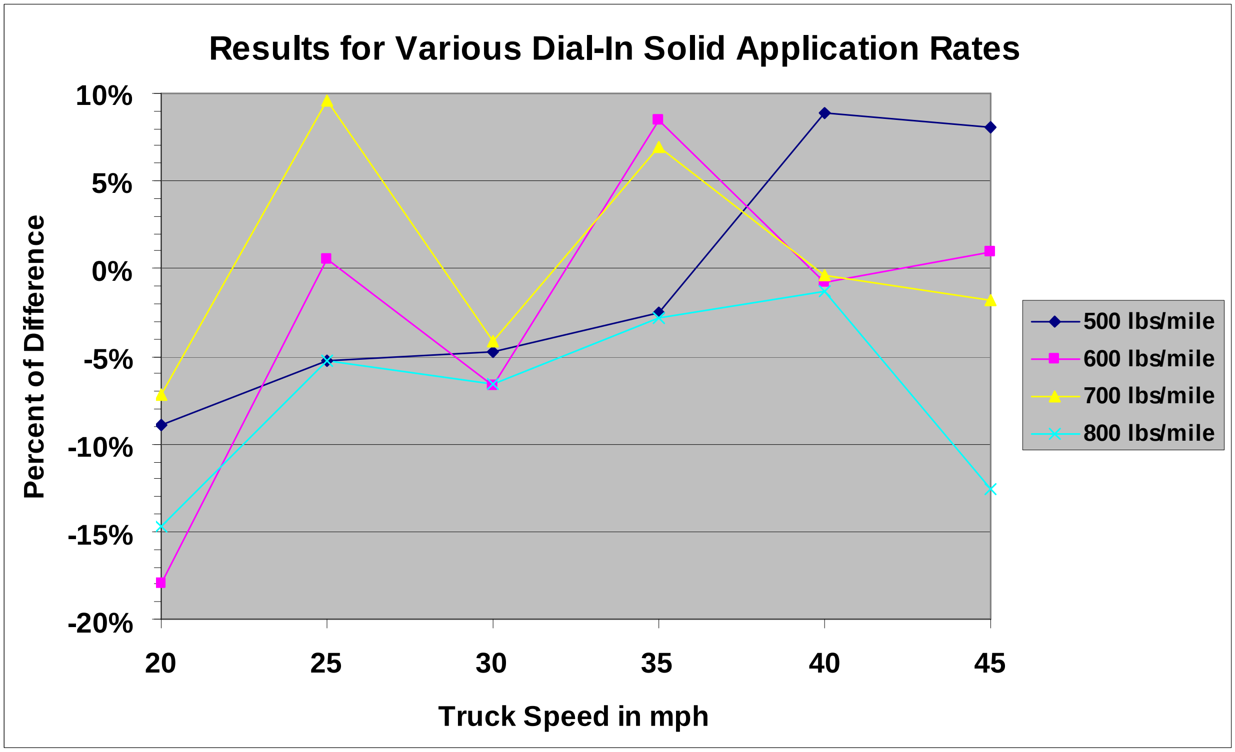

Figure L-4. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Truck Speed

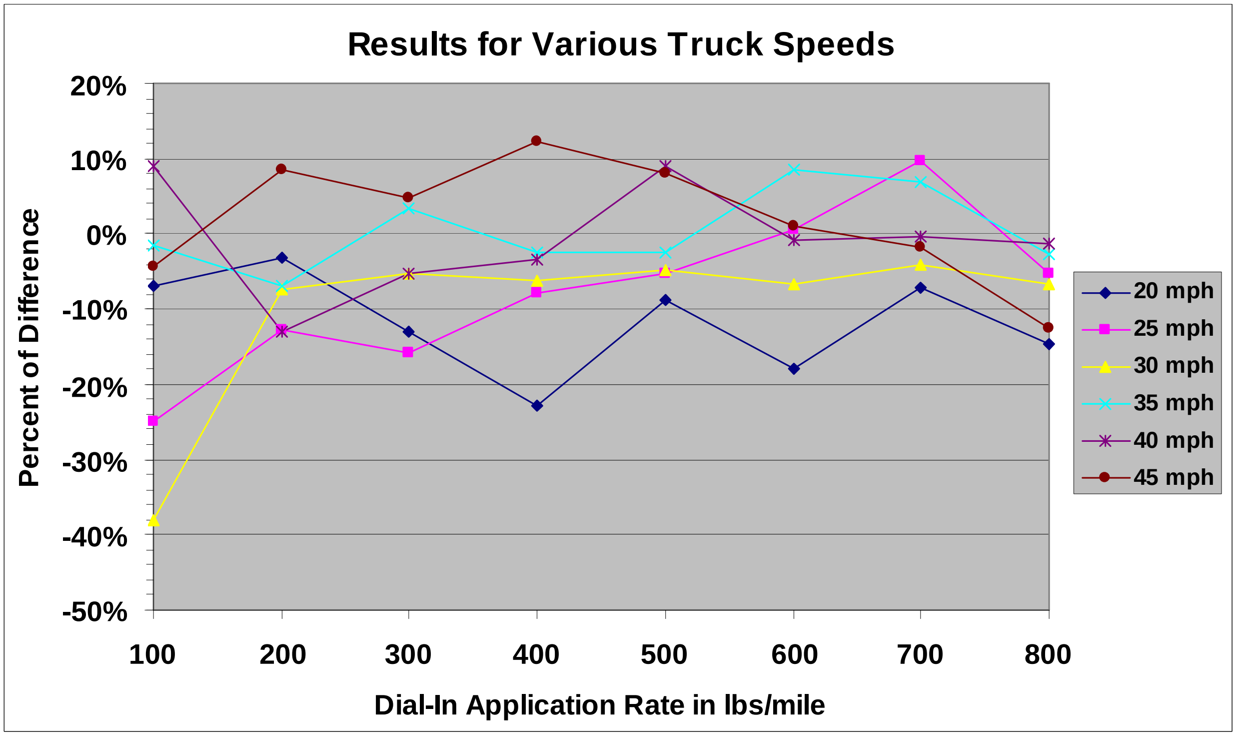

Figure L-5. Percent of Difference between Actual Solid Discharge Rate and Dial-In Solid Application Rate as a Function of Dial-In Solid Application Rate

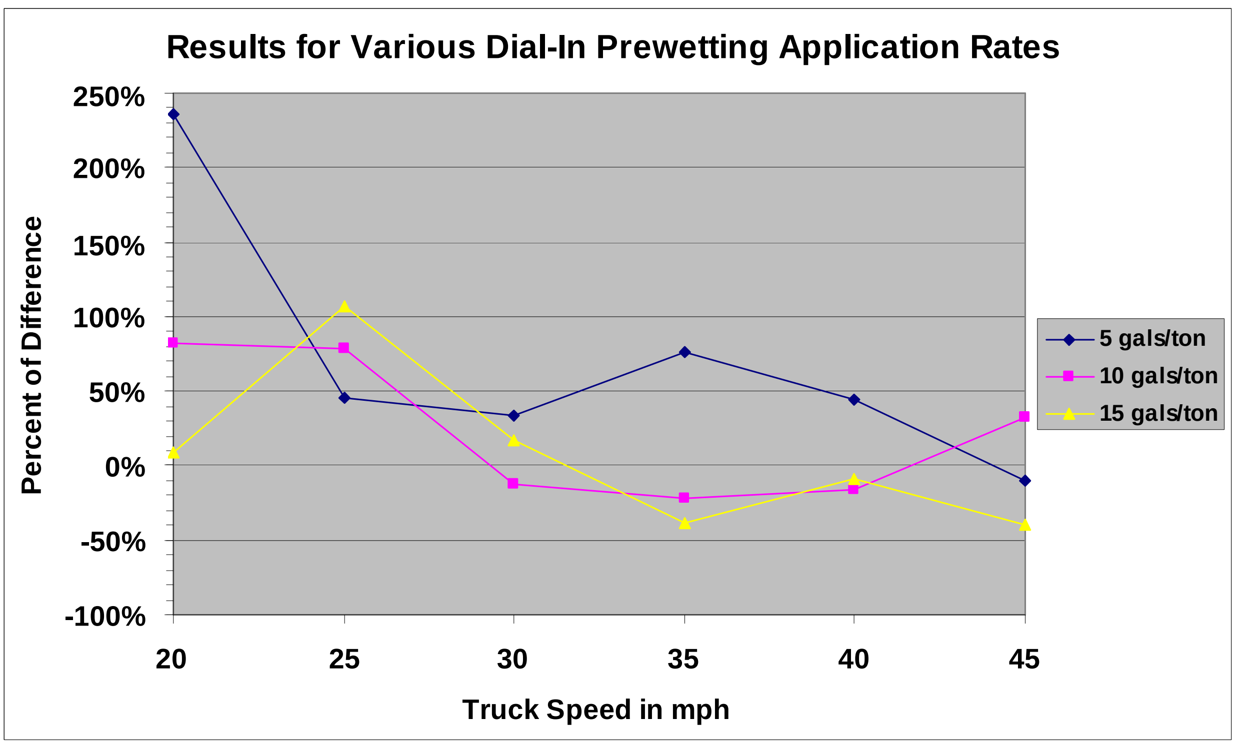

Figure L-6. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed

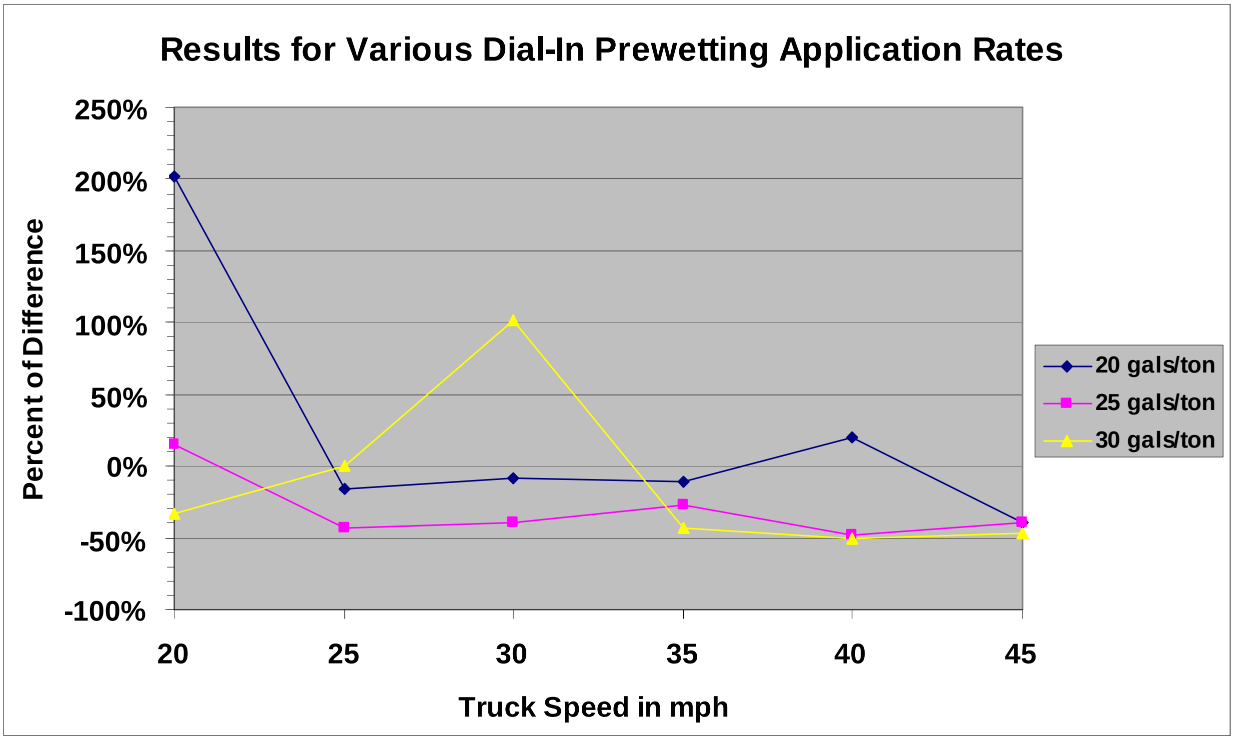

Figure L-7. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Truck Speed

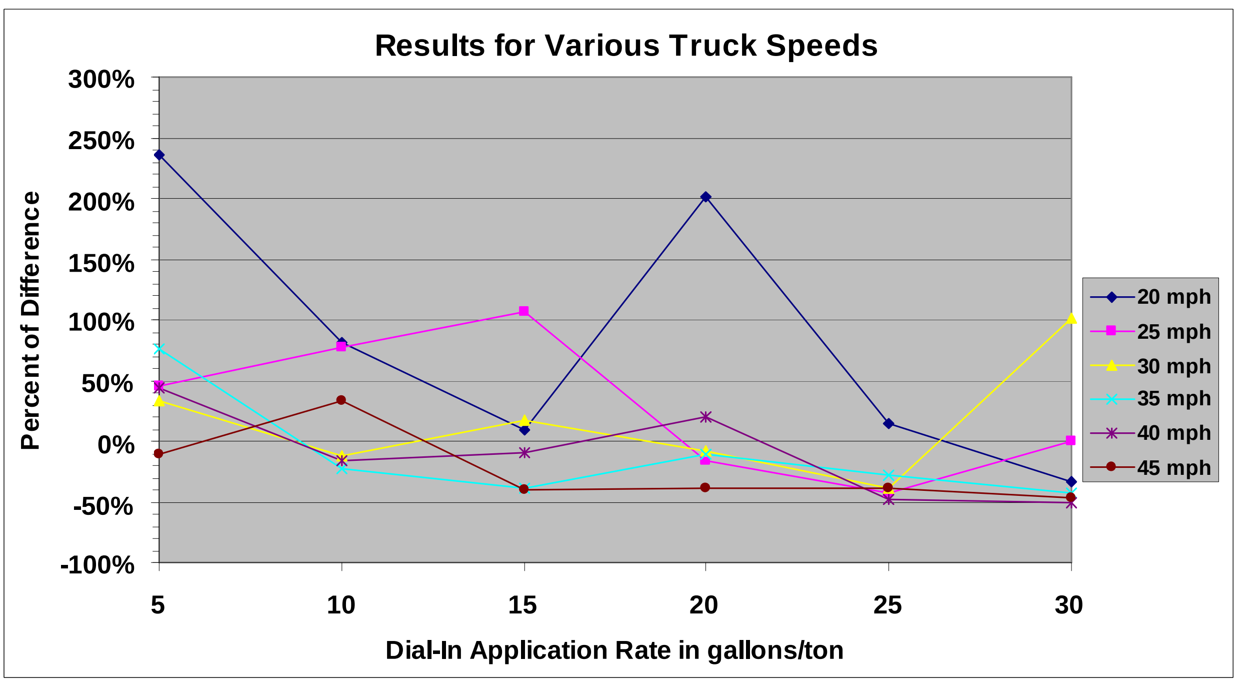

Figure L-8. Percent of Difference between Actual Prewetting Rate and Dial-In Prewetting Application Rate as a Function of Dial-In Prewetting Rate

Table L-11. Statistical Analysis Results for Yard Tests

Yard Test Results for Bias, Accuracy, and Precision	
Solid Discharge	
Bias (lbs/mile)	-16.7
Accuracy	90.0%
Precision	9.0%
Prewetting Discharge	
Bias (gals/ton)	0.1
Accuracy	54.2%
Precision	72.1%

Results from Simulated Scenario Testing

Table L-12. Solid Discharges for Open-loop Mode from Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (lbs)	Actual Discharge (lbs)	Discharge Amount According to Controller	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	5099.7	4440	*	-12.9%	NA	NA	NA	CNC
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	2	5099.7	4500	*	-11.8%	NA	NA	NA	CNC
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	4950	4400	*	-11.1%	NA	NA	NA	CNC
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	4	4950	3500	*	-29.3%	NA	NA	NA	CNC

Note: * = Data not available from the controller.
NA = Could not be computed because data were not available from the controller.
CNC = Could not compute the value because closed-loop information was not available.

Table L-13. Liquid Discharges for Open-loop Mode from Various Simulated Scenario Testing

Scenario	Test Set No.	Theoretical Discharge (gals)	Actual Discharge (gals)	Discharge Amount According to Controller (gals)	Percent of Difference of Actual Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Theoretical Discharge	Percent of Difference of Controller Compared to Actual Discharge	Percent of Difference of Actual Compared to Controller Discharge	Percent of Difference of Actual Discharge for Open-Loop Compared to Closed Loop Operation
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	1	34.456	37.7	*	9.41%	NA	NA	NA	CNC
Freeway Scenario - Open-Loop Mode Test Parameter 200 and 500 lbs/mile Driven: 15, 20,30, & 35 MPH	2	34.456	37.5	*	8.83%	NA	NA	NA	CNC
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	3	31.500	40.8	*	29.52%	NA	NA	NA	CNC
Highway Scenario - Open-Loop Mode Test Parameter: 300 & 600 lbs/mile Driven: 15, 20, 25, 30, & 35 MPH	4	31.500	40.5	*	28.57%	NA	NA	NA	CNC

Note: * = Data not available from the controller.
NA = Could not be computed because data were not available from the controller.
CNC = Could not compute the value because closed-loop information was not available.

Table L-14. Solid Discharge Comparison for Freeway and Highway Scenarios in Open-loop Operations

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Closed-loop	Does not operate in this mode	Does not operate in this mode
Open-loop	-12.35%	No Data
Highway:		
Closed-loop	Does not operate in this mode	Does not operate in this mode
Open-loop	-20.20%	No Data

Table L-15. Solid Discharge Comparison of Open-loop to Closed-loop Operations for Freeway and Highway Scenarios of Actual Discharge and Controller Display Discharge

Scenario/Mode of Operation	Percent of Difference in Discharge for Open-loop Compared to Closed-loop Operations
Freeway:	
Actual Discharge	Does not operate in Closed-loop mode
Controller Display Discharge	Does not operate in Closed-loop mode
Highway:	
Actual Discharge	Does not operate in Closed-loop mode
Controller Display Discharge	Does not operate in Closed-loop mode

Table L-16. Prewetting Discharge Comparison for Freeway and Highway Scenarios in Open-loop Operations

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Closed-loop	Does not operate in this mode	Does not operate in this mode
Open-loop	9.12%	No Data
Highway:		
Closed-loop	Does not operate in this mode	Does not operate in this mode
Open-loop	29.05%	No Data

Table L-17. Solid Discharges for Open-loop and Manual Modes from Various Simulated Scenario Testing

Scenario	Test No.	Theoretical Discharge (lbs)	Actual Weighed Discharge (lbs)	Percent of Difference between Actual Discharge and Theoretical Discharge
Freeway Scenario - Open-Loop Mode Test Parameter:200 and 500 lbs/mile Drive:15, 20,30, and 35 MPH	1	5099.7	5260	3.14%
Freeway Scenario - Open-Loop Mode Test Parameter:200 and 500 lbs/mile Drive:15, 20,30, and 35 MPH	2	5099.7	5100	0.01%
Highway Scenario - Open-Loop Mode Test Parameter:300 and 600 lbs/mile for 30 MPH Drive:15, 20, 25, 30, and 35 MPH	3	4950.0	5080	2.63%
Highway Scenario - Open-Loop Mode Test Parameter:300 and 600 lbs/mile for 30 MPH Drive:15, 20, 25, 30, and 35 MPH	4	4950.0	5380	8.69%
Highway Scenario - Manual Mode Test Parameter:222 lbs/mile @ 30MPH Drive:20, 25, and 30 MPH	5	2775.0	2680	-3.42%
Highway Scenario - Manual Mode Test Parameter:440 lbs/mile @ 30MPH Drive:20, 25, and 30 MPH	6	4400.4	5040	14.54%
Freeway Scenario - Manual Mode Test Parameter:222 lbs/mile @ 30MPH Drive:20 and 30 MPH	7	3330.0	3260	-2.10%
Freeway Scenario - Manual Mode Test Parameter:440 lbs/mile @ 30MPH Drive:20 and 30 MPH	8	6600.6	6560	-0.62%

Table L-18. Solid Discharge Comparison for Freeway and Highway Scenarios in Both Open-loop and Manual Operations

Scenario/Mode of Operation	Percent of Difference in Discharge	
	Actual Compared to Theoretical	Controller Display Compared to Theoretical
Freeway:		
Open-loop	1.57%	No Data
Highway:		
Open-loop	5.66%	No Data

APPENDIX M
BACKGROUND INFORMATION AND PROCEDURES FOR CONDUCTING PHASE 3 TESTS

Accuracy of Ground-Speed Controlled Snow and Ice Control Material Spreaders
(Phase 3)

The purpose of this document is to provide some up-dated information on the Clear Roads project and to describe the continued assistance needed from the Clear Roads states involved in the Phase 3 field studies of the project. The procedures for conducting the Phase 3 tests are presented along with reference to supplemental information associated with those tests. That information is attached to this document. The maintenance yard equipment, facilities, and material needed for the tests follow at the end of this document.

Background

A Clear Roads Pooled Fund research study was initiated in October 2005 with the consulting firm of Blackburn and Associates to investigate the calibration accuracy of manual and ground-speed-controlled salters. The Clear Roads program focuses on field testing and evaluation of materials, methods, and equipment used in highway winter maintenance. Initially, seven mid-western state DOTs, including Indiana, Iowa, Ohio, Michigan, Minnesota, Missouri, and Wisconsin, were part of the program which is also supported by the Federal Highway Administration. After the project began, the state DOTs of Colorado and Illinois were added to the magnificent seven. The spreader accuracy project is managed by the Wisconsin Department of Transportation and is being conducted over a two-year period.

The scope of the research is divided into three phases. The first phase consisted of a literature search and survey of Snow Belt states to access the types of manual and ground-speed-controlled equipment in use, and their calibration and operational experiences with the equipment. Manufacturers of ground-speed controllers in use by the Clear Roads initial members were surveyed to determine their recommended calibration procedures.

The second phase, now completed, was a yard or bench study of new ground-speed controllers that can also be operated in a manual mode. The relatively new equipment was calibrated according to the manufacturers' recommendations. It was then tested in accordance with a developed protocol in the maintenance yard to document the actual solid and liquid discharge amounts under a combination of operational variables.

In the third phase of the study, now underway, the team will document, with the cooperation of six Clear Roads member states, the actual material usage during winter-time conditions for both manually and ground-speed-controlled spreaders that have been calibrated according to the manufacturers' specifications. The six states are Indiana, Iowa, Minnesota, Missouri, Ohio, and Wisconsin. The Phase 3 testing will be conducted at the same maintenance work locations where the yard tests were conducted, with one exception. The Phase 3 tests in Minnesota will be conducted at a Minneapolis Metro garage location, because the yard tests of the Dickey-john controller model use by Mn/DOT were performed in New York State for convenience. The Phase 3 work will be conducted over one winter season.

Seven different controllers from six manufacturers will be tested. Because of the nature of the controllers' design, many units can be operated in different modes, including closed loop, open-loop, and manual. It is anticipated that the Phase 3 test will be conducted with a total of 15 controller-modes of operation. Five will be operated in a closed-loop (CL) ground-speed-controlled mode; four will be operated in an open-loop (OL) ground-speed-controller mode, and six will be operated in a manual (M) mode, if possible. The distribution of state DOTs, controller manufacturer/model, and controller mode of operation involved in the Phase 3 testing are given in Table M-1.

Table M-1. Combination of State DOTs, Controller Manufacturers, and Mode of Controller Operation Involved in Phase 3 Testing

State DOT	Controller Manufacturer/Model	Mode of Controller Operation
Indiana	Muncie Power Products MESP402D	CL, OL
Iowa	Cirus Controls SpreadSmart RX	CL, OL, M
Minnesota	Dickey-john Control Point	CL, OL
Missouri	Component Technology GL-400	CL, OL, M
Ohio	Pengwyn Model 485	OL, M
Wisconsin	FORCE America Model 2100 Model 5100	 OL CL, OL

During the Phase 3 tests, the team will document, through use of specially designed equipment data reporting forms, the controller settings; the solid and liquid chemical application rates used; the truck spreading speed; and the amount of salt, sand, and prewetting liquid chemicals used during the tests. Other data such as salt moisture content (where available) and weather conditions at the time of tests will also be recorded. Verification of the accuracy of the recording method for miles traveled will also be made. The analysis of the test data will include among various items, a cost-performance comparison of the manual versus ground-speed controllers. The respective equipment manufacturers will be invited, as in the yard study, to participate in this final phase of the study.

Assistance Needed from the Clear Roads States Involved in the Phase 3 Study

The levels of assistance needed from the Clear Roads states involved in the Phase 3 tests are described below, beginning with an overview of the Phase 3 tests. This is followed by a description of the procedures for conducting tests that simulate freeway and highway operations. The section ends with a description of the maintenance yard equipment, facilities, and material needed for the Phase 3 testing.

Overview

The Phase 3 tests will be conducted over a six-month period starting in November 2006 and ending about mid-April 2007. The first set of simulation tests will be conducted from about mid-November until about mid-January at the same maintenance locations where the yard tests were performed, with the exception already noted for the testing in Minnesota. The second set of tests will be conducted towards the end of the 2006-2007 winter in the March and April timeframe.

The Phase 3 tests will not be conducted during actual winter storm events as originally envisioned. That approach would have placed too much demand on the truck operator and maintenance support personnel. It would have also extended the cycle times for the test controller/spreader combination to unacceptable levels during winter maintenance operations. In stead, the tests of the controller/spreader combination will be conducted in the maintenance yard with the same controller/spreader used in the yard tests, but under extended run times and speeds that simulate field operations. This way, we avoid the confounding effects of snow and ice accumulations on the truck that would happen if the tests were conducted during winter storm events.

Two scenario runs will be conducted with the calibrated equipment. One run will simulate freeway operations; the other run will simulate highway operations with both a stop sign and signalized intersection delays. The freeway simulation will take about 42 minutes to complete and the highway simulation will take about 32 minutes to complete. About 5,000 lbs of salt and 30-35 gal of salt brine will be discharged during each scenario run. The tests will be conducted in both ground-speed-controlled and manually-controlled modes, except where noted differently below. A member of the project team will be overseeing the test preparations and testing at each given work location. He will work closely with, and seek the advice of the work location DOT maintenance personnel during the testing. **The maintenance yard personnel will be performing the tests.**

A representative of the controller manufacturer will be encouraged to participate in/observe the Phase 3 tests. This activity will be coordinated by the project team member overseeing the tests at a given location.

Procedures for Conducting Simulated Freeway and Highway Operations Tests

Before the simulation tests are conducted, the controller/spreader combination will need to be calibrated in the closed-loop, ground-speed-controlled mode. The calibration will then need to be checked by running four sets of verification discharge tests. If possible, these tests should be conducted using the controller speed simulator. Each scenario run will be replicated as many times as possible, using the controller speed simulator.

The controller/spreader combination will need to be calibrated in the manual mode following the above ground-speed-controlled tests. For the manually-controlled tests, it will be necessary to jack the rear of the truck, block the front wheels of the spreader truck, and make multiple measurements of discharge rates at various speeds as indicated by the speedometer. Replicate discharge tests for each scenario will follow.

If simulation tests using the manual mode can not be run conveniently in the maintenance yard, simulation tests should be conducted using the open-loop, ground-speed-controlled mode of operation. Again, replicate discharge tests for each scenario will follow. In this case, comparison tests between closed-loop, ground-speed-controlled and manually-controlled modes of operation will be conducted in late winter or early spring in selected Clear Roads states using actual highway, or on-the-road conditions.

The steps for conducting the simulated operations tests follow.

1. Calibrate eight, 5-gallon plastic buckets to be used in measuring the liquid discharge. This step includes making a wooden dip stick for measuring the amount of liquid accumulated in a plastic bucket when the amount is less than 5 gal. The procedure for this step is described in Attachment A to this write-up.

2. Attach hoses to the spray nozzles so that the liquid discharge can be channeled to the 5-gallon plastic collection buckets.

3. Measure the specific gravity of the salt brine with a hydrometer and record the results.

4. Load the truck and spreader with the appropriate amounts of salt and salt brine.

5. Calibrate the controller/spreader combination in the closed-loop, ground-speed-controlled mode using the manufacturer's recommended procedure. Record the calibration factors and other appropriate controller data.

6. Recheck the calibration by running verification tests using the following combinations of variables as shown in Table M-2, Calibration Verification Test Variables.

Table M-2. Calibration Verification Test Variables

Solid Application Rate (lbs/mile)	Liquid Application Rate (gal/ton)	Test Speed (mph)	Test Discharge Time (sec.)
200	10	25	73
300	10	25	49
500	15	20	36
600	15	20	30

7. Run three discharge tests for each combination of variables. Weigh and measure the solid and liquid discharge amounts and record the results. The discharge time should produce about 100 lbs of solid material and about ½ and ¾ gallons of liquid.

8. Prepare the truck and spreader for the first simulation test of the **FREEWAY SCENARIO** using the closed-loop, ground-speed-controlled mode by adding solid and liquid material. Top off the fuel tank to a point that can be seen and marked.

9. Weigh and record the weight of the fully loaded truck.

10. Conduct the first simulation run of the closed-loop, ground-speed-controlled mode using the test conditions identified for the **FREEWAY SCENARIO.** The tests conditions, including elapsed time, solid and liquid application rates, and truck speeds are given in Attachment B to this procedure. Use a stop watch to monitor the elapsed time for each task. If more convenient, use the Task duration times on the recording forms in Attachment C to this procedure.

11. During the simulation run, collect the liquid discharge in the 5-gallon plastic buckets and record the total amount discharged at the end of the simulation run using the recording forms in Attachment C to this procedure.

12. During the simulation run, collect the solid material by discharging into a loader bucket to minimize hand work. If this does not work, we may have to use a multi-wheel barrow shuttle to keep the discharge reasonably orderly. Place the discharged material in a pile where it can be retrieved after the test. Do not attempt to weigh the solid discharge at this point.

13. At the end of the simulation run, turn the engine off after recording on the attached forms the following information from the CONTROLLER: the weight (lbs) of solid discharged, the solid application rate discharged (lbs/mile), the distance traveled (miles), the liquid volume (gallons) discharged, and the liquid application rate (gal/ton).

14. Pump the liquid collected in the plastic buckets back into the prewetting tank(s) on the truck. A small utility pump and a small garden hose can be used to get the liquid back into the tank(s).

15. Top off the truck fuel tank to the mark indicated.

16. Weigh the truck and record the weight (lbs) of solid material discharged by differencing the after-test truck weight with the before-test truck weight.

17. Review the data reported to determine any inconsistencies and resolve.

18. Reload the truck with solid material that was set aside.

19. Repeat Steps 9 through 18 to conduct replicate tests with the closed-loop, ground-speed controlled mode and the **FREEWAY SCENARIO**.

This completes the tests with the controller/spreader combination operated in the closed-loop, ground-speed-controlled mode and following the **FREEWAY SCENARIO.**

20. Prepare the truck and spreader for the first simulation test of the **HIGHWAY SCENARIO** using the closed-loop, ground-speed-controlled mode by checking to see that solid and liquid have been added to the unit. Make sure that the fuel tank has been toped off to the mark indicated.

21. Weigh and record the weight of the fully loaded truck.

22. Prepare to conduct the first simulation run of the closed-loop, ground-speed-controlled mode using the test conditions identified in the **HIGHWAY SCENARIO.** The test conditions are given in Attachment B to this procedure. Continue to use a stop watch to monitor the elapsed time for each task of the simulation run.

23. Repeat Steps 11 through 18 to run the first simulation run of the **HIGHWAY SCENARIO.**

24. Repeat Steps 9 through 18 to conduct replicate tests with the closed-loop, ground-speed controlled mode and the **HIGHWAY SCENARIO.**

After Step 5, prepare to run both simulation scenarios using the manual mode of operation. Start with Step 4 and then jack up the rear axels and block the front wheels of the spreader truck.

25. Calibrate the controller/spreader in the manual mode using the manufacturer's recommended procedure, or if none, use that of the Salt Institute. Record the calibration factors and other appropriate data.

26. Recheck the calibration by conducting the verification tests described in Steps 6 and 7 using the manual mode of operation.

27. Repeat Steps 8 through 24 to conduct first and replicate tests with the manual mode of operation for both the **FREEWAY** and **HIGHWAY SCENARIOS**. These tests will require repeated jacking up the rear axels and blocking the front wheels of the spreader truck during the tests and then removing these items for weighing the truck.

This completes the tests with the controller/spreader combination operated in the manual mode of operation. If for some reason, the simulation runs using the manual mode of operation can not be conducted at this time, use the following procedure.

28. Repeat Steps 8 through 24 using the open-loop, ground-speed-controlled mode of operation for both the **FREEWAY** and **HIGHWAY SCENARIOS.**

Maintenance Yard Equipment, Facilities, and Material Needed for the Phase 3 Testing

The equipment, facilities, and material needed for the Phase 3 testing include:

- The same spreader truck that was used in the yard test with same controller and necessary prewetting system mounted.
- A known road distance near the maintenance yard where the spreader truck odometer and speedometer can be checked (if needed).
- About 5-6 cu yd of uniformly prepared solid material to be tested that is stored under cover and free of chunks with dimensions larger than the discharge gate opening.
- A truck scale for weighing the fully loaded truck.
- A calibrated weighing device that will accommodate up to 150 pounds of discharged solid material weight.
- A device for catching the discharged solid material. (A plastic 2' x 3' x 1' deep or deeper mason tub used for mixing mortar might work.)
- Enough prewetting liquid chemical in the truck tank(s) to carry out a number of tests [tank(s) at least ½ full].
- Adaptor hoses suited to capture the entire liquid chemical released from the spray nozzles during prewetting tests.
- Equipment identified in the attached procedures for calibrating plastic bucket for use in measuring liquid discharge.
- Eight, 5-gallon plastic buckets for catching the liquid discharge. Each bucket should be marked with a ring around the inside of the bucket at the 5 gallon level.
- Several smaller graduated plastic containers (to be supplied by the team member).
- A mechanism for storing the discharged liquid chemical for reuse, if preferred over using more than three 5-gallon plastic buckets.
- A mechanism for returning the discharged liquid chemical to the tank(s) on the truck. A small garden hose and a utility pump can be used for this activity.
- A hydrometer for measuring the specific gravity of the prewetting liquid chemical.
- Two stop watches (to be supplied by the team member).
- A way to mechanically keep a constant vehicle speed during each discharge test (such as with a throttle, if equipped). Perhaps a fan belt tensioner and a stick might work in the absence of a throttle.
- A set of highway cones to warn people of rotating rear truck wheels.
- Hard hats (if necessary).
- A small tarp to help retain discharged solid material.
- A mechanized loader bucket.
- Shovels, brooms, wheelbarrows, etc. to help in collecting the discharged solid material.

It is anticipated the team will require the assistance of 3 to 4 agency people to conduct the tests which includes at least one operator of the loader.

The team estimates that it will take up to 3 days to complete the simulated testing of the controller. The schedule for testing is somewhat at the discretion of the work location, but it would be highly beneficial for the project if the testing days are consecutive. Rainy days are okay as long as the work can be done in a salt storage building or other covered location. We do not want to conduct the simulated testing during the time that snow and ice control operations are underway.

Attachment A

Procedures to be Used in Calibrating Plastic Buckets For Use in Measuring Liquid Discharge

Materials Requirements:

1. Minimum of two plastic buckets that has the capacity of slightly more than 5 gallons. The sides of the buckets should be almost as vertical as possible. This is important so that the distance between marks is nearly constant. A third bucket that is not calibrated is also desirable.
2. A two foot carpenter level
3. A carpenter's adjustable square
4. A felt tip indelible marker pen
5. A wooden stick approximately ¾ inch by 1 ½ inch and 17 inches long. This stick will be used to measure the amount of liquid in the plastic bucket when it is less than 5 gallons. Due to the fact that one may not be able to see the level of the liquid within the bucket from the outside of the bucket, the stick will be used to measure the level of the liquid. It should be noted that the wooden stick will displace some liquid volume during the measuring process.
6. A 4-cup (32 ounce) measuring cup that is used by cooks in the kitchen. This cup will be used to calibrate the stick. If a measuring cup is not available, another accurate volume measuring device can be used.
7. A source of water or salt brine.

Procedures for Calibration:

1. Make sure that the bucket that is being calibrated is level in both directions. (North-South and East-West) Check the top of the bucket with the carpenter's level.
2. With the measuring cup or other measuring device, pour into the plastic bucket 64 liquid ounces of liquid.
3. Carefully insert the wood stick vertically and to the edge of the bottom of the bucket. The bottom of the bucket may have a slight convex surface on the bottom. Determine the location of the top of the liquid on the stick. Withdraw the stick and mark the half gallon location using the indelible pen.
4. Repeat Step 3 and mark the one gallon mark.
5. Repeat Steps 3 and 4 until you have poured 5 gallons of liquid into the bucket. Some plastic buckets have indictors inside the bucket at the 5 gallon mark. This mark can serve as a check on the accuracy of measuring out the liquid into the bucket.
6. When 5 gallons of liquid has been poured into the bucket, determine the location of the top of the liquid without the wooden stick in the bucket. Pour out the liquid and using the indelible pen with a carpenter's adjustable square, draw a ring around the inside of the bucket at the 5 gallon level.

7. From the marked wooden stick, determine the average distance between the gallon marks. Don't use the bottom of the stick or the first gallon, as that distance will be greater due to the convex shape of the bottom of the bucket. Record average distance to the nearest $1/16^{th}$ of inch and forward this value to Bob Blackburn.
8. A table will be created that will provide the decimal equivalent of a factor of a gallon of liquid between the marked gallon values.

Procedures for using Calibrated Buckets:

1. Check that hoses have been placed over the nozzles from the prewetting system and the buckets that are being used are level. Check using the carpenter's level.
2. With the hoses from the nozzles, deposit the liquid into the bucket.
3. At the completion of the verification test or the Phase 3 simulation test, remove the hoses and carefully insert the calibrated wooden measuring stick vertically into the bucket and determine the elevation of the liquid on the stick. Withdraw the stick and physically measure to the nearest $1/16^{th}$ of inch, the distance of the "elevation of the liquid" above the nearest marked gallon. From the table that will be provided, read the decimal equivalent of a gallon.
4. Using the value of the observed gallon mark and the decimal equivalent of gallon, record the amount of liquid that was discharged during the test.

Attachment B

Simulator Scenarios

FREEWAY SCENARIO

Task No.	Truck Speed in MPH	Application Rate (Solid) (lbs/mile)	Prewetting Rate (Gal/Ton)	Duration in Minutes	Elapsed Time in Minutes
1	20	200	10	8	8
2	35	200	10	5	13
3	15	200	10	8	21
4	20	500	15	8	29
5	30	500	15	5	34
6	15	500	15	8	42

HIGHWAY SCENARIO

Task No.	Truck Speed in MPH	Application Rate (Solid) (lbs/mile)	Prewetting Rate (Gal/Ton)	Duration in Minutes	Elapsed Time in Minutes
1	20	300	10	3	3
2	15	300	10	3	6
3	25	300	10	3	9
4	Stop			1	10
5	30	300	10	3	13
6	25	300	10	3	16
7	35	300	10	3	19
8	Stop			1	20
9	15	600	15	3	23
10	20	600	15	3	26
11	25	600	15	3	29
12	30	600	15	3	32

Data Sheets for Phase 3, Field Study

State of __________

Controller: _________ Location: ___________
Firmware Version for Controller:_______________ Date:_____________
Truck #: _________________ Year: _______________ Spreader #: _________________
Gate Opening:_____________

Snow and Ice Control Materials:
Solid Material:______________________ Prewetting Material: ________________

Calibration:
Date of last Calibration:__________ Calibration Constant for Solid: ______ Calibration Constant for Liquid: _____

Comments:

Simulator Scenario**: Freeway Operations**

Mode of Controller Operation: **CL** **OL** **M** (Circle the appropriate Mode) Test Set No: _______________

Truck weight fully loaded: ______________Truck weight after Scenario: ____________ Actual amount discharged: __________

Actual amount of liquid discharge in gallons: __________ Specific Gravity: _____________ Computed weight in lbs: _________

FREEWAY OPERATIONS SCENARIO											
Targeted						**Output from Controller**					
Task No.	Truck Speed in mph	Application Rate (Solid) (lbs/mile)	Prewetting Rate (gal/ton)	Duration in Minutes	Elapsed Time in Minutes	Weight of Solid Discharge (lbs)	Application Rate Discharge (Solid) (lbs/mile)	Distance Traveled (miles)	Liquid Volume Discharge (gallons)	Prewetting Rate Discharge (Liquid) (gal/ton)
1	20	200	10	8						
2	35	200	10	5						
3	15	200	10	8						
4	20	500	15	8						
5	30	500	15	5						
6	15	500	15	8						
Total										

Simulator Scenario: **Highway Operation**

Mode of Controller Operation: **CL** **OL** **M** (Circle the appropriate Mode) Test Set No: _______________

Truck weight fully loaded: ______________Truck weight after Scenario: ____________ Actual amount discharged: __________

Actual amount of liquid discharge in gallons: __________ Specific Gravity: _____________ Computed weight in lbs: _________

HIGHWAY OPERATIONS SCENARIO											
Targeted						**Output from Controller**					
Task No.	Truck Speed in mph	Application Rate (Solid) (lbs/mile)	Prewetting Rate (gal/ton)	Duration in Minutes	Elapsed Time in Minutes	Weight of Solid Discharge (lbs)	Application Rate Discharge (Solid) (lbs/mile)	Distance Traveled (miles)	Liquid Volume Discharge (gallons)	Prewetting Rate Discharge (Liquid) (gal/ton)
1	20	300	10	3	3					
2	15	300	10	3	6					
3	25	300	10	3	9					
4	Stop			1	10					
5	30	300	10	3	13					
6	25	300	10	3	16					
7	35	300	10	3	19					
8	Stop			1	20					
9	15	600	15	3	23					
10	20	600	15	3	26					
11	25	600	15	3	29					
12	30	600	15	3	32					
Total										

APPENDIX N
TESTING PROTOCOLS AND FORMS USED IN IOWA

Testing Protocols Used in Iowa

Mode of Operation	Activity	1st loop	2nd loop
First Scenario-Manual Mode	Load, weigh truck, and drive to test route		
	Use settings of 200 lbs/mile for 30MPH and drive at 20 MPH		
	Stop at midpoint on the route		
	Use settings of 200 lbs/mile for 30MPH and drive at 20 MPH		
	Turn around at the end of test route (2.66 miles)		
	Use settings of 200 lbs/mile for 30 MPH and drive at 30 MPH		
	Stop at midpoint on the route		
	Use settings of 200 lbs/mile for 30 MPH and drive at 30 MPH		
	Turn around at the end of first loop and drive 2nd loop using above conditions		
	Weigh truck at the end of 2nd loop **(Reload truck and weigh)**		
Second Scenario-Manual Mode	Drive to test route		
	Use settings of 200 lbs/mile for 30MPH and drive at 20 MPH		
	Stop at midpoint on the route		
	Use settings of 200 lbs/mile for 30MPH and drive at 20 MPH		
	Turn around at the end of test route (2.66 miles)		
	Use settings of 200 lbs/mile for 30 MPH and drive at 30 MPH		
	Stop at midpoint on the route		
	Use settings of 200 lbs/mile for 30 MPH and drive at 30 MPH		
	Turn around at the end of first loop and drive 2nd loop using above conditions		
	Weigh truck at the end of 2nd loop		

Mode of Operation	Activity	1st loop	2nd loop
Third Scenario-Manual Mode	Drive to test route		
	Use settings of 400 lbs/mile for 30MPH and drive at 20 MPH		
	Stop at midpoint on the route		
	Use settings of 400 lbs/mile for 30MPH and drive at 20 MPH		
	Turn around at the end of test route (2.66 miles)		
	Use settings of 400 lbs/mile for 30 MPH and drive at 30 MPH		
	Stop at midpoint on the route		
	Use settings of 400 lbs/mile for 30 MPH and drive at 30 MPH		
	Turn around at the end of first loop and drive 2nd loop using above conditions		
	Weigh truck at the end of 2nd loop **(Reload truck and weigh)**		
Fourth Scenario-Manual Mode	Drive to test route		
	Use settings of 400 lbs/mile for 30MPH and drive at 20 MPH		
	Stop at midpoint on the route		
	Use settings of 400 lbs/mile for 30MPH and drive at 20 MPH		
	Turn around at the end of test route (2.66 miles)		
	Use settings of 400 lbs/mile for 30 MPH and drive at 30 MPH		
	Stop at midpoint on the route		
	Use settings of 400 lbs/mile for 30 MPH and drive at 30 MPH		
	Turn around at the end of first loop and drive 2nd loop using above conditions		
	Weigh truck at the end of 2nd loop		
Fifth Scenario-Closed Loop	Drive to test route		
	Use settings of 200 lbs/mile and drive at 20 MPH		
	Stop at midpoint on the route		
	Use settings of 200 lbs/mile and drive at 20 MPH		
	Turn around at the end of test route (2.66 miles)		
	Use settings of 200 lbs/mile and drive at 30 MPH		
	Stop at midpoint on the route		
	Use settings of 200 lbs/mile and drive at 30 MPH		
	Turn around at the end of first loop and drive 2nd loop using above conditions		
	Weigh truck at the end of 2nd loop		

Mode of Operation	Activity	1st loop	2nd loop
Sixth Scenario-Closed Loop	Drive to test route		
	Use settings of 200 lbs/mile and drive at 20 MPH		
	Stop at midpoint on the route		
	Use settings of 200 lbs/mile and drive at 20 MPH		
	Turn around at the end of test route (2.66 miles)		
	Use settings of 200 lbs/mile and drive at 30 MPH		
	Stop at midpoint on the route		
	Use settings of 200 lbs/mile and drive at 30 MPH		
	Turn around at the end of first loop and drive 2nd loop using above conditions		
	Weigh truck at the end of 2nd loop **(Reload truck and weigh)**		
Seventh Scenario-Closed Loop	Drive to test route		
	Use settings of 400 lbs/mile and drive at 20 MPH		
	Stop at midpoint on the route		
	Use settings of 400 lbs/mile and drive at 20 MPH		
	Turn around at the end of test route (2.66 miles)		
	Use settings of 400 lbs/mile and drive at 30 MPH		
	Stop at midpoint on the route		
	Use settings of 400 lbs/mile and drive at 30 MPH		
	Turn around at the end of first loop and drive 2nd loop using above conditions		
	Weigh truck at the end of 2nd loop		
Eighth Scenario-Closed Loop	Drive to test route		
	Use settings of 400 lbs/mile and drive at 20 MPH		
	Stop at midpoint on the route		
	Use settings of 400 lbs/mile and drive at 20 MPH		
	Turn around at the end of test route (2.66 miles)		
	Use settings of 400 lbs/mile and drive at 30 MPH		
	Stop at midpoint on the route		
	Use settings of 400 lbs/mile and drive at 30 MPH		
	Turn around at the end of first loop and drive 2nd loop using above conditions		
	Weigh truck at the end of 2nd loop **(Reload truck and weigh)**		

Mode of Operation	Activity	1st loop	2nd loop
Ninth Scenario- Manual Mode	Drive to test route		
	Use settings of 400 lbs/mile for 30MPH and drive at 20 MPH		
	Turn around at the end of test route (2.66 miles)		
	Use settings of 400 lbs/mile for 30 MPH and drive at 30 MPH		
	Turn around at the end of first loop and drive 2nd loop using above conditions		
	Weigh truck at the end of 2nd loop		
Tenth Scenario-Close Loop	Drive to test route		
	Use settings of 400 lbs/mile and drive at 20 MPH		
	Turn around at the end of test route (2.66 miles)		
	Use settings of 400 lbs/mile and drive at 30 MPH		
	Turn around at the end of first loop and drive 2nd loop using above conditions		
	Weigh truck at the end of 2nd loop		

DATA LOG FORM FOR IOWA

Date:_______________

First Scenario- Manual Mode
Test Parameter: 200 lbs/mile for 30 MPH
Drive: 20 MPH and 30 MPH

	Begin	**Ending**	**Net**
Time:	____________	____________	____________
Weight:	____________	____________	____________
Revolution:	____________	____________	____________

Second Scenario- Manual Mode
Test Parameter: 200 lbs/mile for 30 MPH
Drive: 20 MPH and 30 MPH

	Begin	**Ending**	**Net**
Time:	____________	____________	____________
Weight:	____________	____________	____________
Revolution:	____________	____________	____________

Third Scenario- Manual Mode
Test Parameter: 400 lbs/mile for 30 MPH
Drive: 20 MPH and 30 MPH

	Begin	**Ending**	**Net**
Time:	____________	____________	____________
Weight:	____________	____________	____________
Revolution:	____________	____________	____________

Fourth Scenario- Manual Mode
Test Parameter: 400 lbs/mile for 30 MPH
Drive: 20 MPH and 30 MPH

Begin **Ending** **Net**

Time:____________________ __________________ _____________

Weight: ____________________ __________________ _____________

Revolution: __________________ __________________ _____________

Fifth Scenario- Closed Loop Mode
Test Parameter: 200 lbs/mile
Drive: 20 MPH and 30 MPH

Begin **Ending** **Net**

Time:____________________ __________________ _____________

Weight: ____________________ __________________ _____________

Revolution: __________________ __________________ _____________

Sixth Scenario- Closed Loop Mode
Test Parameter: 200 lbs/mile
Drive: 20 MPH and 30 MPH

Begin **Ending** **Net**

Time:____________________ __________________ _____________

Weight: ____________________ __________________ _____________

Revolution: __________________ __________________ _____________

Seventh Scenario-Closed Loop Mode
Test Parameter: 400 lbs/mile
Drive: 20 MPH and 30 MPH

Begin **Ending** **Net**

Time:_____________________ _________________ _____________

Weight: ___________________ _________________ _____________

Revolution: _________________ _________________ _____________

Eighth Scenario-Closed Loop Mode
Test Parameter: 400 lbs/mile
Drive: 20 MPH and 30 MPH

Begin **Ending** **Net**

Time:_____________________ _________________ _____________

Weight: ___________________ _________________ _____________

Revolution: _________________ _________________ _____________

Ninth Scenario-Manual Mode
Test Parameter: 400 lbs/mile for 30 MPH
Drive: 20 MPH and 30 MPH

Begin **Ending** **Net**

Time:_____________________ _________________ _____________

Weight: ___________________ _________________ _____________

Revolution: _________________ _________________ _____________

Tenth Scenario-Closed Loop Mode
Test Parameter: 400 lbs/mile
Drive: 20 MPH and 30 MPH

	Begin	**Ending**	**Net**
Time:	____________________	________________	____________
Weight:	__________________	________________	____________
Revolution:	________________	________________	____________

Comments:

APPENDIX O
MANUFACTURER'S RECOMMENDATIONS FOR CALIBRATION

Manufacturer's Recommendations for Calibrating

Manufacturer and Model of Controller:

Calibration for What Mode of Operation: (Closed-Loop), (Open-Loop), (Manual)

ANS – addressed but not specific**, NA –** not addressed

Factors in Calibration Process	**Solid (dry) Material**	**Liquid Pre-wetting Material**
Truck Speedometer and Controller Distance Measurement Check		
Specify minimum distance traversed. *(miles/feet/**ANS/NA)***		
Accuracy of the established distance. *(specify accuracy**/ANS/NA**)*		
Is the speed output of controller cross checked with the truck speed? *(yes-how?/no/**ANS/NA)***		
Truck and Spreader Hydraulic System		
Warm truck and hydraulic system to specified temperature or for a certain period of time. *(specify temp/specify time/**ANS/NA)***		
Specify upper limit of hydraulic oil temperature during test. *(specify temp/ **ANS/NA)***		
Specify <u>ALL</u> control functions that need to be engaged during testing, i.e., solid conveyor, liquid chemical pumps, spinners, etc. *(list all functions/ **ANS/NA)***		
RPM of truck during testing. *(specify RPM/ **ANS/NA)***		
Specify range of trim settings. *(specify min and max/ **ANS/NA)***		
Does the unit regulate fluid flow in continuous or step increments? *(continuous/step/both/ **ANS/NA)***		

Material Spreader, Hopper, Truck Body, Gates and Augers		
Recommended load level in truck box or hopper box. *(specify percent full/* ***ANS/NA)***		
For tailgate spreaders, specify box position. *(lowered/raised, and to what level?* ***ANS/NA*** *)*		
Gate opening for full range of desired application rates. *(specify height of opening/* ***ANS/NA)***		
Straightness (level) of gate and how opening is measured (from where to where). *(specify procedure/* ***ANS/NA)***		
Recommended auger or conveyor speed for uniform output. *(specify speed/* ***ANS/NA)***		
Proper auger discharge plate for material being tested. *(specify plate configuration/* ***ANS/NA)***		
Material to be Tested		
Representative and uniform. *(specify how determined/* ***ANS/NA)***		
Relatively lump free. *(specify how determined/* ***ANS/NA)***		
Free of excessive moisture. *(specify how determined/* ***ANS/NA)***		

"Catch" or "Drop" Tests		
Recommended amount of materials discharged. *(lbs./ ozs/ **ANS/NA**)*		
Recommended duration of discharge. *(specify time (sec)/specify no. of pulses/specify no. of revolutions/ **ANS/NA)***		
Recommended number of tests or other precision requirements. *(specify no. of tests/ **ANS/NA)***		
Tests conducted at high and low end of application rate range. *(yes/high end only/mid-range/ **ANS/NA)***		
What are units of measure for calibration constants i.e., lbs/rev, pulses/lb, etc.? *(specify units/ **ANS/NA)***		
Does the unit allow for, or require, "fine tuning" to meet customer expectation and how is this accomplished? *(yes-specify procedure/no/ **ANS/NA)***		
Recommend aborting test if discontinuity in flow of material discharge is observed? *(yes/no/**NA**)*		
If unit features the hydraulic valve going to full open when the truck starts moving, do you recommend that the duration of that period of full open be at the least adjustable level? *(yes/no/ **ANS/NA)***		

Calibration Frequency and Record Keeping		
Recommended frequency of calibration. *(specify frequency/specify conditions for calibration/* ***ANS/NA)***		
Recommendations for creating and maintaining repair and calibration records. *(specify recommendations/* ***ANS/NA)***		
Items Unique to the Liquid Prewetting Calibration of the Controller		
Specify ALL control functions that need to be engaged during calibration of liquid prewetting system i.e., solid conveyor, liquid chemical pumps, spinners, etc. *(list all functions/* ***ANS/NA)***		
Does solid material need to be discharged during liquid calibration? *(yes/no/* ***ANS/NA)***		
Nozzles in liquid discharge line during calibration testing? *(yes/no/* ***ANS/NA)***		
Type of pump used with prewetting system. *(electric, hydraulic, either electric or hydraulic/* ***ANS/NA*)**		
Can water be used to calibrate the liquid portion of the system in place of the normal liquid chemical used by the agency during winter operations, if so, why? *(yes – why?/no-why?/unknown/* ***ANS/NA)***		

CLEAR ROADS

research for winter highway maintenance

Lead state:
Wisconsin Department of Transportation
4802 Sheboygan Ave.
P.O. Box 7965
Madison, WI 53707-7965