Development of New Test Roller Equipment and Construction Specifications for Subgrade Compaction Acceptance

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16. Abstract (Limit: 250 words)

The current test rolling program as used by Mn/DOT is in need of an update and/or supplement to existing equipment, procedures and specifications. The traditional roller is very heavy and cumbersome and the current construction specification is not technically based. Due to the heavy weight, the roller is only appropriate in approving lifts that are three to four feet thick. While this is ideal for large projects where thick lifts are to be evaluated, most projects do not need this magnitude of loading. This implementation project has developed a more adaptable test roller system and an appropriate construction specification for this modified system. The new test roller and construction specification allow for variation in the weight applied, which will allow varying site conditions to be tested. Such a system would be especially appropriate for roadways that are designed for less than 10 ton loads. This system is easily transported, such that mobilization will be more efficient, and data are continuously recorded during test rolling. The modified test roller is an instrumented system mounted on a standard dump truck. A new test specification has been proposed for the new system and deflection criteria have been established for several combinations of subgrade types and roller weights. The results of the project have also provided a method for comparing pavement structures and layer properties as constructed to their intended design, linking roller deflections to pavement performance. The new system has been utilized on several regional projects and has been shown to work effectively.

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Final Report

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Executive Summary

The overall purpose of this implementation project was to develop a new test rolling system and an associated construction test specification that can be utilized by Mn/DOT to accept compacted subgrades on construction projects. This development has been accomplished and a functional system and specification have been produced.

The initial task associated with this project was to implement the critical findings of the study conducted by the University of Minnesota in product and specification development. Hambleton and Drescher (2008) came to the following conclusions appropriate to this implementation project, in addition to a number of additional conclusions:

- Test rolling has the potential to be a very successful tool for characterizing mechanical properties of soils with a continuous record of measurement.
- Since much of the deformation induced by a test roller is permanent, this deformation is to be associated with soil failure rather than elastic compression. The conclusion of the authors was that test rolling should not be used to evaluate elastic parameters such as resilient modulus. However, test rolling was perceived to be a practical way of obtaining continuous strength properties.
- Wheel flexibility can influence sinkage significantly and should be taken into account in the analytic (and/or numerical) model(s).
- Validation of the models should ultimately be done using well-controlled field tests of a test rolling system.

The Hambleton and Drescher study (2008) also included a number of recommendations. These may be summarized as follows:

- Light weight deflectometers and/or intelligent compaction systems should be used to determine elastic properties rather than test rolling.
- The models developed should be considered to be approximate until they can be validated with experimental data.
- Test rollers with different weights and wheel configurations can give similar results. A heavy wheel load with a large wheel contact area can yield results similar to a small load on a smaller wheel area. The influence depth will be less, however, for the smaller wheel/load combination.
- Rigid wheels would be preferred to flexible wheels for test rolling applications. A stiff pneumatic tire with appropriate inflation pressure can approximate a rigid wheel.
- A test roller wheel should travel ahead of the driving wheels, as when using the front axle of a standard dump truck as a test rolling device.

Based on the Hambleton and Drescher (2008) study and using the analytic model developed therein, sinkage was estimated for the prototype test rolling system for the expected wheel geometry and wheel loads anticipated for various soil strengths. Assuming the wheel flexibility coefficient of 3.5 inches per ton (0.01 m/kN) as estimated for the existing test roller also applies to a standard wheel on a dump truck, and using a density of 20 kN/m^3 and wheel dimensions for a 385/65R22.5 tire (overall diameter = 1.072 m and overall width = 0.379 m), a table was developed that provides the sinkage expected for various soil strengths and wheel loads.

This implementation project included an effort to correlate the sinkage of the new test roller vehicle's tire to eventual pavement performance after the entire pavement is constructed, an evaluation of the effects of inadequate subgrade compaction on pavement performance, and an application of these results to the development of the new test roller equipment and the updated test rolling specification.

The analysis contained in this report relative to the correlation of tire sinkage and pavement performance indicated that while such a correlation may be possible, it can be very difficult and requires field testing to determine the "soil sinkage parameters" as described in this report. As a result, the concept of correlating tire sinkage to soil strength and stiffness properties and thus to pavement performance was divided into two analyses – allowable sinkage and the correlation between soil properties and pavement performance.

The draft construction specifications contained in this report, and developed by the project team and Office of Grading and Base, indicate a maximum allowable sinkage of 0.6 to 0.9 inch for granular material to be covered by stabilizing aggregate, and 0.4 to 0.6 inch for all other materials. For reasonable soil properties and tire loads, the actual expected sinkage values are estimated to be somewhat lower for granular materials (and ranging from lower to somewhat higher for other materials) than those allowed in the specification. For granular materials, then, the specification will allow slightly more sinkage than expected, to compensate for variability in subgrade soils, and in acceptable levels of compaction.

The analysis of effects of compaction on pavement performance had greater success, and multiple models were combined with the MnPAVE software to conduct pavement performance computations. The results of this analysis include a model relating the resilient modulus ratio (as-constructed / as-designed) and the subgrade's R value to the expected increase in pavement rutting damage.

The relative impact on pavement performance was not correlated with the levels of ESALs for which a pavement is designed nearly as much as with the R-value of the subgrade and the combination of other soil properties which make up the resilient modulus ratio component. In general, as the ratio of as-constructed to as-designed resilient modulus decreases, the expected increase in rutting damage increases almost linearly. In addition, soils with a higher R-value will experience a steeper relationship between modulus ratio and increased rutting damage.

The analyses conducted as part of this project are important in relating the new test roller equipment to the revised construction specifications and in providing a meaningful understanding of the pavement performance expected for a given subgrade density. Although other construction specifications require certain levels of compaction and soil density, the density-performance relationship developed as part of this project provides an important link between the components of design, construction, and performance.

With the new test roller equipment, field engineers and contractors are able to test roll the subgrade more often and at lower cost in both time and money. At each desired test interval, a comparison can be made to the allowable sinkage (and effects on pavement performance related to compaction and density). Thus, intermediate lifts can be tested more easily and problem areas can potentially be identified earlier than by testing at the final elevation of the grading grade.

The correlation of soil type, wheel load, and wheel dimensions helps Mn/DOT be more comfortable in the levels of allowable sinkage required by the revised specification. Although additional verification and validation should be conducted on future grading projects, and the allowable sinkage levels may need to be adjusted, the basic theory and analysis are sound, and will support modification suggested by additional field testing.

Since initial discussions of this project began, several possible systems were discussed. The final consensus of the TAP group was to develop a truck-mounted system having two ultrasonic sensors mounted to the front axle of a dump truck to measure displacement. A GPS antenna is part of the system so displacements measured can be associated with GPS coordinate positions to sub-meter accuracy. A data acquisition system allows data entry to provide site and test roller/truck identification. A "rolling zero" of the system can be performed on a smooth, "rigid" (bituminous or concrete pavement) material to initialize the system. After this zeroing of the system, the roller can be used to test the section of interest. Once test rolling is complete, the data can be stored and uploaded by a USB connection to identify problem areas based on the failure criteria appropriate for the site, material, and roller conditions.

This modified test roller system has been developed and implemented on several projects at this time. The deflection model developed by the University of Minnesota has been evaluated on a limited number of projects to date. It appears that the limits proposed in the draft specification will be reasonable and applicable to the subgrade soils anticipated. Additional validation of these criteria will be needed as the roller system is implemented on additional projects with varying materials and axle weights. The prototype fabricated, while not perfect, seems to do a nice job in recording data for projects, which allows quick and continuous deflection profiles for projects. This data can be stored and reviewed during the course of pavement monitoring and maintenance to identify potential points of concern where marginal subgrade response was experienced. Recommendations to improve future versions of the system have been included in this report. Overall, using this system or a similar tool, Mn/DOT will be able to gain much more information during the course of roadway construction that can be beneficial for many projects in the future.

1 Introduction

1.1 Scope of Project

The overall purpose of this implementation project is to develop a new test rolling system and an associated construction test specification that can be utilized by the Minnesota Department of Transportation (Mn/DOT) to accept compacted subgrades on construction projects. The initial task of the project (Task 1) involved implementing some of the findings of a study by the University of Minnesota (Hambleton and Drescher, 2008) in the development of the new test roller system and associated construction specifications for this project. The results of the study at the University of Minnesota have provided a relationship between the load applied to the subgrade by both rigid wheel and pneumatic tire test rollers and the permanent deflection due to this load. The model developed at the University of Minnesota has been reviewed and modified, as appropriate, to meet the needs of this project with respect to tire diameter, axle load, etc. This adjusted model was used in Task 2 to establish deflection criteria for a range of conditions.

Minnesota State University (MSU) and Mn/DOT personnel have worked together to determine which components of the University of Minnesota's project were applicable to this test roller implementation project. Chapter 2 will summarize which information has been incorporated into the test roller and specification development and which was not, with additional discussion as to the reason for this.

The correlation of tire sinkage at the top of a compacted subgrade to long-term pavement performance is a key component of this project. Two distinct analyses are presented in Chapter 3 – the allowable sinkage beyond which the subgrade should be reworked, recompacted, and retested, and the correlation to performance on uniformly compacted subgrade. The first analysis consists of correlating the test roller tire sinkage with problems in the quality of compaction. This may be due to inadequate compactive effort, improper moisture content, or both. In either case, the test roller tire sinks into the surface of the subgrade material significantly more than in other locations where the compaction is adequate.

The first section of Chapter 3 is an analysis of allowable sinkage (of the test roller tire into the compacted subgrade). In most cases, the compacted subgrade will be uniform and the tire will sink a nominal amount due to the concentrated load of the tire on the surface. The first test is to determine what the allowable sinkage can be for a particular subgrade soil. If the sinkage is within the allowable limits, additional analysis can be conducted to correlate the density and other properties of the soil with expected pavement performance. If the sinkage exceeds allowable limits, the area where this sinkage occurred should be reworked and recompacted, and thus is not subject to the additional analysis.

There are several steps required in the correlation of subgrade soil properties to ultimate pavement performance, each of which brings its own level of variability and uncertainty into the results. Chapter 3 describes the development of a procedure for estimating the impact of (uniformly) lower quality subgrade compaction on the ultimate performance of the final pavement structure. The two analyses – “allowable sinkage” and “performance correlation” – are described in the remaining sections of this chapter.

As discussed, the overall purpose of this implementation project was to develop a new test rolling system and an associated construction test specification that can be utilized by the Mn/DOT to approve compacted subgrades on construction projects. Chapter 4 presents the development process used to identify the specifications/requirements for the test roller system which would meet Mn/DOT's needs and expectations such that development of the prototype could proceed (Chapter 5.) Minnesota State University (MSU), Kessler Soils Engineering Products, Inc. (KSE) and Mn/DOT personnel worked together to develop the device parameters and specifications for the equipment, software (for data collection, storage and presentation) and test/validation procedures. Representatives from KSE traveled to Minnesota to discuss the expectations and needs of Mn/DOT and to obtain measurements for the standard dump trucks in order to design appropriate instrumentation for the prototype test roller (as per Chapter 5). Chapter 4 summarizes the specifications outlined by Mn/DOT which were incorporated into the prototype test rolling system.

The next task was to develop a trial/prototype system for the truck-mounted test roller. The system developed can be mounted on a standard dump truck, such that deflection measurements and a GPS package can record roller deflections as a function of position. This system is adaptable such that it can be utilized on several available dump trucks. Such a system is significantly more flexible than the existing roller and advantageous with respect to mobilization and safety concerns experienced with the existing roller. The benefits of having continuous recorded data as a function of position from a construction site are also significant, as recorded data may be referenced in the future as pavement performance monitoring and maintenance continues.

The truck-mounted system includes the following:

- GPS capability
- Microprocessor
- Deflection measurement devices
- Software for data collection, storage and presentation
- X, Y, ΔZ deflection data in tabular format

After the system had been developed, the project team brought the prototype to Minnesota (August 2008) to demonstrate the equipment. Chapter 5 displays the components of the system, the user interface of the software, and the results of the testing/demonstration of the new equipment.

This next task was to validate the system which had been developed for the truck-mounted test roller. During the course of and subsequent to that initial demonstration and evaluation, several modifications to the system were recommended by Mn/DOT and project personnel and changes to the system were implemented in the prototype during the winter and spring (2008-2009). Several changes in the text and output in the user interface, modifications to the data collection frequency and algorithm, and other recommendations were incorporated into the prototype.

During the following construction season (summer 2009), arrangements were made for using the test roller at three sites; Highway 14 expansion near Waseca (Susan Museus), Cottonwood County (Ron Gregg) and Scott County (Mitch Rasmussen). It was desired to test multiple sites with several soil subgrades in order to ensure that the modified system functioned as intended and desired, along with allowing the deflection model to be validated.

The system was used effectively on the TH 14 expansion project. Results from that project are included in Chapter 6. However, the two additional projects were delayed (due to a combination of contracting delays and adverse weather conditions) until the following (2010) construction season. The hardware and software have been shown to be primarily acceptable with the validation to date. Additional opportunities to validate the deflection model were pursued during the 2010 construction season. While several previously identified projects did not implement the new test roller system, the implementation was successful on a project with Olmsted County County State Aid Highway (CSAH) 10 reconstruction. This implementation will be included in Chapter 6, as well.

In conjunction with this new test roller system, the final task was to develop an appropriate construction specification for this system. The new roller allows for variation in the weight applied, which will allow varying soil and site conditions to be tested. Such a system would be more appropriate for CSAH routes that are designed for less than 10 ton loads, along with other cases when thinner lifts/layers are to be evaluated. The new test specification has been developed for the new system such that deflection criteria for a range of roller weights has been compiled for both plastic and granular soils, allowing more appropriate criteria to be addressed on a case by case basis. Overall, an improved test roller and testing specification has been developed that will improve the effectiveness and flexibility of Mn/DOT's testing program.

2 University of Minnesota Study

The research conducted by the University of Minnesota included several main components. The first task was to review the literature to determine what models are currently available to predict subgrade deformations due to wheel loads and the subgrade-wheel interaction. The second task involved developing two models (one by analytic method and one by numerical analysis) that could be used to predict deflections under such wheel loads. The third task involved a parametric study of each of these models to determine which inputs are most influential in the model. The final task was intended to be a validation of these models by full-scale testing and/or scaled model testing. Each of these tasks will be briefly addressed and summarized, along with a discussion of how the task relates to the implementation project.

2.1 Task 1 – Analysis of Previous Findings (Hambleton and Drescher, 2008)

As mentioned, Task 1 was a literature review designed to provide insight with respect to the current understanding and application of test rolling, along with any models available at present to relate roller and subgrade properties to deformation under the wheel load. It was noted that the state of practice of test rolling varies significantly throughout the United States, but that most states with a test roller program in practice utilize "a heavily-loaded dump truck" with pneumatic tires "with a total weight of 20 to 40 tons" to perform such test rolling (page 5 of Hambleton and Drescher, 2008). Current Mn/DOT practice uses a two-wheeled roller with a wheel load of 30,000 lbs (134 kN), which is substantially higher than most other states. The deflection criteria for various states range from 0 inches to 3 inches (0 mm - 75 mm), based primarily on the discretion of the project engineers. Mn/DOT's specification requires sinkage to be less than 2 inches (50 mm) for all soils. One additional inch (so, < 3 inches (75 mm) sinkage) is allowed in granular soils that are to be stabilized after test rolling. In all cases, it appears that the justification for such values is very limited, again being based more or less on past precedent and engineering judgment.

The Wisconsin DOT concluded a study several years ago (Crovetti 2002) that provided recommendations for sinkage requirements for a loaded dump truck being used as a test roller. This study proposed that sinkage measured at the wheels of the front axle of a standard quad-axle dump truck with a wheel load of 12,000 lbs (53 kN) should not exceed 1.5 inches (38 mm) with a tire pressure between 110 and 125 psi (760 kPa and 860 kPa). Crovetti concluded that such a test rolling system is effective in identifying weak material within 12 inches (30 mm) of the surface.

The conclusion that many states use loaded dump trucks as test rollers (in spite of the variability in the acceptance criteria) and that such rollers can detect weak layers within the top 12 inches (30 mm) are important for this project, since the recommended system to be developed is a truck-mounted system with measurements taken at the front axle. Although the depth of influence is relatively small when compared to the existing test roller system (which is not to be used to check thicknesses less than 30 inches (0.76 m)), this can be an advantage and will be accounted for in the construction specifications.

Bevameter Tests and Cone Penetrometer tests were discussed with reference to the Terramechanics discipline. However, these tests were not considered useful for the current implementation project.

A large number of papers and references were discussed relating to studies of subgrade-wheel interaction. As mentioned in Hambleton and Drescher (2008), with the exception of the WisDOT study (Crovetti 2002), only a few of these projects were specifically intended to examine test roller deflection applications. Wheel stresses, soil stresses, soil flow zones, rolling resistance and other related information were investigated, but the relationship between wheel load and deflection was not directly addressed in many of the studies.

Some studies did provide useful information relating to implementation of a new test roller system. For example, the study by Çarman (1994) investigated the effect of vehicle speed on sinkage values obtained. In the velocity range of 1.7 to 5.6 miles per hour (2.7 to 9.0 km/h), the higher the speed of the vehicle the smaller the measured sinkage of the subgrade. This will be addressed in the construction specification for the new test rolling system. However, it was also noted that the influence of the speed of the vehicle was small compared to the effect of the wheel load, such that specifying the wheel load will be more critical than extensively outlining the required vehicle velocity.

Another study by Arvidsson and Ristic (1996) provided some additional points of interest with respect to the implementation project. This study was focused on the influence of tire pressure on rut depth and profile, among other things (penetration resistance, subgrade stresses, etc.) A 5,700 lb (25 kN) wheel load applied by a standard pneumatic tractor tire (four tires used, including a 24 inch (600 mm) wide Michelin XM 108 600/65 R 38). For such tires, with loads from 8.7 psi (60 kPa) to 20.2 psi (140 kPa), subgrade stresses were measured from depths of 8 to 16 inches (0.20 to 0.40 m) beneath the tire and up to 11 inches (0.28 m) from the centerline of the tire. This applies most directly to the development of the new test rolling system and specification, such that placement of the deflection sensors will need to be outside some minimal distance from the centerline of the tire.

The final section of the Task 1 Summary report related to the various sinkage models available in the literature. These included empirical models, analytical models and numerical models. The empirical models are predominantly based on the bevameter tests briefly mentioned earlier. Three subgrade parameters are determined based on plate-sinkage tests performed, and deflections can be predicted based on these subgrade parameters for a range of loadings. The question as to the validity of such plate tests compared to a rolling wheel was discussed, and the conclusion that such an empirical relationship is not practical with respect to test rolling was made.

The analytical models showed more promise with respect to test rolling applications. While the empirical models do incorporate empirically determined constants relating to soil stiffness, the analytical models have been developed based on elastic and plastic soil parameters. Models such as Evans (1964), Hetherington and Littleton (1978), and Kim and Shin (1986) used bearing capacity theory to provide the relationship between applied pressure and sinkage. The University of Minnesota study would further investigate the application of such models to test roller theory.

A number of numerical (finite element method) models were reviewed in the literature review. The advantage of these models is that they can incorporate both strength and stiffness values based on actual soil parameters. Of course, this requires knowing such parameters to include them as inputs to the model, and there can be a level of uncertainty (and/or variability) in some of these parameters, especially in field applications. In the simplest models, basic strength, stiffness and/or material properties result in a reasonable number of input parameters. In more complex models, elastic, plastic, and viscous parameters alone might yield six parameters (as with Chung and Lee 1975). A 1990 study by Saliba used the finite element method to model the subgrade using five parameters, which included the modulus of elasticity, Poisson's ratio, the internal friction angle of the soil, the cohesion of the soil, and a fluidity parameter to address viscous properties of the soil. Many studies were discussed briefly, but few of the studies had been performed to specifically model sinkage as a function of wheel load for the desired application. It was proposed, however, that the study develop a finite element model in ABAQUS that could be used to develop such a relationship. However, the researchers were quick to admit that there are certain difficulties in using the finite element method for numerical analyses due to "numerical limitations and possible errors resulting from operating with highly nonlinear numerical schemes" (page 25 of Task 1 Summary Report by Hambleton and Drescher), and that these challenges would be difficult to overcome in developing an accurate model.

2.2 Task 2 – Theoretical Models (Hambleton and Drescher, 2008)

The second task in the University of Minnesota study was to develop models for test rolling based on the information obtained from the initial literature review. An analytical model was developed based on traditional bearing capacity theory. The ABAQUS finite element code was also used to develop a numerical model to simulate test rolling conditions. The full discussion of each of these models can be found in the Hambleton and Drescher final report (2008).

2.2.1 Analytic Method

For the analytical model, the subgrade soil was assumed to be a rigid-perfectly plastic material. This means that there is no strain in the material until the yield stress is reached, at which point deformation (strain) continues with no change in stress due to strain hardening or strain softening. The Mohr-Coulomb yield criterion was used to replace the yield stress, such that the internal friction angle (ϕ) and the cohesion (c) of the material will be included in the model. The unit weight will be the final input parameter for the model.

As mentioned earlier, the analytic method is based on Karl Terzaghi's Bearing Capacity theory (Terzaghi 1943), which was developed to analyze an infinitely long strip footing subjected to a distributed load. Meyerhof (1963) modified Terzaghi's formula to address rectangular footings and account for capacity due material above the embedment depth of the footing, among other things. The bearing capacity formula is available through almost all geotechnical references and will not be repeated here. Suffice it to say that the formula includes three terms to address soil capacity as a function of the soil unit weight, the friction angle, the cohesion, and the original bearing capacity factors along with shape, depth, inclination and other factors, as appropriate. Given these values, for a given set of soil parameters the ultimate capacity of the soil can be estimated.

Hambleton and Drescher (2008) continue to present the concept of rigid wheel indentation (as opposed to pneumatic tires), which they propose is the most realistic application when using bearing capacity theory models in the test rolling sphere. Granted, from a theoretical standpoint the rigid wheel is more readily evaluated and better supported by bearing capacity theory. However, from a practical standpoint, developing a test roller that utilizes a rigid wheel becomes more problematic and expensive. Since Mn/DOT recommends developing a pneumatic tire system (for a dump truck mounted test rolling device), the discussion of rigid wheel behavior is not warranted at this time. For further discussion of the indentation of a right-circular wheel and a toroidal wheel and evaluation of a rigid wheel rolling using the inclined load method or the inclined footing method, please refer to the Hambleton and Drescher (2008) report.

The next discussion of interest relates to the indentation of a flexible wheel, such as the pneumatic wheels which are to be used in the truck-mounted test roller implementation for this project. For such wheels, both the tires and the soil deform due to the load on the tire. One approach is to determine an equivalent diameter d_e of the deformed tire to better indicate the contact area of the tire for a given load. Of various possible methods available, for simplicity and without any observed basis for a different approach, a linear relationship between this equivalent diameter, the original diameter and the wheel load was proposed, which included a wheel flexibility coefficient, λ_i. This proposed relationship was given in the following form:

$$d_e = d + \lambda_i Q_v$$ **Equation 2.1**

The contact area under the pneumatic tire then becomes a function of this equivalent diameter (or, the contact length based on this equivalent diameter and the sinkage) and the width of the tire. Using these values of contact length (a function of sinkage, tire diameter, tire load and wheel flexibility coefficient) and tire width in the bearing capacity equations as the footing length and width for a rectangular footing, Hambleton and Drescher (2008) develop a relationship between wheel load and sinkage, as provided in Equation 3.63 and Equation 3.64 on page 47 of the report. Although not a simple relationship to approach using hand calculations, this equation can be solved readily using a spreadsheet or similar calculation tool, as developed by Hambleton as part of the project.

Once the indentation relationship was established, Hambleton and Drescher (2008) modified the relationship to account for the flexible wheel rolling by applying the inclined footing approach as presented for the case of a rigid wheel. The relationships and theory are essentially the same as with the indentation relationship, except that a modified "rolling wheel flexibility coefficient" (λ_r) was used in providing the equivalent diameter and incorporating the modified inclination factors into the bearing capacity relationship. The relationships for the rolling flexible wheel are provided in Equation 3.71 and Equation 3.72 in the Hambleton and Drescher report (2008).

At the recommendation of the Technical Advisory Panel for this implementation project, this relationship between the sinkage of a rolling flexible wheel was applied to the test roller specification development (in association with Task 2, Task 5 and Task 6) in order to establish acceptable deformations for given wheel loads on various subgrade materials.

2.2.2 Numerical Simulation

The University of Minnesota study considered three potential software packages to use for the numerical modeling portion of the project. Eventually, ABAQUS/Explicit was used to develop a model to simulate test rolling. Similar evaluations were performed to those conducted for the analytic model, including indentation of a rigid wheel, a rigid wheel rolling, pneumatic (flexible) tire indentation, and a pneumatic tire rolling.

Although certainly very comprehensive and thorough evaluations, from a practical standpoint Mn/DOT will not be able to use such models due to the necessary software and computation time involved and also the need to have a strong working knowledge of ABAQUS and it's associated input parameters. However, based on this model (and as can be demonstrated in Figure 2.1 and Figure 2.2, after Hambleton and Drescher, 2008) it can be seen that the effects of bulging near the tire are limited to a distance of approximately one tire width from the edge of the tire. This is true in both the case of the rigid wheel (Figure 2.1) and the pneumatic wheel (Figure 2.2). This information will be incorporated into the prototype test roller with respect to appropriate sensor locations for measuring displacements.

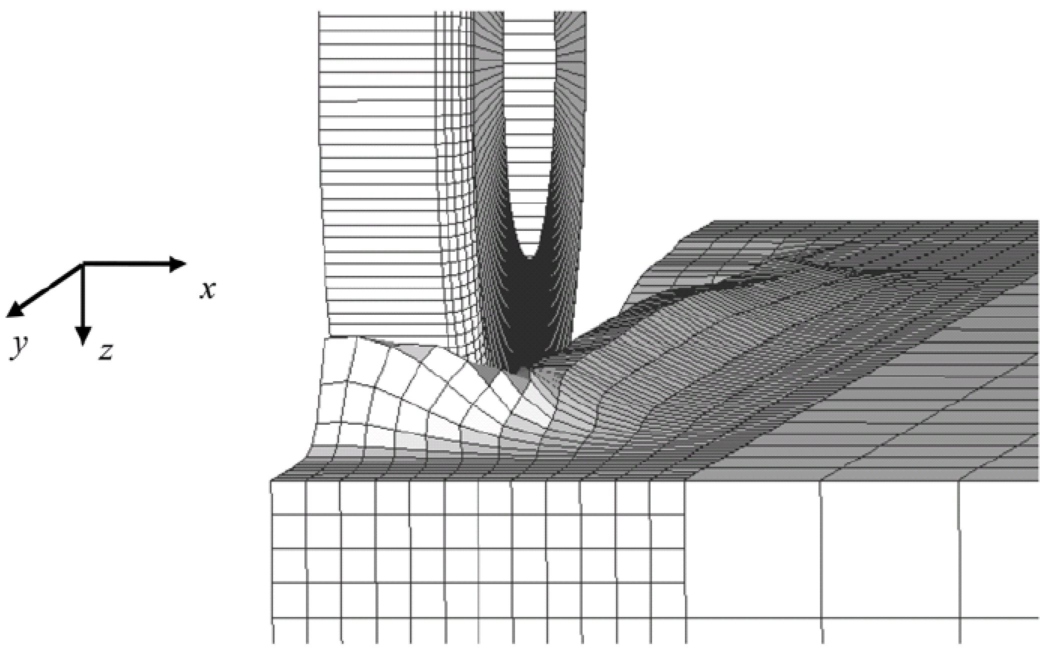

Figure 2.1. Example of Soil Deformation Near Wheel in Numerical Simulation of Rigid Wheel Rolling (after Hambleton and Drescher, 2008).

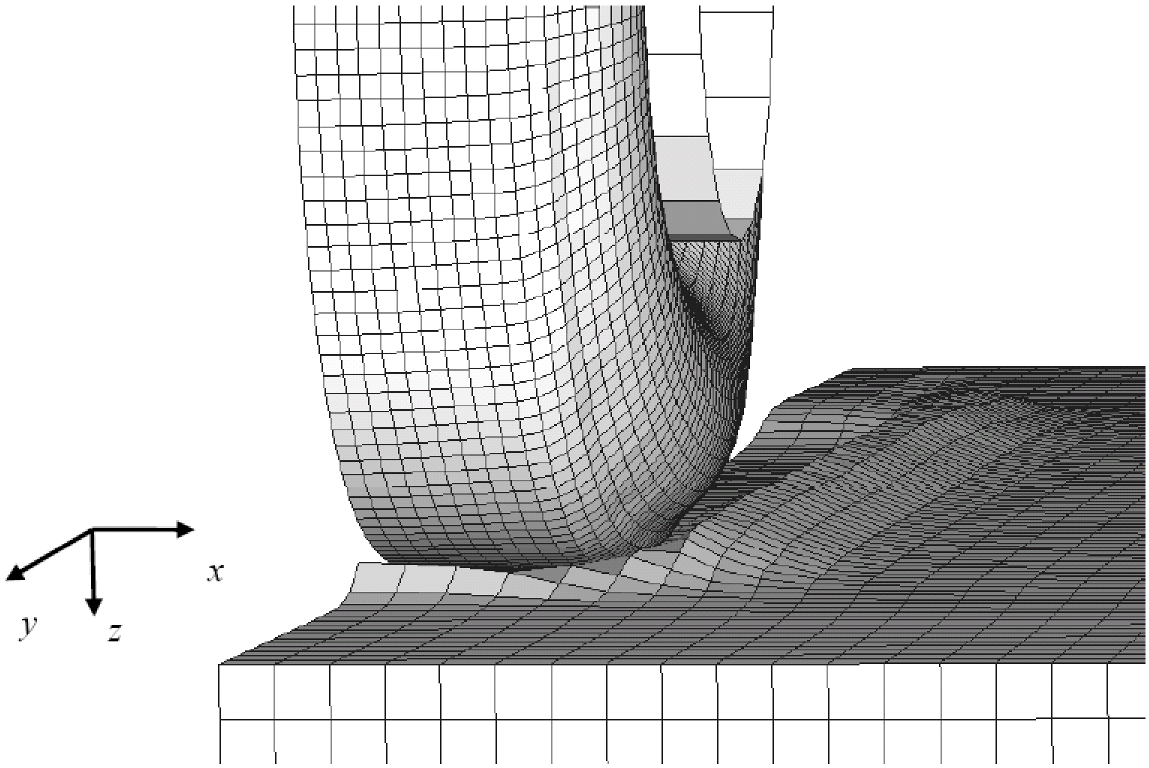

Figure 2.2. Soil Deformation Near Wheel from Simulation of Pneumatic Tire Rolling (after Hambleton and Drescher, 2008).

2.2.3 Additional Information from Task 2

Subsequent sections of the Task 2 portion of the study related to the effects of layering on the various models. Since, based on results of both the University of Minnesota study and the Wisconsin DOT study (Crovetti 2002), the influence depth for a pneumatic-tired roller for a reasonable wheel load is on the order of 18 to 24 inches (0.46 to 0.61 m), a recommendation will be developed for the new test rolling system to evaluate subgrades at a maximum thickness of 12 to 18 inches (0.30 to 0.46 m), to be established in the construction specification. With this in mind, the effects of layering are anticipated to be minimal. This is especially true when considering the fact that the TAP group requested additional evaluation and application of the analytic model, which does not easily account for the effects of layering. While the numerical models developed in ABAQUS can certainly accommodate layered systems, the fact that Mn/DOT will not be pursuing additional development of the ABAQUS model (coupled with the fact that minimal layering will be present in relatively thin lifts) means that additional discussion is not warranted.

2.3 Task 3 – Parametric Study and Sensitivity Analysis (Hambleton and Drescher, 2008)

The third task associated with this study was a parametric study of the models developed during the Task 2 work. This task was intended to quantify the effects of variation of such parameters as the applied wheel load, the geometry of the wheel, the soil properties, and any other input values. As in the development of the models in Task 2, the parametric study addressed both the indentation (static) models and the rolling models.

The authors note that the parametric analysis considered a rigid, right-cylindrical wheel and did not address the flexible wheel models. This was followed by a statement that a "rigid (or nearly rigid) wheel is the preferred wheel type for test rolling, and it is believed that one of the foremost improvements to the current Mn/DOT test roller will be the change from a pneumatic tire to a rigid wheel. Wheel flexibility adds tremendous difficulty to the analysis and only obscures field measurements" (page 73 of Hambleton and Drescher, 2008).

In discussions during the course of the current test roller implementation project, although the possibility of developing a rigid-wheeled test roller was addressed, the prohibitive cost for such a system expected to have a relatively limited lifespan (due to the development of other technologies such as intelligent compaction) led to the pursuit of the less expensive option of a pneumatic-tired roller. The technical advisory panel felt that the "obscured" field measurements cited in the University of Minnesota study could still provide reasonable results when appropriate specifications were developed relating to the new system. Although significant effort is expected, development of a new flexible wheel test roller system that can provide useful evaluation of subgrade compaction and uniformity is realistic.

The study performed a parametric study for the rigid wheel models developed for both the analytic model and the numerical model. For the analytic method, the sinkage was shown to be a function of the wheel load, the wheel width, the contact length of the wheel (a function of the diameter of the wheel), the unit weight of the soil and the Mohr Coulomb strength parameters ϕ and c. Two relationships were originally developed: one for indentation and one for rolling. Since the rolling wheel with an inclined footing approach was considered more appropriate, this analytic model was further evaluated by the parametric evaluation.

For the ABAQUS model, there were additional parameters involved. In this case the sinkage was shown to be a function of the wheel load, the Drucker-Prager strength parameters (ϕ_{DP} and c_{DP}), the elastic parameters of the soil E_s and ν_s, the wheel width and contact length (again a function of the wheel diameter), the unit weight of the soil and the coefficient of friction between the soil and the wheel.

Hamberton and Drescher (2008) proceeded to outline reasonable soil and wheel parameters as available in practice and for the purposes of test rolling projects (see pages 76-77 of the report.) These data were provided in multiple tables in the report. Table 4.2 provides cohesive strengths for naturally occurring cohesive soils with a friction angle of zero. Values of cohesion ranged from 0 to 2 psi (0 to 14 kPa) for a very soft clay to 14 to 28 psi (96 to 192 kPa) for a very stiff clay, with higher values for hard clays. Table 4.3 reports friction angles for naturally occurring cohesionless soils with rounded or angular grains. For rounded grains the friction angle ranged from 28 degrees to 38 degrees for the range of loose to dense sands, where for angular sands the values ranged from 30 degrees to 45 degrees for loose to dense sands and up to 48 degrees for sandy gravel. Tables 4.4 and 4.5 show statistics on soils with a combination of cohesive strength and frictional strength from two studies. In these cases, the results of testing fine-grained soils yielded a mean friction angle of 36 degrees and a mean cohesion of 15 psi (100 kPa) while results of testing sand with fine particles gave a mean friction angle of 49 degrees and mean cohesion of 3 psi (20 kPa). Although obviously soil/site dependent, these values provide a reasonable range of strengths with which to predict deflections of a test roller for validation of the model.

Table 4.6 shows a similar range of values for Young's modulus for various soils (loose sand, dense sand, silty sand, soft clay and stiff clay.) As the analytic model is strength-based and not stiffness-based, values of Young's modulus are not required in the analytical deflection model. Such values would be necessary in the numerical model if such a model were pursued further.

Table 4.7 provides the range of material parameters considered in the University of Minnesota's parametric study of the analytic and numerical models of the test roller. These will be used in applying the University of Minnesota's analytic model to the test roller system to be implemented by Mn/DOT in order to validate this model and incorporate the deflections into specification acceptance criteria. Anticipated deflections for a test roller on various soils will be calculated based on the analytic model, and such deflections can be validated by field tests of the system. The material parameters suggested in Table 4.7 are provided in Table 2.1.

Table 2.1. Proposed Range of Material Parameters for Deflection Model Validation.

	c (psf)			ϕ (deg)		
Soil Type	min	typical	max	min	typical	max
Cohesive	3	15	30	0	30	50
Granular	0	3	7.5	30	45	60

Initially, two additional intermediate combinations of strength values will be included in the analysis to provide a better feel for the anticipated deflection behavior. Each combination of cohesion and friction angle will be subjected to several wheel loads to quantify the variation in deflection due to the wheel load. This will be applied further in developing the construction specifications for the new test roller system.

Results of the parametric study showed the following points:

- Sinkage drops substantially with small increases in cohesion in a nearly-cohesionless (predominantly frictional strength) material,
- Sinkage does not change substantially when increasing the friction angle in a primarily cohesive soil,
- Sinkage increases significantly with increased wheel load, ranging from 2 times (cohesionless) to 4 times (cohesive) the sinkage when doubling the wheel load, depending on the soil,
- The effect of soil unit weight on sinkage was minimal for predominantly cohesive soils, while significant for cohesionless soils.

These points were determined to hold valid for both the static indentation models and the rolling wheel models.

A parametric study was also performed for the numerical (ABAQUS) model. As previously, since the panel requested this implementation study to work with the analytic model rather than a numerical model, a thorough discussion of the results of the parametric study will not be provided in this report. However, several points are worth noting at this time:

- For most reasonable combinations of strength properties, the sinkage ranges from 1% to 3% of the wheel diameter for a dimensionless wheel load ($Q_v/\gamma d^3$) of 2, which corresponds to deflection of between 0.4 to 1.2 inches (10 to 30 mm) for a prototype test roller system wheel load of approximately 4,000 lbs (18 kN).
- Reducing the dimensionless wheel load to 1 (corresponding to a wheel load of about 2,000 lbs (9 kN)) yields deflections between 0.5% and 1.5% of the wheel diameter, or 0.2 to 0.6 inches (5 to 15 mm) for the standard dump truck wheel used in prototype evaluation.
- For practical purposes, the effect of unit weight on sinkage was insignificant in the numerical model in all cases except the soil with very a high friction angle and low cohesion.
- The effect of wheel width was shown to be significant, but this can be accommodated in the construction specification.
- Poisson's ratio and interface friction were shown to have a negligible effect on the sinkage.
- As with the analytical model, higher deflections were predicted using the rolling wheel model compared to the indentation model, on average 20% higher for the rolling model than the indentation model.
- Other trends in the indentation model were confirmed by similar results in the rolling wheel model.

As mentioned previously, due to the anticipated depth of influence being limited to 18 inches or less, further discussion of the effects of layering in subgrade soils will not be addressed further in this implementation project.

The following points of interest relating to a RIGID-wheel test roller as made in the University of Minnesota's parametric study are of consideration in the test roller implementation project:

- Sinkage due to the test roller load in granular soils is linearly proportional to the load (doubling the load doubles the deflection) while in cohesive soils there is a second order relationship (doubling the load quadruples the deflection),
- Sinkage due to the test roller load in granular soils is inversely proportional to the width of the tire (half the tire width doubles the deflection) and in cohesive soils is inversely proportional to the square of the width of the tire (half the tire width yields four times the deflection,)
- Sinkage due to the test roller load in both granular and cohesive soils is inversely proportional to the diameter of the wheel, such that reducing the wheel diameter by one half will double the deflection,
- The depth of influence of strength and elastic parameters is limited to a depth of one half the wheel diameter, such that the prototype test rolling system would be expected to have a depth of influence on the order of 18 to 24 inches (0.46 to 0.60 m).

To summarize, the third task of the University of Minnesota study (Hambleton and Drescher, 2008) provided several useful models that could be implemented to predict test roller deflections either analytically or numerically. As requested, the analytical models will be further implemented in the new test roller system development, and these models can be adjusted (based on field data) to predict deflections appropriately with the new system.

2.4 Task 4 – Scaled Field Testing / Indentation and Rolling Tests (Hambleton and Drescher, 2008)

The original objective of Task 4 of the University of Minnesota study was to calibrate the models developed in Task 3 with actual field data for the existing test rollers used by Mn/DOT. Due to a variety of reasons (a list is provided in the report), only limited data was obtained from test roller field testing. Due to this fact, validation of the models was not done to the extent desired. In lieu of facing additional difficulties in obtaining field test roller data, the scope of the project was modified to use controlled laboratory experiments to validate the sinkage models developed. In this way, the roller and soil properties could be easily controlled, allowing a more effective check of the models to be made.

Two soils were prepared for this experiment. One was a cohesive silty clay obtained from northern Minnesota, while the second was Quikrete sand with minimal cohesion. These soils were used in order to test both a cohesive material and a cohesionless material in order to verify the deflection models at each end of the spectrum of anticipated soils used in construction of subgrades. The cohesive material was compacted at a water content near saturation and just above the plastic limit of the soil. The sand was compacted to the desired range of densities and tested under air-dried conditions.

A testing bed with dimensions of 12 in long x 10 in wide x 4 in deep (0.30 m x 0.25 m x 0.10 m) was used for the scaled tests. Two rigid circular wheels, each with a width to diameter ratio of 0.33, were used in the tests with instrumentation to measure wheel force and displacement during the tests. A number of tests were performed to relate the wheel force to the sinkage for the soils tested. Laboratory tests were performed to obtain the necessary soil parameters for the models, as given in Chapter 6 of the full report (Hambleton and Drescher, 2008). With these soil properties for both the cohesive and the cohesionless soils, the models developed to relate sinkage to wheel load could be compared to the scaled model studies performed to validate the models.

For the cohesive soil, the models for sinkage versus wheel load for a rolling wheel provided the results shown in Figure 2.3 and Figure 2.4. In general, the analytic model underpredicts the sinkage for small loads and overpredicts the sinkage for higher loads. However, overall the model appears to be reasonable for the scaled data collected through the range of sinkage extending to over 10 percent of the wheel diameter.

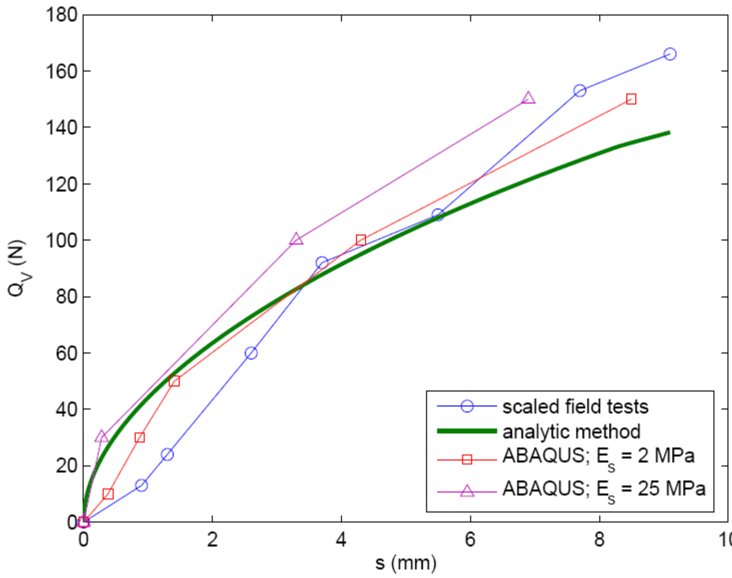

Figure 2.3. Results of Study of Scaled Model Wheel in Cohesive Material – Comparison with Smaller (d = 78 mm) Model Wheel (after Hambleton and Drescher, 2008).

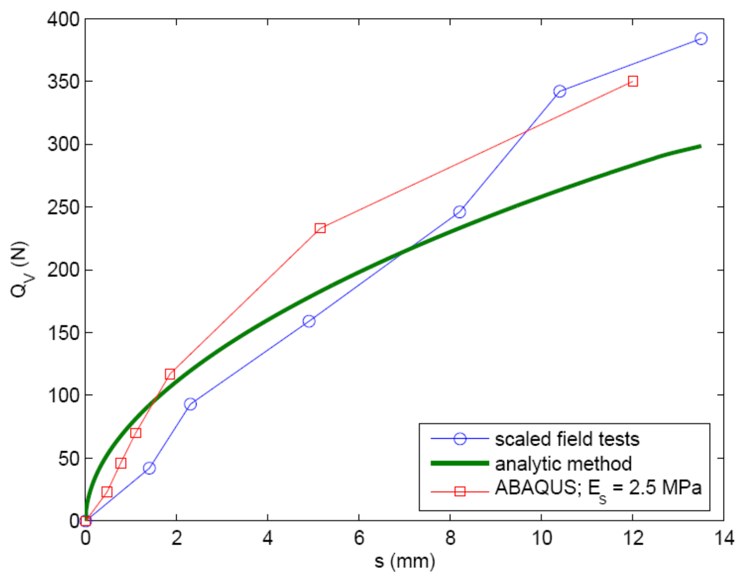

Figure 2.4. Results of University of Minnesota Study of Scaled Model Wheel in Cohesive Material – Comparison with Larger (d = 115 mm) Model Wheel (after Hambleton and Drescher, 2008).

For the cohesionless soil, the models for sinkage versus wheel load for a rolling wheel provided the results shown in Figure 2.5 and Figure 2.6. Due to the nature of the analytic model (based on bearing capacity theory), the model is quite sensitive to changes in the friction angle as well as the presence of any cohesion in the soil. The triaxial shear tests that were performed to determine the strength properties of the sand yielded a best-fit combination of a friction angle of 35.5 degrees with an apparent cohesion of (0.6 psi) 4.0 kPa, which was noted to be unrealistic of the sand being tested. Assuming a more realistic zero cohesion yielded a best-fit friction angle of 39.0 degrees. Choosing to use the slope associated with the original best-fit (35.5 degree friction angle) but using a zero cohesion value also seemed like a practical option. Each of these combinations was used in the model, with the varying results provided.

Based on the data shown for the smaller wheel (Fig. 2.5), the original best-fit friction angle (35.5 degrees) with zero cohesion assumed provided the best correlation to the scaled model data. Along with providing the best fit to the data, since these strength values also made the most sense from a practical standpoint, it appears as though the model is validated using the best estimate for parameters.

Similar findings are given for the tests with the larger wheel (Fig. 2.6). Again, for the practical values of friction angle and zero cohesion assumed, the analytic model does a good job in predicting sinkage for the range of wheel loads provided.

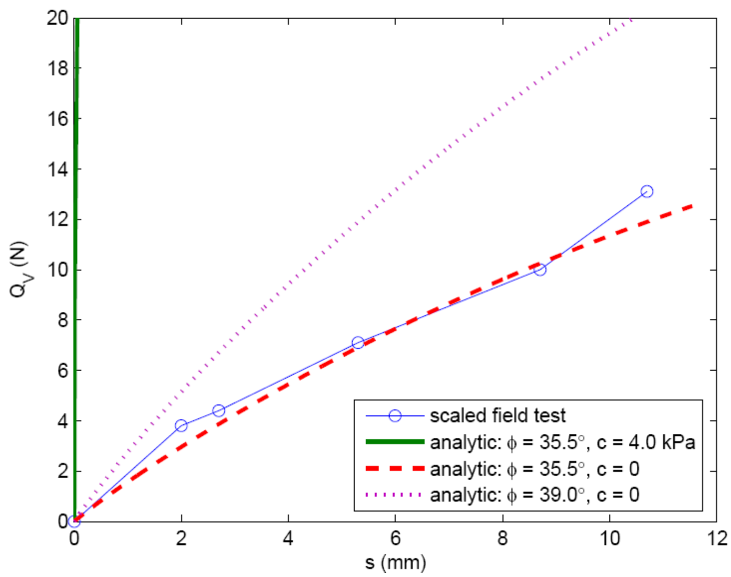

Figure 2.5. Results of University of Minnesota Study of Scaled Model Wheel in Loose Cohesionless Material – Wheel Diameter = 115 mm (after Hambleton and Drescher, 2008).

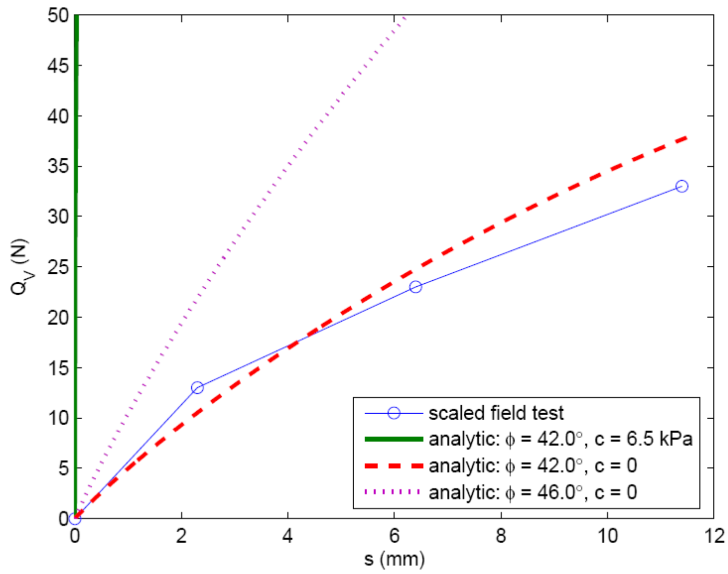

Figure 2.6. Results of University of Minnesota Study of Scaled Model Wheel in Dense Cohesionless Material – Wheel Diameter = 115 mm (after Hambleton and Drescher, 2008).

Similar correlations were also performed for the numerical (ABAQUS) models developed for the test roller. Since such models will not be pursued further at this time, no additional discussion will be given in this report.

Hambleton and Drescher (2008) also validate these models with data from the literature. Based on these additional correlations, the analytical model developed appears to be reasonably sound and will be the initial basis of the construction specification for the new test roller system.

2.5 Conclusions from Hambleton and Drescher, 2008

There were a number of conclusions presented based on the University of Minnesota study. These may be summarized as follows:

- Test rolling has the potential to be a very successful tool for characterizing mechanical properties of soils with a continuous record of measurement.
- Both analytic and numerical models were developed to relate test roller wheel sinkage to wheel load as a function of soil strength parameters and the test roller wheel geometry. The analytic model is easy to use, although more approximate in nature.
- The scaled model studies performed support the analytic model developed.
- Graphs relating sinkage to wheel geometry, soil strength, etc. could be used rather than the analytic expressions developed.
- Since much of the deformation induced by a test roller is permanent, this deformation is to be associated with soil failure rather than elastic compression. Thus, the conclusion of the authors was that test rolling should not be used to evaluate elastic parameters such as resilient modulus. However, test rolling was perceived to be a practical way of obtaining continuous strength properties.
- While unit weight and moisture content may be the primary means of quality assurance, they play only an indirect role in the models developed by the study. Unit weight and moisture content affect the soil strength and are important to monitor in obtaining

maximum strength, but moisture content is not directly incorporated into the analytic model.

- Inference of strength properties can be done in either a cohesionless or purely cohesive material, but not by a soil with combined strength properties, without additional effort. If wheels of two different sizes are used to evaluate the soil, or if the same wheel is used with two separate wheel loads, strength values can be deduced.
- The influence depth for the existing test roller system varies from 2 ft to 4 ft (0.6 to 1.2 m).
- The larger the magnitude of the wheel load, the greater the sensitivity of the sinkage to small changes in the soil strength. For smaller wheel loads, small strength changes will not lead to significant changes in sinkage.
- Wheel flexibility can influence sinkage significantly and should be taken into account in the analytic (and/or numerical) model(s). Uncertainty in this wheel flexibility could lead to large differences in test rolling results if significant variation in tire construction, etc. exist.
- Validation of the models should ultimately be done using well-controlled field tests of a test rolling system.

2.6 Recommendations from Hambleton and Drescher, 2008

The Hambleton and Drescher study (2008) also included a number of recommendations. These may be summarized as follows:

- Light weight deflectometers and/or intelligent compaction systems should be used to determine elastic properties rather than test rolling.
- The models developed should be considered to be approximate until they can be validated with experimental data.
- Test rollers with different weights and wheel configurations can give similar results. A heavy wheel load with a large wheel contact area can yield results similar to a small load on a smaller wheel area. The influence depth will be less, however, for the smaller wheel/load combination.
- Rigid wheels would be preferred to flexible wheels for test rolling applications. However, a stiff pneumatic tire with appropriate inflation pressure can approximate a rigid wheel.
- A towed wheel is recommended over a driven wheel, and the models developed apply to a towed wheel only.
- A test roller wheel should travel ahead of the driving wheels, as when using the front axle of a standard dump truck as a test rolling device.

2.7 Summary and Initial Sinkage Values

Based on the Hambleton and Drescher (2008) study and using the analytic model developed therein, sinkage can be estimated for the prototype test rolling system for the expected wheel geometry and wheel loads anticipated for various soil strengths. Assuming the wheel flexibility coefficient of 3.5 inches per ton (0.01 m/kN) as estimated for the existing test roller also applies to a standard wheel on a dump truck, and using a density of 127 pcf (20 kN/m3) and wheel dimensions for a 385/65R22.5 tire (overall diameter = 42 in (1.072 m) and overall width = 15.0

in (0.379 m)), the table given below provides the sinkage expected for soil strengths as shown for the wheel loads listed.

Table 2.2. Initial Sinkage Values Based on Hambleton and Drescher (2008).

		Predicted Sinkage (in)								
		Wheel Load								
Friction Angle (deg)	Cohesion (psf)	1500 lb	2000 lb	2500 lb	3000 lb	3500 lb	4000 lb	4500 lb	5000 lb	5500 lb
0	417.7	1.10	1.57	2.17	2.76	3.46	4.13	N/A	N/A	N/A
15	1044.2	0.05	0.07	0.10	0.13	0.17	0.21	0.25	0.30	0.35
30	2088.5	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
30	20.9	2.48	3.35	4.33	N/A	N/A	N/A	N/A	N/A	N/A
35	208.8	0.061	0.091	0.126	0.163	0.205	0.246	0.291	0.339	0.390
45	417.7	0.002	0.003	0.004	0.006	0.007	0.009	0.011	0.013	0.015

3 Relate Test Roller Deflections to Pavement Performance

3.1 Background

The correlation of tire sinkage at the top of a compacted subgrade to long-term pavement performance is a key component of this project. Two distinct analyses are presented in this section – the allowable sinkage beyond which the subgrade should be reworked, recompacted, and retested, and the correlation to performance on uniformly compacted subgrade. The first analysis consists of correlating the test roller tire sinkage with problems in the quality of compaction. This may be due to inadequate compactive effort, improper moisture content, or both. In either case, the test roller tire sinks into the surface of the subgrade material significantly more than in other locations where the compaction is adequate.

The first section that follows is an analysis of allowable sinkage (of the test roller tire into the compacted subgrade). In most cases, the compacted subgrade will be uniform and the tire will sink a nominal amount due to the concentrated load of the tire on the surface. The first test is to determine what the allowable sinkage can be for a particular subgrade soil. If the sinkage is within the allowable limits, additional analysis can be conducted to correlate the density and other properties of the soil with expected pavement performance. If the sinkage exceeds allowable limits, the area where this sinkage occurred should be reworked and recompacted, and thus is not subject to the additional analysis.

There are several steps required in the correlation of subgrade soil properties to ultimate pavement performance, each of which brings its own level of variability and uncertainty into the results. This section also describes the development of a procedure for estimating the impact of (uniformly) lower quality subgrade compaction on the ultimate performance of the final pavement structure. The two analyses – "allowable sinkage" and "performance correlation" – are described in the remaining sections of this chapter.

3.2 Allowable Sinkage

The expected sinkage for a pneumatic tire in a compacted subgrade has been modeled theoretically by Hambleton and Drescher (2008a). This model is based on the load and geometric parameters of the wheel, and the cohesion of the subgrade material on which the sinkage test is conducted. The model is arranged to compute the wheel load for a given sinkage value, s, and this form of the model is the most convenient. A solution for s given a particular wheel load has been developed and was submitted as part of Task 1. The model for sinkage is given below, taken from Hambleton and Drescher (2008a).

$$Q = 5.14bch\left(1 + 0.19\frac{h}{b}\right)\left(1 + 0.07\frac{s}{h}\right)\left(1 - 0.64\sqrt{\frac{s}{d\left(1 + \lambda_r Q\right)}}\right)^2$$

Equation 3.1

for h < b, and

$$Q = 5.14bch\left(1 + 0.19\frac{b}{h}\right)\left(1 + 0.07\frac{s}{b}\right)\left(1 - 0.64\sqrt{\frac{s}{d(1 + \lambda_r Q)}}\right)^2$$

Equation 3.2

for h ≥ b,

where:

Q = wheel load, kN

b = wheel width, m

c = soil cohesion, kPa

s = wheel sinkage, m

λ_r = wheel flexibility coefficient for rolling (1.0 for rigid, lower than 1.0 for pneumatic. The models use $\lambda_r = 0.01$.),

h = $\sqrt{ds(1 + \lambda_r Q) - s^2}$ **Equation 3.3**

= length of contact between the wheel and soil, m

d = wheel diameter, m.

Hambleton and Drescher (2008b) also published a larger model, which utilizes both the soil cohesion and friction angle.

$$Q = bh\left\{cN_c\left(1 + \frac{hN_q}{bN_c}\right)\left(1 + \frac{0.03s}{h/2}\right) + 0.17\gamma sN_q\left(1 + \frac{h\tan\phi}{b}\right)\left(1 + \frac{0.17s\tan\phi(1+\sin\phi)^2}{h/2}\right) + \gamma hN_\gamma\left(1 - \frac{0.8h}{2b}\right)\right\}$$

Equation 3.4

for h ≤ b, and

$$Q = bh\left\{cN_c\left(1 + \frac{bN_q}{hN_c}\right)\left(1 + \frac{0.07s}{h/2}\right) + 0.17\gamma sN_q\left(1 + \frac{b\tan\phi}{h}\right)\left(1 + \frac{s\tan\phi(1+\sin\phi)^2}{3b}\right) + \gamma bN_\gamma\left(0.5 - \frac{0.1b}{h/2}\right)\right\}$$

Equation 3.5

for h > b.

where:

ϕ = angle of internal friction, deg

N_c, N_γ, N_q = bearing capacity parameters

$$\mathbf{N_q} = \tan^2\left(\frac{\pi}{4}+\frac{\phi}{2}\right)e^{\pi \tan\phi}$$ **Equation 3.6**

$$\mathbf{N_c} = \left(N_q - 1\right)\cot\phi$$ **Equation 3.7**

$$\mathbf{N_\gamma} = 2\left(N_q + 1\right)\tan\phi$$ **Equation 3.8**

h = $2\sqrt{ds - s^2}$ = length of contact between the wheel and soil, m.

γ = soil unit weight, kN/m^3.

Hambleton also developed a spreadsheet to implement the model above, which is shown in Figure 3.1.

SINKAGE CALCULATIONS

variable	description	value	units
s	calculated sinkage; valid when box is green	**0.0008578**	m
		0.86	mm
Qv	specified weight on wheel	40	kN
ϕ	soil friction angle	45	deg
c	soil cohesion	20	kPa
γ	soil unit weight	20	kN/m^3
d	wheel diameter	1.072	m
b	wheel width	0.379	m
λ_r	wheel flexibility coefficient	0.01	m/kN
d_e	equivalent wheel diameter	1.501	m
η	coefficient for equivalent depth	1.993	
B	smaller dimension of soil-wheel contact area	0.036	m
L	larger dimension of soil-wheel contact area	0.379	m
D	equivalent depth	0.000	m
β	angle of inclination of wheel force	1.37	deg
N_c	bearing capacity factor	133.87	
N_q	bearing capacity factor	134.87	
N_γ	bearing capacity factor	271.75	
F_{cs}	shape factor	1.095	
F_{qs}	shape factor	1.067	
$F_{\gamma s}$	shape factor	0.962	
F_{cd}	depth factor	1.003	
F_{qd}	depth factor	1.001	
$F_{\gamma d}$	depth factor	1.000	
F_{ci}	inclination factor	0.970	
F_{qi}	inclination factor	0.970	
$F_{\gamma i}$	inclination factor	0.940	
q_u	average inclined stress over contact area	2942.3	kPa
$(Q)_{comp}$	total wheel force computed with formula	40.01	kN
$(Q_V)_{comp}$	wheel weight computed with formula	**40.00**	kN

Figure 3.1. Spreadsheet Developed by Hambleton, Implementing the Wheel-sinkage Model.

In order to use this spreadsheet tool, the wheel load (Q_v) must be measured, as well as the wheel diameter and width (d and b, respectively) and the soil friction angle, cohesion, and unit weight (ϕ, c, and γ, respectively).

Chapter 2 of this report considered the Hambleton model and developed a table of expected soil sinkage levels in soils with different properties. Table 3.1 presents a table with additional expected sinkage values in soils of various cohesion and friction parameters. The data in this table are presented with a reasonable upper value of 4 in (100 mm), meaning that if the tire sinks into the subgrade deeper than this amount, it would be unreasonable to expect that the vehicle could continue to drive efficiently in this manner. Thus, after the first result with increasing wheel load where the predicted sinkage is greater than 4 in (100 mm) the analysis was discontinued for that set of soil parameters.

Table 3.1. Effects of Cohesion, Friction Angle, and Wheel Load on Predicted Sinkage[a].

Friction Angle (deg)	Cohesion psf (kPa)	Approximate Soil Type	Predicted Sinkage, in. (mm) Wheel Load, lbs (kN) 6000 (26.7)	7500 (33.4)	9000 (40)
Cohesive Soils					
0	**418 (20)**	Soft Clay	6.9 (175)	N/A	N/A
0	**835 (40)**	Med. Clay	2.0 (50)	3.3 (83)	4.3 (110)
0	**2088 (100)**	Stiff Clay	0.4 (10)	0.7 (17)	0.9 (22)
5	**418 (20)**	Soft Silty Clay	5.6 (143)	11.5 (293)	N/A
5	**627 (30)**	Med.Silty Clay	2.5 (63)	4.3 (109)	N/A
5	**835 (40)**	Med.Silty Clay	1.5 (37)	2.5 (63)	3.3 (83)
5	**2088 (100)**	Stiff Silty Clay	0.3 (7)	0.5 (12)	0.6 (15)
15	**418 (20)**	Clayey Silt	1.9 (47)	3.1 (78)	4.2 (106)
15	**835 (40)**	Clayey Silt	0.5 (13)	0.9 (23)	1.2 (30)
15	**2088 (100)**	Clayey Silt	0.1 (2)	0.2 (4)	0.2 (6)
25	**418 (20)**	Loose Silt	0.6 (14)	0.9 (23)	1.2 (30)
25	**835 (40)**	Med. Silt	0.2 (4)	0.3 (7)	0.4 (9)
25	**2088 (100)**	Dense Silt	0.0 (1)	0.0 (1)	0.1 (2)
Granular Soils					
30	**104 (5)**	Med. Clean Sand	2.4 (61)	3.7 (95)	5.7 (145)
30	**209 (10)**	Med. Sand	0.9 (22)	1.4 (36)	1.8 (46)
30	**418 (20)**	Med. Silty Sand	0.3 (7)	0.4 (11)	0.6 (15)
45	**104 (5)**	Dense Clean Sand	0.2 (4)	0.2 (6)	0.3 (8)
45	**209 (10)**	Dense Sand	0.0 (1)	0.1 (2)	0.1 (3)
45	**418 (20)**	Dense Silty Sand	0.0 (0)	0.0 (1)	0.0 (1)

[a]computed from Hambleton and Drescher, 2008a.

As part of this project, the original spreadsheet was reviewed. There are a few discrepancies that should be noted here. An updated set of computations is shown in Table 3.2.

Mn/DOT personnel requested that the influence depth predicted by the University of Minnesota model be included in the table above. An assessment of this depth of influence was performed. Since the calculated sinkage and the depth of influence are based on the same soil and loading parameters, it makes sense that the two would be related. However, the observed relationship (very small depth of influence for a soil with a very small sinkage) was counterintuitive in a practical sense. For stiff soils with small sinkage, the depth of influence was only a few millimeters (a fraction of an inch). For softer soils with greater sinkage, the depth of influence was hundreds of millimeters (tens of inches.) Further consideration of this relationship would be needed before including such results in the table above.

Table 3.2. Effects of Cohesion, Friction Angle, and Wheel Load on Predicted Sinkage[a].

Friction Angle (deg)	Cohesion psf (kPa)	Approximate Soil Type	Predicted Sinkage, in. (mm) Wheel Load, lbs (kN) 6000 (26.7)	7500 (33.4)	9000 (40)
Cohesive Soils					
0	**418 (20)**	Soft Clay	N/A	N/A	N/A
0	**835 (40)**	Med. Clay	8.9 (225)	N/A	N/A
0	**2088 (100)**	Stiff Clay	0.6 (16)	0.9 (24)	1.3 (34)
5	**418 (20)**	Soft Silty Clay	N/A	N/A	N/A
5	**627 (30)**	Med.Silty Clay	7.3 (186)	N/A	N/A
5	**835 (40)**	Med.Silty Clay	2.8 (71)	4.9 (124)	10.4 (264)
5	**2088 (100)**	Stiff Silty Clay	0.4 (9)	0.6 (14)	0.7 (19)
15	**418 (20)**	Clayey Silt	3.5 (90)	11.7 (297)	N/A
15	**835 (40)**	Clayey Silt	0.7 (19)	1.1 (29)	1.5 (39)
15	**2088 (100)**	Clayey Silt	0.1 (3)	0.2 (4)	0.2 (6)
25	**418 (20)**	Loose Silt	0.7 (19)	1.1 (27)	1.4 (36)
25	**835 (40)**	Med. Silt	0.2 (5)	0.3 (7)	0.4 (10)
25	**2088 (100)**	Dense Silt	0.0 (1)	0.0 (1)	0.1 (2)
Granular Soils					
30	**104 (5)**	Med. Clean Sand	7.6 (193)	N/A	N/A
30	**209 (10)**	Med. Sand	1.2 (30)	1.7 (43)	2.2 (57)
30	**418 (20)**	Med. Silty Sand	0.3 (8)	0.5 (12)	0.6 (16)
45	**104 (5)**	Dense Clean Sand	0.2 (4)	0.2 (6)	0.3 (7)
45	**209 (10)**	Dense Sand	0.1 (2)	0.1 (2)	0.1 (3)
45	**418 (20)**	Dense Silty Sand	0.0 (0)	0.0 (1)	0.0 (1)

[a]based on revised calculations, from Hambleton and Drescher, 2008a.

The enumerated changes are as follows.

1. *Equivalent wheel diameter.*

   Equation 3.65 in Hambleton and Drescher (2008a) and Equation 3.56 in Hambleton (2006) seem to be contradictory, without ample explanation as to why the change is evident. In his thesis, Hambleton (2006) uses:

$$\frac{d_e}{d} = 1 + \lambda_r Q$$

   Which is equivalent to

$$d_e = d + d\lambda_r Q$$

However, in a subsequent report to the Minnesota LRRB, the equivalent wheel diameter is shown as

$$d_e = d + \lambda_r Q\,.$$

The original spreadsheet obtained for this project also had the latter formula for equivalent wheel diameter. For the revised values in Table 3.2, the equation which seems to be more correct mathematically was used.

2. *Coefficient for equivalent depth.*

   In the thesis (Hambleton, 2006) there is no mention of this parameter (η) or the larger equation it represents. However, in the subsequent LRRB report this parameter is "introduced for convenience) as a coefficient for equivalent depth:

$$\eta = \frac{\sin\left(\frac{\pi}{4} - \frac{\phi}{2}\right)}{\sin\left(\frac{\pi}{4} + \frac{\phi}{2}\right)} e^{\frac{\pi}{2}\tan\phi}$$

   In addition, the original spreadsheet that was provided used a hard-coded value of 6 for this coefficient, which corresponds to a friction angle of almost 65°. This equation was used in computing the revised sinkage values in Table 3.2.

3. *Shape, depth, and inclination factors.*

   In the thesis, shape, depth, and inclination factors were given for cohesive soils only. However, in a subsequent paper in the journal Terramechanics (2009), additional parameters were provided. The original spreadsheet did not include the factors for granular soils, and these were added to the revised spreadsheet. Additional factors were obtained through some references cited in Hambleton's works (2006, 2008a). These include Hansen (1970) and Das (2005).

The information in these tables relates to the allowable tire sinkage currently in the draft test rolling specification developed by the Mn/DOT Office of Materials and Road Research, and shown in Table 3.3. For loads of 6,000, 7,500, and 9,000 lbs (26.7, 33.4, and 40 kN), reasonable sinkage is in the 0.3 to 0.6 inch (7.5 to 15 mm) range (for a soil with friction angle of 30º and cohesion of 418 psf. The acceptable range in the draft specification for similar granular soils is 0.6 to 0.9 inch (15 to 22 mm), which provides some additional flexibility in the field for less-than-perfect conditions. For cohesive soils similar to those tested in the development of Table 3.3 (friction angle of about 14º and cohesion of almost 2000 psf (100 kPa)), the values in the two tables are very similar. It will be important to compare expected sinkage values with actual field data in future test roller validation testing.

Table 3.3. Acceptable Tire Sinkage.

TABLE 2111-3			
ACCEPTANCE CRITERIA			
Roller Type	**Tire Load**	**Allowable Deflection (Note 1)**	
		Granular to be Covered by Stabilizing Aggregate	**All Other Materials**
Standard	29,800 to 30,200 lb (13,500 to 13,700 kg)	3 in (75 mm)	2 in (50 mm)
Sonic (Note 2)	5,800 to 6,200 lb (2,630 to 2,800 kg)	0.6 in (15 mm)	0.4 in (10 mm)
	7,300 to 7,700 lb (3,300 to 3,500 kg)	0.75 in (19 mm)	0.5 in (13 mm)
	8,800 to 9,200 lb (4,000 to 4,200 kg)	0.9 in (23 mm)	0.6 in (15 mm)

Other models have been developed to predict sinkage for rigid and pneumatic wheels. The basic model for sinkage with a pneumatic tire, developed by Bekker (1960) and is a function of contact (ground) pressure, p_{gr}, tire width, b, and three soil parameters, k_c, k_ϕ, and n. The parameters in this equation are not dependent on any system of units, therefore any correct usage of US customary or SI units will suffice.

$$z = \left[\frac{p_{gr}}{k_c/b + k_\phi} \right]^{1/n}$$

Equation 3.9

where:

z = tire sinkage,

p_{gr} = ground pressure between the tire and soil,

k_c = modulus of soil deformation for cohesion,

k_ϕ = modulus of soil deformation for friction,

n = exponent of soil deformation, and

b = tire width.

These three parameters (k_c, and k_ϕ, and n) are empirical quantities of soil, and several sources (Gerhart et al., 2006; Wong, 1993) state that they can be "readily found in soil property books". A search for these parameters with respect to other soil properties yielded few results. Wong (1993) presented a table of empirical values for these parameters, referencing Bekker (1969), himself (Wong, 1989), and Harrison (1975). These values do not seem to be correlated well with the basic soil strength properties. A typical correlation plot is shown in Figure 3.2, while the data that shows the best correlation (of plots comparing cohesion and friction angle with k_c, k_ϕ, and n) is shown in Figure 3.3, comparing cohesion and n.

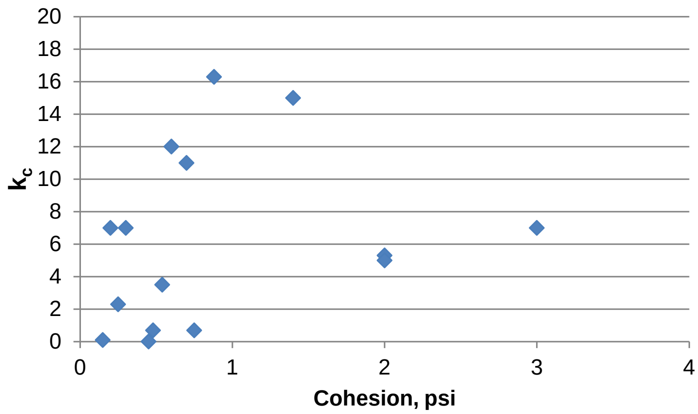

Figure 3.2. Correlation of Cohesion with the Parameter k_c (from Wong, 1993).

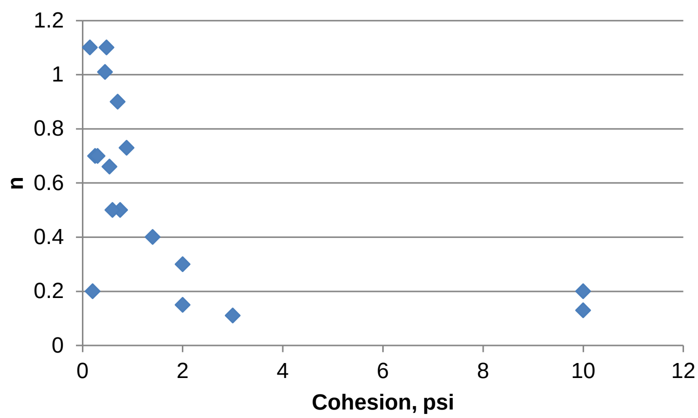

Figure 3.3. Correlation of Cohesion with the Parameter n (from Wong, 1993).

Gerhart et al. (2006) indicate that for larger values of tire width, b, and the same ground pressure, p, sinkage will be larger. They state that the phenomenon is not well understood, but from field experience has been consistently valid. Wider tires can increase the allowable safe pressure of soil, but causes larger amounts of sinkage.

An expansion of the Bekker model by a finite element software analysis company (FunctionBay, 2006) includes the empirical pressure-sinkage parameters (k_c, k_ϕ, and n):

$$F_Z = b\left(\frac{k_c}{b} + k_\phi\right) \cdot \sqrt{D} \cdot z_0^{n+0.5} \cdot \left(1 - \frac{n}{3}\right)\left(\sqrt{1 + \frac{f_0}{z_0}} + \sqrt{\frac{f_0}{z_0}}\right) \quad \textbf{Equation 3.10}$$

where:

F_z = wheel load,

z_0 = sinkage, and

f_0 = relative tire deformation.

Bekker (1969) states that "the inherent variability of soils and the error associated to the imperfect modeling of the [tire-soil] interaction may even make it impossible to estimate the accurate parameters [k_c, k_ϕ, and *n*]".

3.3 Performance Correlation

The primary steps in the pavement performance correlation include the following.

1. Determine maximum dry density of the subgrade soil in the laboratory, and obtain other soil properties during routine laboratory tests.
2. Determine actual dry density in the field.
3. For cohesive subgrades, compute the relative density.
4. Using the resilient modulus models below, estimate the subgrade resilient modulus ratio
5. Predict impact on pavement performance (rutting and cracking) predicted from resilient modulus ratio.

Each of these steps is described in this section, in addition to a description of the laboratory testing plan and analysis, and how the results of the testing program were used in the overall analysis.

3.3.1 Model Review

Several models have been developed over the past 40-50 years to attempt to correlate basic soil properties (such as Atterberg limits, gradation, and friction / cohesion) to stiffness properties (primarily resilient modulus). Several of these are reviewed here, and one model is recommended for use in the further analysis.

3.3.1.1 Rahim (2005)

Rahim conducted field and laboratory tests on granular and clay samples taken from several locations in Mississippi, with AASHTO classifications ranging from A-1-a to A-7. The confining pressure used in the resilient modulus test was representative of the field conditions for 1-, 2-, and 3-foot depths beneath the subgrade surface. The following soil index properties were used in the development of the models.

- Liquid Limit (LL)
- Moisture content (w_c), %
- Dry density (γ_d), kN/m^3
- Dry density ratio (γ_{dr}), the ratio of actual dry density to maximum dry density
- Percent passing #200 sieve (#200), %
- Uniformity coefficient ($c_u = D_{60} / D_{10}$), where D_{10} and D_{60} are the maximum size of the smallest 10% and 60% of the soil, respectively

The models developed by Rahim are:

Fine-grained soils (R^2 = 0.70, N = 110)

$$M_R = 17.29\left[\left(\frac{LL \cdot \gamma_{dr}}{w_c + 1}\right)^{2.18} + \left(\frac{\#200}{100}\right)^{-0.609}\right]$$

Equation 3.11

Coarse-grained soils (R^2 = 0.75, N = 70)

$$M_R = 324.14\left[\left(\frac{\gamma_d}{w_c + 1}\right)^{0.8998} + \left(\frac{\#200}{\log c_u}\right)^{-0.4652}\right]$$

Equation 3.12

3.3.1.2 Rahim and George (2005)

Another method of predicting resilient modulus of a soil is to use the soil index properties to estimate the coefficients used in modified k-θ models. The modifications to the standard $M_R = k_1\theta^{k_2}$ model include a ratio of the stress states (deviator stress / confining pressure for fine-grained and bulk stress / deviator stress for coarse-grained). The resulting models, using the same soils as in the Rahim (2005) models, are not as robust, with R^2 values ranging from 0.61 to 0.72. The models developed by Rahim and George are shown below.

Fine-grained soils (R^2 = 0.66 and 0.61, respectively, N = 110)

$$k_1 = 1.12\gamma_{dr}^{1.996}\left(LL/w_c\right)^{0.639}$$

Equation 3.13

$$k_2 = -0.27\gamma_{dr}^{1.04} w_{cr}^{1.46} \left(LL / \#200 \right)^{0.47}$$ **Equation 3.14**

Coarse-grained soils (R^2 = 0.72 and 0.65, respectively, N = 70)

$$k_1 = 0.12 + 0.90\gamma_{dr} - 0.53w_{cr} - 0.017(\#200) + 0.314\log c_u$$ **Equation 3.15**

$$k_2 = 0.226(\gamma_{dr} w_{cr})^{1.2385} \left(\#200 / \log c_u \right)^{0.124}$$ **Equation 3.16**

The resilient modulus models using these coefficients are:

Fine-grained soils

$$M_R = k_1 P_a \left(1 + \frac{\sigma_d}{1 + \sigma_c} \right)^{k_2}$$ **Equation 3.17**

Coarse-grained soils

$$M_R = k_1 P_a \left(1 + \frac{\theta}{1 + \sigma_d} \right)^{k_2}$$ **Equation 3.18**

The variables in these models are the same as for those in the Rahim (2005) models, with the following exceptions.

- Atmospheric pressure (P_a),
- Deviator stress (σ_d),
- Confining pressure (σ_c),
- Bulk stress (θ), and
- Moisture content ratio (w_{cr}), the ratio of actual moisture to optimum moisture.

3.3.2 Model Implementation

Using the constitutive model developed by Rahim and George (2005), a relative resilient modulus can be developed which provides the ratio of expected to predicted (in-place) resilient modulus. This method can help to eliminate some of the variables in the models, since the in-place M_R is divided by the expected M_R to arrive at the ratio.

As an example, using the models given in Equations 3.17 and 3.18, estimating the resilient modulus of cohesive and granular soils requires the use of appropriate stress state equations. In this example for computing these stress states, which is likely to be typical for many pavement applications, it is assumed that the minimum pavement structure (e.g. 30 inches of bituminous, aggregate base and subbase) is to be constructed above the subgrade in question. For cohesive soils, this requires the estimate of deviator stress, σ_d, and confining pressure, σ_c. These can be estimated by the following.

$$\boldsymbol{\sigma_d = \sigma_V + p_0 - \sigma_c} \qquad \textbf{Equation 3.19}$$

$$\boldsymbol{\sigma_c = \sigma_H + K_o p_0} \qquad \textbf{Equation 3.20}$$

$$K_o = \frac{\nu}{1-\nu} \qquad \textbf{Equation 3.21}$$

where:

σ_d = deviator stress

σ_c = confining pressure

σ_V = vertical stress at top of subgrade

σ_H = horizontal stress at top of subgrade

p_0 = at-rest vertical pressure from overlying pavement structure

K_o = coefficient of at-rest earth pressure

ν = poisson's ratio of the subgrade soil

The horizontal and vertical stresses are determined through elastic layer theory, and in this case, the assumptions were as follows.

Table 3.4. Parameters Used to Compute Subgrade Stress State.

Layer	**Thickness, in.**	**Assumed M_R, psi**	**Assumed Poisson's Ratio**
Surface	6	400,000	0.35
Base	6	35,000	0.40
Subbase	18	20,000	0.40
Subgrade		10,000	0.45

Using these parameters, and a 34-kip (151 kN) dual-tandem axle, elastic layered analysis was used to determine the vertical and horizontal stresses due to the axle load at σ_V = 2.3 psi (16 kPa) and σ_H = 1.0 psi (7.0 kPa). In addition, the overburden pressure from the pavement structure was computed to be 2.0 psi (14 kPa) (2.5 ft (0.75 m) thick and 120 pcf (19 kN/m^3). From these values, the stress state parameters were computed to be the following.

$$\boldsymbol{\sigma_c = \sigma_H + K_o p_0 = 1.0 + 0.82(2.0) = 2.6 \text{ psi}}$$ **Equation 3.22**

$$\boldsymbol{\sigma_d = \sigma_V + p_0 - \sigma_c = 2.3 + 2.0 - 2.6 = 1.7 \text{ psi}}$$ **Equation 3.23**

For granular soils, the models require bulk stress (θ) and deviator stress. Deviator stress has already been developed. The bulk stress is simply the sum of the three principal stresses, as shown below.

$$\boldsymbol{\theta = \sigma_1 + \sigma_2 + \sigma_3}$$ **Equation 3.24**

Since σ_2 and σ_3 are the horizontal stresses in opposing directions, and are often similar in magnitude, the bulk stress is often computed as:

$$\boldsymbol{\theta = 3\sigma_c + \sigma_d}$$ **Equation 3.25**

Since the horizontal stresses are similar in the x and y direction, this analysis can be used, so that θ = 9.5 psi.

3.3.3 Resilient Modulus Ratio

For cohesive soils, the resilient modulus prediction equation is given in Equation 3.17. Using this equation for both the designed (M_{R-d}) and constructed (M_{R-c}) resilient moduli, resulting ratio of constructed to designed resilient modulus (M_{R-r}) is

$$M_{R-r} = \frac{k_{1-c} P_a \left(1 + \frac{\sigma_d}{1+\sigma_c}\right)^{k_{2-c}}}{k_{1-d} P_a \left(1 + \frac{\sigma_d}{1+\sigma_c}\right)^{k_{2-d}}}$$ **Equation 3.26**

With the following modifications, the M_{R-r} equation can be reduced.

- Set γ_{dr} = 1 and w_{cr} = 1 in the M_{R-d} equation, since it is expected that the subgrade will be compacted to nearly the maximum density determined in the laboratory proctor testing.
- Assume a 30 inches of pavement material above the subgrade, producing a consistent deviator stress (vertical stress due to overburden of the pavement layers and tire loading) and confining pressure (horizontal stress due to lateral earth pressures).

$$M_{R-r} = \frac{k_{1-c}}{k_{1-d}}\left(1+\frac{\sigma_d}{1+\sigma_c}\right)^{\frac{k_{2-c}}{k_{2-d}}}$$ **Equation 3.27**

Using Equations 3.13 and 3.14, the ratios of k_1 and k_2 (constructed to designed) become:

$$k_{1-r} = \gamma_{dr}^{1.996}\left(\frac{w_{c-opt}}{w_{c-c}}\right)^{0.639}$$ **Equation 3.28**

$$k_{2-r} = \gamma_{dr}^{1.04} w_{cr}^{1.46}$$ **Equation 3.29**

Equation 3.27 then becomes

$$M_{R-r} = k_{1-r}\left(1+\frac{\sigma_d}{1+\sigma_c}\right)^{k_{2-r}}$$ **Equation 3.30**

Similarly, for granular materials, the resilient modulus prediction equation is given by Equation 3.18. The ratio of constructed to designed resilient modulus (M_{R-r}) is then as shown below.

$$M_{R-r} = \frac{k_{1-c}P_a\left(1+\frac{\theta}{1+\sigma_d}\right)^{k_{2-c}}}{k_{1-d}P_a\left(1+\frac{\theta}{1+\sigma_d}\right)^{k_{2-d}}}$$ **Equation 3.31**

As with the model for cohesive soils, similar assumptions are made, and the ratio equation can be reduced to

$$M_{R-r} = \frac{k_{1-c}}{k_{1-d}}\left(1+\frac{\theta}{1+\sigma_d}\right)^{\frac{k_{2-c}}{k_{2-d}}}$$ **Equation 3.32**

Using Equations 3.15 and 3.16, the k_1 and k_2 ratios (constructed to designed) become:

$$k_{1-r} = \frac{0.12+0.90\gamma_{dr}-0.53w_{cr}-0.017(\#200)+0.314\log c_u}{0.49-0.017(\#200)+0.314\log c_u}$$ **Equation 3.33**

$$k_{2-r} = \left(\gamma_{dr} w_{cr}\right)^{1.2385}$$ **Equation 3.34**

Similar to the cohesive soils, the M_R ratio (Equation 3.32) becomes

$$M_{R-r} = k_{1-r}\left(1+\frac{\theta}{1+\sigma_d}\right)^{k_{2-r}}$$ **Equation3.35**

3.3.4 Rutting Damage Ratio

The primary objective of this task is to evaluate the effects of inadequate compaction on the subgrade stiffness and the performance of the pavement to be constructed above the subgrade. In this effort, an evaluation was conducted using Mn/DOT's MnPAVE software. Two pavements were evaluated with difference traffic regimes (500,000 and 5,000,000 design ESALs, respectively). Within each of these pavements, various subgrade strength parameters were used in the design (R-values of 13, 25, 50 and 75). All other parameters were kept constant.

For each R-value, the pavements were designed to produce a damage factor of 1.00 in both cracking and rutting over the 20-year design life, based on the expected resilient modulus suggested by MnPAVE. A standard 6-inch base layer consisting of Class 5 or 6 material (depending on ESAL level) was used, and the thickness of the bituminous and subbase layers were changed to produce a damage of 1.00 predicted over the analysis period (for cracking and rutting). The exception to this is the case of fatigue damage with the 500,000 ESALs, where a reasonable minimum pavement thickness was still too thick to bring fatigue damage to 1.00. In this case the damage (for fatigue only) was constant at 0.42. The rutting damage was started at 1.00 and decreased with decreasing resilient modulus.

Once the pavement structure was designed for these parameters and level of performance, subsequent designs were developed for subgrade resilient modulus (in Fall, Late Spring, and Summer) decreasing by 5% increments (95%, 90%, 85%, 80%, and 75%). As mentioned, the cracking damage increased very little relative to the change in subgrade resilient modulus, and thus is not considered further in this analysis. The resulting change in rutting damage estimates by MnPAVE were recorded and are presented in Figure 3.4 and Figure 3.5.

The following parameters were used in the analysis.

- Climate: Standard values provided for Blue Earth County
- Traffic:

  Lifetime ESALs: 500,000 and 5,000,000

  Heaviest Single Tire Axle: 22 kips, 100 psi tire pressure

  Heaviest Dual Tire Axle: 28 kips, 100 psi tire pressure, 13.5-in tire spacing

- Structure:

  HMA: Thickness varies, PG58-34

  AggBase: Thickness: 6 in., Class 6

  Subbase: Thickness varies, Class 3 or 4 (for 500,000 or 5,000,000 ESALs, respectively)

  UndSoil: Design Modulus (ksi):

    R 13: Fall: 5.156; Winter/Early Spring: 50; Late Spring: 3.609; Summer: 4.383

R 25: Fall: 6.735; Winter/Early Spring: 50; Late Spring: 4.715; Summer: 5.725

R 50: Fall: 7.905; Winter/Early Spring: 50; Late Spring: 5.533; Summer: 6.719

R 75: Fall: 9.718; Winter/Early Spring: 50; Late Spring: 6.802; Summer: 8.260

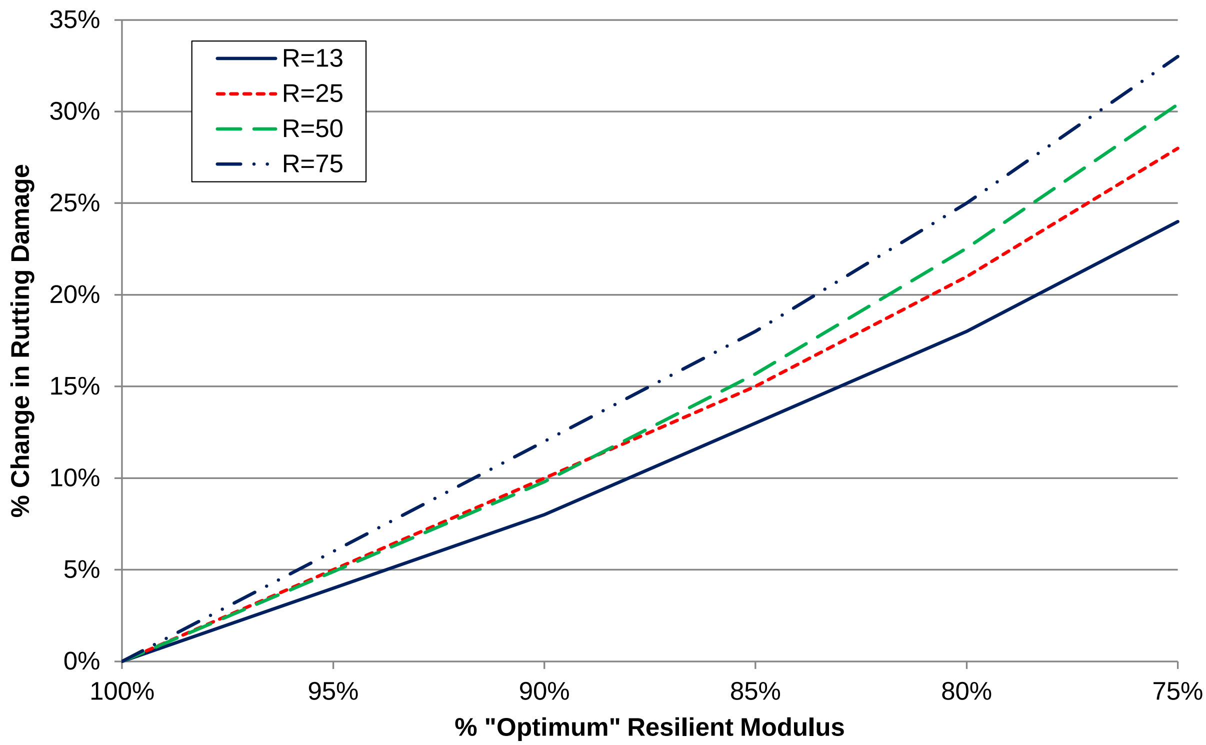

Figure 3.4. Rutting Damage vs. Resilient Modulus – 500,000 ESAL Pavement.

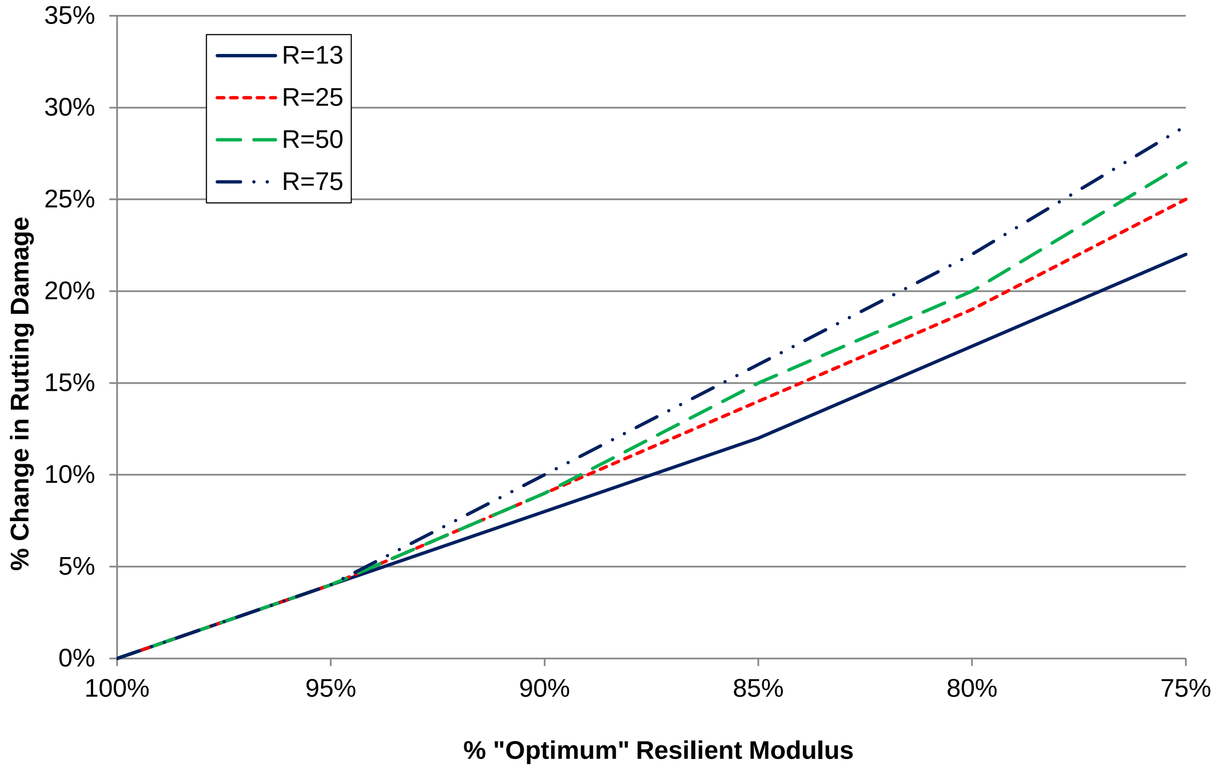

Figure 3.5. Rutting Damage vs. Resilient Modulus – 5,000,000 ESAL Pavement.

Although there are differences in the relationships between change in resilient modulus and change in rutting damage for various R-value subgrades, they follow a close pattern. In the range of decreased resilient modulus values that might be expected in the field (up to 15% reduction due to construction practices) there is almost a linear relationship with rutting damage – a 12 to 15% increase. Fatigue cracking is a distress that is related much more closely to the stiffness and thickness of the asphalt layer at the surface, and thus changes in subgrade resilient modulus does not affect this distress nearly as much. In fact, for the analyses conducted to develop the rutting relationships, the fatigue damage only varied by ±1%.

The model of the rutting damage as a result of decreased resilient modulus, D_{MR}, takes the form

$$D_{MR} = \ln(M_{R-r})^a$$ **Equation 3.36**

where:

D_{MR} = subgrade R-value,

M_{R-r} = resilient modulus ratio, and

a = rut damage equation coefficient.

The increased rutting damage as a function of resilient modulus ratio, as shown in Figures 3.4 and 3.5, while modeled using the complex MnPAVE pavement design tool, can be estimated as a function of M_{R-r} and the R-value of the subgrade soil. As can be seen in the figures, the rut damage equation coefficient is also a function of R-value, which is shown in Equation 3.36 and Figure 3.6, below.

Rut Damage Equation Coefficient = -0.154 ln(R) - 0.4068 **Equation 3.37**

where:

R = subgrade R-value,

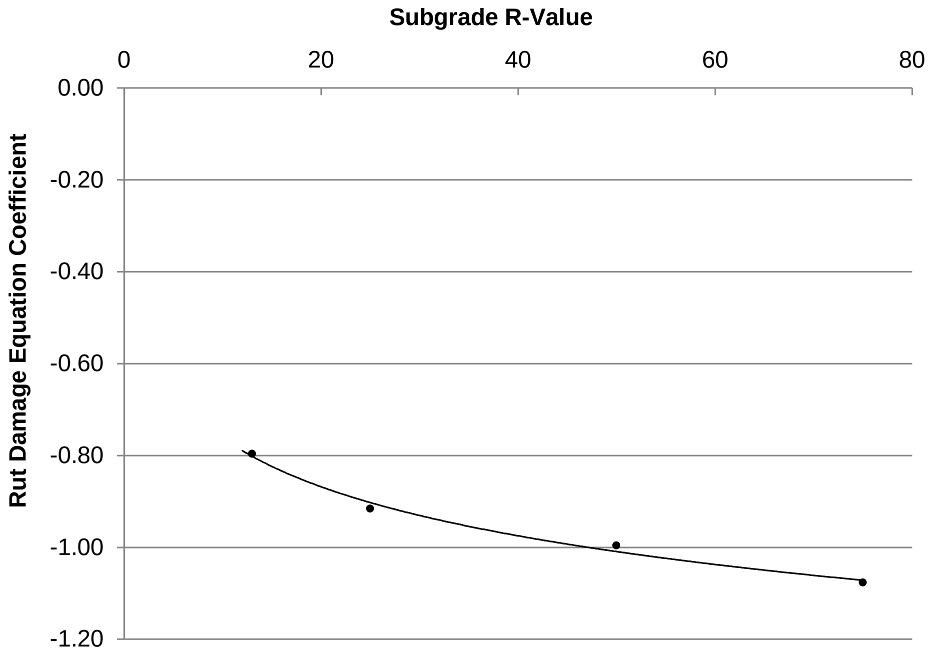

Figure 3.6. Rut Damage Equation Coefficient as a Function of Subgrade R-value.

The relationship between rut damage and decreased resilient modulus ratio then becomes:

$$D_{MR} = \ln(M_{R-r})^{[-0.141 \cdot \ln(R) - 0.4068]}$$ **Equation 3.38**

It is important to note that this relationship is only valid for subgrade R-values between 12 and 75, which likely encompasses most of the soils in Minnesota.

3.4 Laboratory Testing

As part of this task, quantities of cohesive and granular soils were obtained and tested in the laboratory. Both the clay and sandy materials were obtained from the subgrade at the US 14 construction site near Waseca, Minnesota. Three soil types were tested, including the original cohesive and granular materials obtained at the site, and a 1:1 mixture of the two. The basic properties and classification of these three soils are provided in Table 3.5.

Table 3.5. Basic Properties of Evaluated Soils.

	Proctor Maximum Dry Density, pcf	Proctor Optimum Moisture Content, %
Clay	102.0	20.5
Mixed	113.0	13.0
Sand	119.0	12.0

In addition to the proctor testing and classification of the soils, each were tested to determine the R-value, resilient modulus, and triaxial strength at various levels of compactive effort and moisture content. The "clay" was tested at 16%, 20%, and 24% moisture content, while the "mixed" and "sand" were tested at 8% to 16% moisture content at 2% intervals (although the sand was not tested at 16% moisture content). The results of the laboratory testing are provided in Tables 3.6 through 3.8.

Table 3.6. Laboratory Stabilometer Test Results.

		Stabiliometer Testing			
	Target Moisture Content, %	Unit Wt. (pcf)	Moisture Content (%)	Dry Unit Wt. (pcf)	R-value
Cohesive	16	119.0	17.7	101.2	85
	20	123.0	22.3	100.6	63
	24	119.7	25.9	95.1	25
Granular	8				
	10	130.3	10.1	118.4	93
	12	134.0	10.4	121.4	88
	14	129.5	12.4	115.2	83
Mixed	8	114.0	6.9	106.7	62
	10	120.1	10.2	109.0	61
	12	124.4	11.4	111.6	57
	14	127.8	13.3	112.8	46
	16	129.7	15.6	112.2	14

Table 3.7. Laboratory Triaxial Test Results.

		Triaxial Testing			
	Target Moisture Content, %	Moisture Content (%)	Dry Unit Wt. (pcf)	Friction Angle (deg)	Cohesion (psi)
Cohesive	16	17.2	103.2	40.0	7.6
	20	20.4	102.4	14.0	14.3
	24	24.0	100.2	4.0	8.7
Granular	8	8.4	116.8	39.0	6.2
	10	9.7	116.1	37.0	9.8
	12	11.6	117.6	39.0	6.7
	14	14.2	122.9	36.0	0.0
Mixed	8	7.9	109.0	35.0	16.3
	10	10.1	111.2	24.0	19.1
	12	12.1	113.4	28.0	19.4
	14	13.3	114.0	25.0	8.6
	16	16.4	111.8	0.0	16.3

Table 3.8. Laboratory Resilient Modulus Test Results.

		Resilient Modulus Testing					
	Target Moisture Content, %	Unit Wt. (pcf)	Moisture Content (%)	Dry Unit Wt. (pcf)	k1	k2	Mr (at field stress conditions)
Cohesive	16	115.6	17.8	98.1	31041	-0.171	28348
	20	120.3	20.4	99.9	26428	-0.373	21682
	24	122.6	24.8	98.2	3749	-0.31	3180
Granular	8	122.0	7.4	113.6	34918	-0.23	20805
	10	126.6	9.8	115.3	37626	-0.24	21920
	12	127.4	11.9	113.8	19058	-0.399	7762
	14	126.9	14.3	111.0	5150	-0.183	3411
Mixed	8	113.6	6.7	106.5			
	10	114.6	9.4	104.7	9167	0.1448	12700
	12	124.8	11.6	111.9	3917	0.3727	9065
	14	128.6	13.5	113.2	3509	0.3397	7539
	16	129.5	15.0	112.6			

3.5 Conclusions

This section includes a summary of the efforts described in this task, and the correlation of the results to the larger effort described in this report. The objectives of this task were as follows.

1. Attempt to correlate the sinkage of the new test roller vehicle's tire to eventual pavement performance after the entire pavement is constructed.
2. Evaluate the effects of inadequate subgrade compaction on pavement performance.
3. Relate the results of this task to the development of the new test roller equipment and the updated test rolling specification.

These objectives are discussed in the remaining segments of this section.

3.5.1 Sinkage Correlation

The analysis contained in this report relative to the correlation of tire sinkage and pavement performance indicated that while such a correlation may be possible, it can be very difficult and requires field testing to determine the "soil sinkage parameters" as described in this report. As a result, the concept of correlating tire sinkage to soil strength and stiffness properties and thence to pavement performance was divided into two analyses – allowable sinkage and the correlation between soil properties and pavement performance.

The draft construction specifications contained in this report, and developed by the project team and Office of Grading and Base, indicates a maximum allowable sinkage of 0.6 to 0.9 inch (15 to 22 mm) for granular material to be covered by stabilizing aggregate, and 0.4 to 0.6 inch (10 to 15 mm) for all other materials. These are the values shown in Table 3.3. The results of the analysis utilizing the results of research by Hambleton and Drescher (2008a) are shown in Table 3.2. For reasonable soil properties and tire loads, the actual expected sinkage values are estimated to be somewhat lower for granular materials (and ranging from lower to somewhat higher for other materials) than those allowed in the specification. For granular materials, then, the specification will allow slightly more sinkage than expected, to compensate for variability in subgrade soils, and in acceptable levels of compaction.

3.5.2 Effects of Inadequate Compaction on Pavement Performance

The analysis of effects of compaction on pavement performance had greater success, and multiple models were combined with the MnPAVE software to conduct pavement performance computations. The results of this analysis include a model relating the resilient modulus ratio (as-constructed / as-designed) and the subgrade's R value to the expected increase in pavement rutting damage. This model is given in Equation 3.36, and repeated below.

$$D_{MR} = \ln\left(M_{R-r}\right)^{\left[-0.141\cdot\ln(R)-0.4068\right]}$$

where:

D_{MR} = subgrade R-value,

M_{R-r} = resilient modulus ratio, and

R = subgrade R-value.

The relative impact on pavement performance was not correlated with the levels of ESALs for which a pavement is designed nearly as much as with the R-value of the subgrade and the combination of other soil properties which make up the resilient modulus ratio component. In general, as the ratio of as-constructed to as-designed resilient modulus decreases, the expected increase in rutting damage increases almost linearly. In addition, soils with a higher R-value will experience a steeper relationship between modulus ratio and increased rutting damage. These impacts are shown in Figures 3.4 and 3.5.

3.5.3 Relevance to New Equipment and Specifications

The analyses conducted as part of this project are important in relating the new test roller equipment to the revised construction specifications and in providing a meaningful understanding of the pavement performance expected for a given subgrade density. Although other construction specifications require certain levels of compaction and soil density, the density-performance relationship developed as part of this project provides an important link between the components of design, construction, and performance.

With the new test roller equipment, field engineers and contractors are able to test roll the subgrade more often and at lower cost in both time and money. At each test interval, a comparison can be made to the allowable sinkage (and effects on pavement performance related to compaction and density). Thus, intermediate lifts can be tested more easily and problem areas can potentially be identified earlier than by testing at the final elevation of the grading grade. The correlation of soil type, wheel load, and wheel dimensions helps Mn/DOT be more comfortable in the levels of allowable sinkage required by the revised specification. Although additional verification and validation should be conducted on future grading projects, and the allowable sinkage levels may need to be adjusted, the basic theory and analysis are sound, and will support modification suggested by additional field testing.

4 Test Roller Product Specifications Development

4.1 Task Overview

4.1.1 Scope of Task

The overall purpose of this implementation project was to develop a new test rolling system and an associated construction test specification that can be utilized by the Minnesota Department of Transportation (Mn/DOT) to approve compacted subgrades on construction projects. This task of the project (Task 3) involves developing the specifications for the test roller system which meet Mn/DOT's needs and expectations such that development of the prototype can proceed (Task 4). This stage in the development of the test roller is often called the “pre-alpha” stage.

Minnesota State University (MSU), Kessler Soils Engineering Products, Inc. (KSE) and Mn/DOT personnel have worked together to develop the device parameters and specifications for the equipment, software (for data collection, storage and presentation) and test/validation procedures. Representatives from KSE traveled to Minnesota to discuss the expectations and needs of Mn/DOT and to obtain measurements for the standard dump trucks in order to design appropriate instrumentation for the prototype test roller (see Task 4). This task report summarizes the specifications outlined by Mn/DOT which will be incorporated into the prototype test rolling system.

4.2 Test Roller Specifications

Development of a prototype test roller system involves both the development of the hardware needed to obtain the necessary data and also the software needed for data collection, analysis and output. Specifications relating to hardware and software, as discussed and required by Mn/DOT, are provided in this section.

4.2.1 Hardware Specifications

This implementation project originated from discussions of the limitations of the current test rolling system used by Mn/DOT. The existing roller is sufficiently heavy that it is only appropriate for compaction acceptance of thick (> 30 inches) layers of subgrade. Although such a massive roller has the advantage of a deep zone of influence, there are also a number of disadvantages associated with the current system. First, due to the sheer bulk of the roller, mobilization of the test roller is difficult. It must be loaded onto a tractor-trailer and carried from site to site. This becomes an issue when the roller is needed on several sites throughout the state such that these mobilization difficulties and costs become prohibitive. Additionally, even moving the roller on site (typically by a large tractor) can be difficult in areas with softer materials near the right of way. Second, since the tires on the existing roller are no longer manufactured, they have not been replaced for a number of years and are beginning to visibly deteriorate such that safety is a concern. Lastly, the specifications relating to the existing roller were not well-established and require additional investigation and modification.

Initial discussions as to what type of system should be developed varied during the time in which the proposal and the work plan for this implementation project were being developed. Several options were considered, each having some advantages and disadvantages.

One option was to simply re-write the construction specification for the existing roller while developing a more extensive deflection-measuring system. The specification could be evaluated and modified to meet a slightly wider range of applications. A deflection sensor system and data acquisition system could be developed to mount on the existing roller and use in conjunction with the new construction specification as an improvement to the current system. However, this option did not address the mobilization and safety concerns or the limited application of the large roller, each of which was originally discussed and facilitated the need for a new roller system being made available.

Another option was to fabricate a new, smaller version of the test roller, along with an associated deflection-measuring system and construction specification. This smaller roller would meet the needs of improved mobility and safety as well as being useful for acceptance of thinner subgrade layers. A modified construction specification would provide a more robust standard for a wider range of projects, allowing greater flexibility than the current system. However, knowing that the future of test rolling may be limited as Intelligent Compaction technology continues to develop, Mn/DOT did not consider the investment to fabricate a new roller (in addition to developing a new deflection/data acquisition system and a new construction specification) to be worthwhile.

A third option was to develop a trailer system for a standard belly-dump or similar trailer. The deflection system could be mounted to the trailer, which would require a battery to run the data acquisition (rather than a power cable extending from the truck cab that could easily be damaged during testing.) A similar outcome as that of fabricating a new, smaller test roller was possible, except for this case an existing trailer could be loaded with gravel (or other material) to use for the testing. With the exception of the battery need (or the option of a power cable) this seemed to be a feasible option.

The final option which would become the objective of the project was to develop a system that could be mounted to the axle of a standard dump truck. The truck could be loaded to a specified load, which could be incorporated into the construction specification. Since the data acquisition system could be plugged into the truck cab's cigarette lighter to provide power, no external power cords would be necessary. Cords connecting the deflection sensors to the data acquisition system could be extended into the truck cab, along with the cable from the GPS antenna. The system could be placed on the seat next to the truck operator for convenience in entering the necessary testing information and performing the testing. This option was pursued by KSE and MSU personnel.

Once the decision to move forward with a truck-mounted system was made, options were discussed relating to the hardware required for such a system. Two key components of the system were the deflection sensors and the GPS system.

Two types of deflection sensors were considered based on studies and implementation projects in other states. Laser sensors have been used for applications in states such as Washington (Briggs et al. 1999) in Rolling Weight Deflectometer (RWD) development for pavement testing. Lasers appear to do a nice job in measuring the deflection of concrete pavements for this application. However, based on studies in Wisconsin (Crovetti 2002), lasers were not found to be successful in measuring deflections on compacted or existing materials (such as road subgrades), especially when either the particle size was large or, more critically, when moisture on the surface prevented the laser from returning to the source. Also, inherent to the laser is the fact that the deflection is measured at a single point. This leads to significant effects of localized bumps and/or holes in the material.

To avoid issues with respect to using lasers to measure deflections, a sonic sensor was recommended. The sonic sensor takes an average measurement over the footprint of a truncated cone, such that the effect of localized holes and bumps is significantly reduced. Also, moisture on the surface does not influence or prevent deflection readings from being obtained. These two factors resulted in pursuing sonic sensors as deflection-measuring devices.

Further discussion addressed how many of such sensors were necessary to provide the appropriate information. The WisDOT study (2002) and similar studies initially considered an array with multiple sensors surrounding the tire of the truck or being mounted to the axle and bumper of the truck, as shown in Figure 4.1.

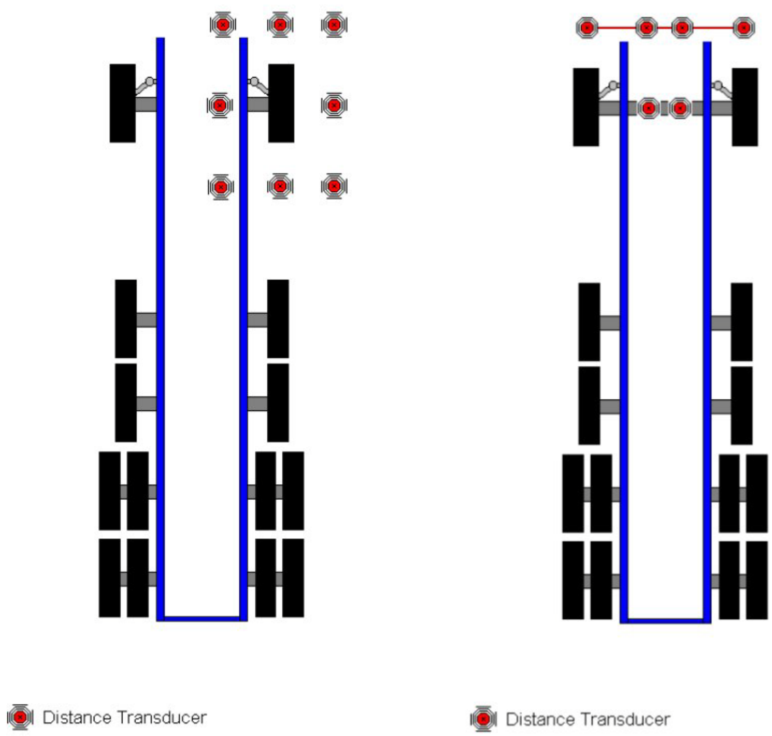

Figure 4.1. Potential Sensor Arrangements for Test Roller System.

The conclusion of the study for WisDOT was that the additional information provided by the additional sensors was not worth the additional cost involved in the additional sensors, additional data collection capability, additional hardware to attach the sensors, and additional processing time needed for such a system. The recommended configuration was to attach two sensors to the front axle of the truck (one on the right side, one on the left). The sensors would be placed far enough from the tire to avoid bulging of the soil near the tire and also be located outside of the deflection basin of the tire. A simple bracket would be designed that could be attached to most common axles to connect the sensor securely to the axle.

In order to provide a reference for the data collected, Mn/DOT required the data output to include GPS coordinates to show the position of the deflection points obtained by the test roller system. The intent of the GPS coordinates was determined to be to provide X and Y coordinates for the data, with the sonic sensors providing the Δz (deflection) values. Although GPS systems are available that can provide sub-centimeter accuracy of elevations (Z) along with the X and Y coordinates, based on discussion with Mn/DOT the GPS system was needed to provide accurate coordinates for X and Y only, such that the increased costs of a sub-centimeter elevation reading were not necessary. A GPS system with such properties (sub-meter in X, Y and Z) was recommended for the test roller system.

The requirements of the data acquisition system were to be able to record data at sufficient intervals to provide the inspector with areas passing (or failing) the deflection criteria. This would allow sections not meeting the criteria to be fixed while those passing the criteria would move forward. The smallest area considered by the TAP group to warrant rejection was an area 5 ft by 5 ft (2 m by 2 m) in size. If a section smaller than this was found in the test rolling program, it would not be worth the effort of fixing the subgrade. For any larger area, the fix would be considered justifiable. To this end, the data acquisition software needs to be capable of providing a deflection reading over a maximum distance of 5 ft (2 m), although higher frequency output may certainly be feasible.

4.2.2 Software Specifications

Much discussion was focused on the required output and the format of this output from the test roller system. At a minimum, the output needed to show GPS coordinates and the sensor deflection readings. Additional items such as project information, stationing, etc. were also recommended for inclusion in the output file. Discussions at the 20 March 2008 TAP meeting finalized the software expectations (input, function and output) for the test roller system.
The first phase of the data acquisition software was to set up and initialize the system. First, the instrumentation (sonic displacement sensors, GPS antenna, and data collection box) needs to be installed on the truck. Once the instrumentation is in place and the truck has been loaded to the required weight (axle load), the axle load needs to be verified. Portable scales and/or truck scales (if locally available) will be part of the final specification. Once the axle weight is known and the tire pressure in the front tires is checked, the system should allow the user to enter appropriate background information for the project, including the project number, the date, the truck weight, the tire pressure, etc. The input parameters made available by the software are included in Table 4.1.

Table 4.1. Input Data Available for Test Roller System.

Input Title (as shown on control panel display)	Input Format	Description
Project Number	Alpha/Numeric	20 character capability
Date	Numeric	MM/DD/YYYY
Weight of Truck	Numeric	XX,XXX LBS
Tire Pressure	Numeric	Left Tire = XX PSI; Right Tire = XX PSI
Distance between sensor and hard surface for calibration, Left and Right	Numeric	Left, XXX mm Right, XXX mm
Tire Size	Alpha/Numeric	20 character capability
Inspector Name	Alpha	20 character capability
Operator Name	Alpha	20 character capability
Type of Material	Alpha	XX – such as CL, CH etc.
Depth from Grading Grade	Numeric	+/- XX.X FT such as -25.2 FT
Start Station	Numeric	Station XXXX+XX such as Station 0125+20
Center Line Offset, Up-station	Alpha/Numeric	Right (+)or left |(-)of CL – such +/- XX.X FT, such as -25.2 FT
Test Roller System Serial Number & the 2 Sensor Serial Numbers	Alpha/Numeric	20 character capability

Once the background data in Table 4.1 is entered by the operator, the system needs to obtain an initial rolling deflection reading (a zero reading). This is to be accomplished by collecting data while the roller is in motion on a stiff, smooth surface. (Smooth asphalt or concrete pavement would be best.) This allows the system to determine the zero reading for the sensors in an environmental with negligible deflections compared to anticipated deflections in subgrade materials to be tested. After the test roller has collected zero readings over a certain distance, the initial reading can be calculated and the roller will be ready to move to the site to test the subgrade at the test section.

Once the roller has moved from the "rigid" pavement where the zero readings are collected to the project site, the operator can begin collecting data at the test section. Table 4.2 shows the data that can be entered prior to commencement of the test rolling.

Table 4.2. Output Data Obtained from Test Rolling System.

Collected Data as shown on control panel display	Output Format	Description
Location X Direction **(From GPS Receiver)**	Numeric	Longitude (WGS84) Station XXXX+XX such as Station 0125+20
Location Y Direction **(From GPS Receiver)**	Numeric	Latitude (WGS84) Offset Distance from centerline of road such as +/- XX.X FT such as -25.2 FT
Location Z Direction **(From GPS Receiver)**	Numeric	Elevation above sea level such as +/- XXX FT such as -25 FT (WGS84)
Deflection (From Ultrasonic Sensors)	Numeric	Distance from sensor on front axle to ground surface. Measurement will be in millimeters such as XXX mm
Speed of the Truck **(Calculated from GPS)**	Numeric	Speed of the truck will be presented as feet per second such as XX FT/SEC and also MPH such as XX MPH

Once data has been collected for the test section, the operator can stop the data collection. The system will store the data to a file which can be downloaded through a USB connection for evaluation. A simple Excel spreadsheet can show displacements and identify coordinates for which deflection criteria are not met such that additional actions can be taken.

4.2.3 Proposed System Schematic

This project will develop a test roller system with two sonic sensors, a GPS antenna, and a data collection system with associated software for use in measuring and recording deflections due to the test roller tire load. A schematic showing the components of the system and the placement of the sensors is given in Figure 4.2.

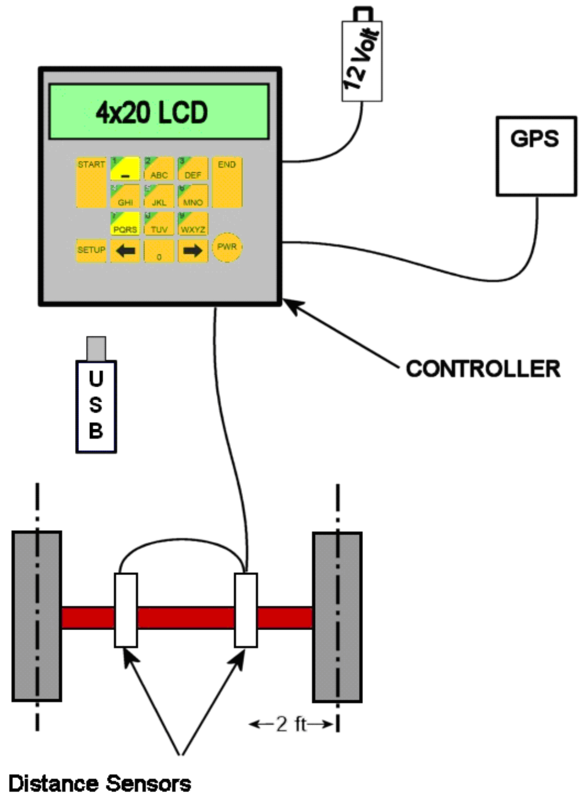

Figure 4.2. Schematic of Test Roller System.

4.3 Summary

Since initial discussions of this project began, several possible systems have been discussed. The final consensus of the TAP group was to develop a truck-mounted system having two ultrasonic sensors mounted to the front axle of a dump truck to measure displacement. A GPS antenna will be part of the system so displacements measured can be associated with GPS coordinate positions to sub-meter accuracy. A data acquisition system will allow data entry to provide site and test roller/truck identification. A "rolling zero" of the system will be performed on a smooth, "rigid" (bituminous or concrete pavement) material to initialize the system. After this zeroing of the system, the roller can be used to test the section of interest. Once test rolling is complete, the data can be stored and uploaded by a USB connection to identify problem areas based on the failure criteria appropriate for the site, material, and roller conditions.

5 Develop Trial System for Truck-mounted Roller

5.1 Task Overview

5.1.1 Scope of Task

This task has developed a trial system for the truck-mounted test roller. The system can be mounted on a standard dump truck, such that deflection measurements and a GPS package can record roller deflections as a function of position. This system is adaptable such that it can be utilized on several available dump trucks. Such a system is significantly more flexible than the existing roller and advantageous with respect to mobilization and safety concerns experienced with the existing roller.

The truck-mounted system includes the following:

- GPS capability
- Microprocessor
- Deflection measurement devices
- Software for data collection, storage and presentation
- X, Y, ΔZ deflection data in tabular format

After the system had been developed, the project team brought the prototype to Minnesota (August 2008) to demonstrate the equipment. To conclude this task, this report has been prepared for Mn/DOT to show the components of the system, the user interface of the software, and the results of the testing of the new equipment. Mn/DOT can use this report, in addition to discussions with those present at the testing, to determine any modifications necessary in the prototype to pursue for the remaining project tasks.

5.2 Test Roller Components

Development of a prototype test roller system involved both the development of the hardware needed to obtain the necessary data and also the software needed for data collection, analysis and output. Specifications relating to hardware and software, as discussed and required by Mn/DOT, were provided in Chapter 4. This task report is intended to show the final prototype components and the interfaces established to be utilized in the test rolling program.

5.2.1 Hardware Components

Initial discussions as to what type of system should be developed varied during the time in which the proposal and the work plan for this implementation project were being developed. Several options were considered, each having some advantages and disadvantages. The option which would become the objective of the project was to develop a system that could be mounted to the axle of a standard dump truck. The truck could be loaded to a specified load, which could be incorporated into the construction specification. Since the data acquisition system could be plugged into the truck cab's cigarette lighter to provide power, no external power cords would be necessary. Cords connecting the deflection sensors to the data acquisition system could be extended into the truck cab, along with the cable from the GPS antenna. The system could be placed on the seat next to the truck operator for convenience in entering the necessary testing information and performing the testing. This system has been developed by KSE and MSU personnel.

Two key components of the system were the deflection sensors and the GPS system, in addition to the necessary data collection system. Two types of deflection sensors were originally considered based on studies and implementation projects in other states. A sonic sensor was recommended based on research into sensor types and with the consent of the TAP group. The sonic sensor takes an average measurement over the footprint of a truncated cone, such that the effect of localized holes and bumps is significantly reduced. Also, moisture on the surface does not influence or prevent deflection readings from being obtained. These two factors resulted in pursuing sonic sensors as deflection-measuring devices.

In order to provide a reference for the data collected, Mn/DOT also required the data output to include GPS coordinates to show the position of the deflection points obtained by the test roller system. The intent of the GPS coordinates was determined to be to provide X and Y coordinates for the data, with the sonic sensors providing the Δz (deflection) values. Although GPS systems are available that can provide sub-centimeter accuracy of elevations (Z) along with the X and Y coordinates, based on discussion with Mn/DOT the GPS system was needed to provide accurate coordinates for X and Y only, such that the increased costs of a sub-centimeter elevation reading were not necessary. A GPS system with such properties (sub-meter in X, Y and Z) has been implemented in the test roller system.

The requirements of the data acquisition system were to be able to record data at sufficient intervals to provide the inspector with areas passing (or failing) the deflection criteria. This would allow sections not meeting the criteria to be fixed while those passing the criteria would move forward. The smallest area considered by the TAP group to warrant rejection was an area 5 ft by 5 ft in (2 m by 2 m) size. If a section smaller than this was found in the test rolling program, it would not be worth the effort of fixing the subgrade. For any larger area, the fix would be considered justifiable. To this end, the data acquisition software has been developed to be capable of providing a deflection reading over a maximum distance of less than 5 ft (2 m), although higher frequency output may certainly be feasible.

Figure 5.1 shows the basic hardware components of the test roller system. Included in the figure are two sonic sensors held in the brackets used to install them on the truck axle, the GPS antenna and cable, and the data collection box used to collect the test roller information.

Figure 5.1. Hardware Components of the Prototype Test Roller System.

5.2.2 Software Components

Much of the initial discussion of the project was focused on the required output and the format of this output from the test roller system. At a minimum, the output needed to show GPS coordinates and the sensor deflection readings. Additional items such as project information, stationing, etc. were also recommended for inclusion in the output file. Discussions at the 20 March 2008 TAP meeting finalized the software expectations (input, function and output) for the test roller system, and these requirements were confirmed in the Meeting Summary submitted following said meeting (included as an Appendix).

The first phase of the data acquisition software is to set up and initialize the system. First, the instrumentation (sonic displacement sensors, GPS antenna, and data collection box) needs to be installed on the truck. Once the instrumentation is in place and the truck has been loaded to the required weight (axle load), the axle load needs to be verified. Portable scales and/or truck scales (if locally available) will be part of the final specification. Once the axle weight is known and the tire pressure in the front tires is checked, the system allows the user to enter appropriate background information for the project, including the project number, the date, the truck weight, the tire pressure, etc. The input parameters made available by the software are included in Table 5.1, as previously provided in the Chapter 4.

Table 5.1. Input Data Available for Test Roller System.

Input Title (as shown on control panel display)	Input Format	Description
Project Number	Alpha/Numeric	20 character capability
Date	Numeric	MM/DD/YYYY
Weight of Truck	Numeric	XX,XXX LBS
Tire Pressure	Numeric	Left Tire = XX PSI; Right Tire = XX PSI
Distance between sensor and hard surface for calibration, Left and Right	Numeric	Left, XXX mm Right, XXX mm
Tire Size	Alpha/Numeric	20 character capability
Inspector Name	Alpha	20 character capability
Operator Name	Alpha	20 character capability
Type of Material	Alpha	XX – such as CL, CH etc.
Depth from Grading Grade	Numeric	+/- XX.X FT such as -25.2 FT
Start Station	Numeric	Station XXXX+XX such as Station 0125+20
Center Line Offset, Up-station	Alpha/Numeric	Right (+)or left |(-)of CL – such +/- XX.X FT, such as -25.2 FT
Test Roller System Serial Number & the 2 Sensor Serial Numbers	Alpha/Numeric	20 character capability

Figure 5.2 through Figure 5.33 provide photographs of the interface screens for the test roller system. These allow the inputs mentioned above to be entered by the operator prior to the test rolling taking place. These figures are given to allow feedback from Mn/DOT to ensure that the appropriate functions are made available in the final system.

Figure 5.2. Input Screen 1 for Prototype Test Roller System (Wait for GPS).

Figure 5.3. Input Screen 2 for Prototype Test Roller System (Press Start to Begin).

Figure 5.4. Input Screen 3 for Prototype Test Roller System (Begin Survey?).

Figure 5.5. Input Screen 4 for Prototype Test Roller System (Timestamp from GPS).

Figure 5.6. Input Screen 5 for Prototype Test Roller System (Project ID).

Figure 5.7. Input Screen 6 for Prototype Test Roller System (Start Station).

Figure 5.8. Input Screen 7 for Prototype Test Roller System (Down or Up Station).

Figure 5.9. Input Screen 8 for Prototype Test Roller System (Depth of Grade).

Figure 5.10. Input Screen 9 for Prototype Test Roller System (Material Type).

Figure 5.11. Input Screen 10 for Prototype Test Roller System (Save Survey).

Figure 5.12. Input Screen 11 for Prototype Test Roller System (No USB Drive Warning).

Figure 5.13. Input Screen 12 for Prototype Test Roller System (RWD Ready).

Figure 5.14. System Setup Screen 1 for Prototype Test Roller System (Zero Sensors).

Figure 5.15. System Setup Screen 2 for Prototype Test Roller System (Setup Vehicle).

Figure 5.16. System Setup Screen 3 for Prototype Test Roller System (Time and Date).

Figure 5.17. System Setup Screen 4 for Prototype Test Roller System (USB Test).

Figure 5.18. System Setup Screen 5 for Prototype Test Roller System (About Test Roller).

Figure 5.19. Zero Sensors Screen 1 for Prototype Test Roller System (To Zero, Press Start).

Figure 5.20. Zero Sensors Screen 2 for Prototype Test Roller System (Deflection Zero).

Figure 5.21. Zero Sensors Screen 3 for Prototype Test Roller System (Sensor Tare Values).

Figure 5.22. Truck Setup Screen 1 for Prototype Test Roller System (Truck Setup Press Start).

Figure 5.23. Truck Setup Screen 2 for Prototype Test Roller System (Left Wheel Load).

Figure 5.24. Truck Setup Screen 3 for Prototype Test Roller System (Right Wheel Load).

Figure 5.25. Truck Setup Screen 4 for Prototype Test Roller System (Left Tire Pressure).

Figure 5.26. Truck Setup Screen 5 for Prototype Test Roller System (Right Tire Pressure).

Figure 5.27. Truck Setup Screen 6 for Prototype Test Roller System (Left Tire Manufacturer).

Figure 5.28. Truck Setup Screen 7 for Prototype Test Roller System (Right Tire Manufacturer).

Figure 5.29. Truck Setup Screen 8 for Prototype Test Roller System (Left Tire Model No.).

Figure 5.30. Truck Setup Screen 9 for Prototype Test Roller System (Right Tire Model No.).

Figure 5.31. Truck Setup Screen 10 for Prototype Test Roller System (Saving Truck Setup).

Figure 5.32. Sensor Setup Screen 1 for Prototype Test Roller System (View Live Readings).

Figure 5.33. Sensor Setup Screen 2 for Prototype Test Roller System (Adjust Calibration).

Figure 5.34. Sensor Setup Screen 3 for Prototype Test Roller System (Sensor Serial Number).

Figure 5.35. Recording Deflection Screen for Prototype Test Roller System.

Once the background data in Table 5.1 is entered by the operator, the system needs to obtain an initial rolling deflection reading (a zero reading). This is accomplished by collecting data while the roller is in motion on a stiff, smooth surface. (Smooth asphalt or concrete pavement would be best.) This allows the system to determine the zero reading for the sensors in an environment with negligible deflections compared to anticipated deflections in subgrade materials to be tested. After the test roller has collected zero readings over a certain distance, the initial reading can be calculated and the roller will be ready to move to the site to test the subgrade at the test section.

Once the roller has moved from the "rigid" pavement where the zero readings are collected to the project site, the operator can begin collecting data at the test section. Table 5.2 shows the data that can be entered prior to commencement of the test rolling.

Table 5.2. Output Data Obtained from Test Rolling System.

Collected Data as shown on control panel display	Output Format	Description
Location X Direction **(From GPS Receiver)**	Numeric	Longitude (WGS84) Station XXXX+XX such as Station 0125+20
Location Y Direction **(From GPS Receiver)**	Numeric	Latitude (WGS84) Offset Distance from centerline of road such as +/- XX.X FT such as -25.2 FT
Location Z Direction **(From GPS Receiver)**	Numeric	Elevation above sea level such as +/- XXX FT such as -25 FT (WGS84)
Deflection (From Ultrasonic Sensors)	Numeric	Distance from sensor on front axle to ground surface. Measurement will be in millimeters such as XXX mm
Speed of the Truck **(Calculated from GPS)**	Numeric	Speed of the truck will be presented as feet per second such as XX FT/SEC and also MPH such as XX MPH

Once data has been collected for the test section, the operator can stop the data collection. The system will store the data to a file which can be downloaded through a USB connection for evaluation. A simple Excel spreadsheet can show displacements and identify coordinates for which deflection criteria are not met such that additional actions can be taken. An example of the output file is contained in Figure 5.34.

```
Project:        BIG HIGHWAY
Date:   01/02/2008
Time:   13:23:42
Operator:       SUPER SURVEYOR

TRUCK SETUP
Right Wheel Load lbs:   10245
Left Wheel Load lbs:    10240
Right Tire Pressure PSI:        85
Left Tire Pressure PSI: 86
Right Wheel Manufacture:        GOODYEAR
Left Wheel Manufacture: GOODYEAR
Right Wheel Model Number:       195P65 125
Left Wheel Model Number:        195P65 125

DEFLECTION MONITORING SYSTEM
Control Unit Serial Number:     1881
Control Unit Calibration Date:  01/01/2008
Right Deflection Sensor Serial Number:  1235
Left Deflection Sensor Serial Number:   1452
Right Deflection Sensor Tare Value:     10.11
Left Deflection Sensor Tare Value:      10.12
Right Deflection Sensor Tare Time Stamp:        01/02/2008
Left Deflection Sensor Tare Time Stamp: 01/02/2008
Right Deflection Sensor Tare Noise:     0.05
Left Deflection Sensor Tare Noise:      0.04
GPS Status:     +-1.8m

SURVEY SETUP
Start Station:  012+00
Offset: RIGHT 1.5 FT
Direction:      UP
Material Type:  CLAY
Depth from Final Grade: 6 IN

SURVEY DATA
STATION SPEED   DEFLECTION RIGHT        DEFLECTION LEFT GPS
100+00  0.0     0.10    0.05    33.192508, -82.529541
100+03  0.8     0.15    0.15    33.192510, -82.529535
100+06  1.5     0.12    0.18    33.192514, -82.529532
100+09  2.7     0.08    0.20    33.192520, -82.529536
```

Figure 5.36. Sample Output File from Test Roller Prototype.

Sample data collected during the prototype demonstration at MNROAD are included in Figure 5.35. Data from each sensor are plotted as a function of the distance along the test section.

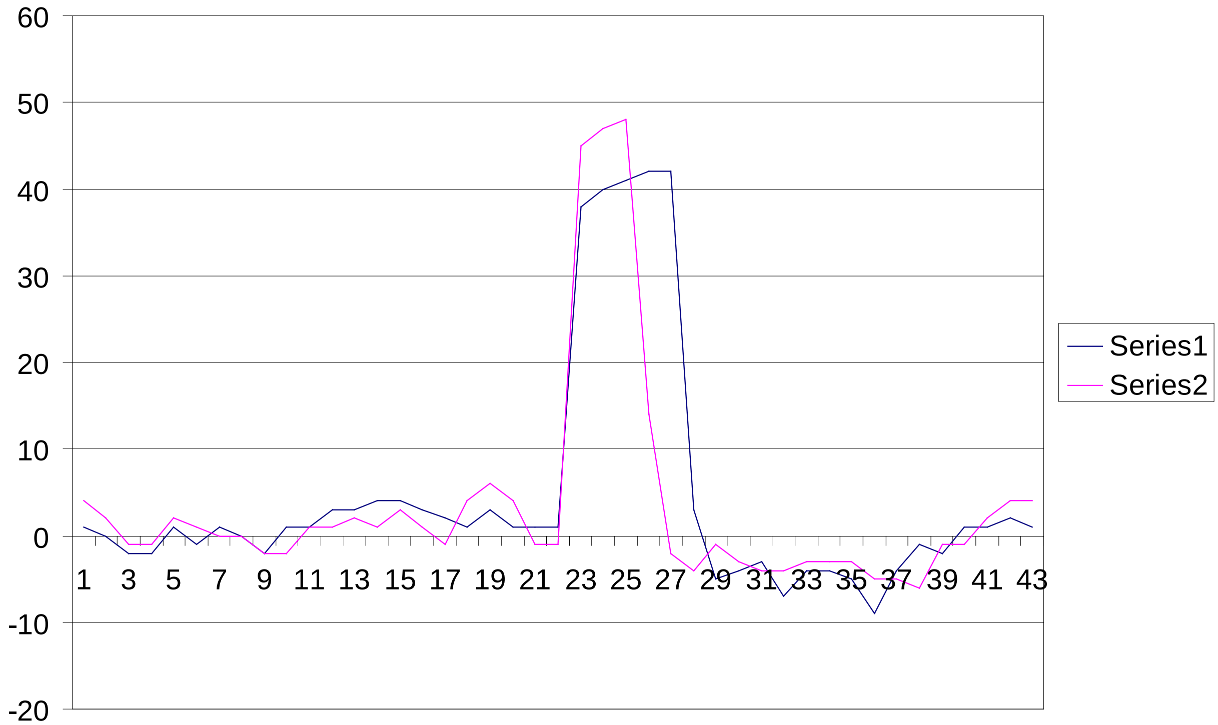

Figure 5.37. Sample Output Data from Test Roller Prototype.

5.3 Summary

Since initial discussions of this project began, several possible systems have been discussed. The final consensus of the TAP group was to develop a truck-mounted system having two ultrasonic sensors mounted to the front axle of a dump truck to measure displacement. A GPS antenna is part of the system so displacements measured can be associated with GPS coordinate positions to sub-meter accuracy. A data acquisition system allows data entry to provide site and test roller/truck identification. A "rolling zero" of the system can be performed on a smooth, "rigid" (bituminous or concrete pavement) material to initialize the system. After this zeroing of the system, the roller can be used to test the section of interest. Once test rolling is complete, the data can be stored and uploaded by a USB connection to identify problem areas based on the failure criteria appropriate for the site, material, and roller conditions.

6 Prototype and Deflection Formula Validation

6.1 Task Overview

6.1.1 Scope of Task

This task has validated the system which has been developed for the truck-mounted test roller. As has been shown during the course of previous tasks, the system can be mounted on a standard dump truck, such that deflection sensors and a GPS package can record roller deflections as a function of position. This system is adaptable such that it can be utilized on several available dump trucks of various wheel sizes and axle loads. The system is significantly more flexible than the existing test roller and advantageous with respect to mobilization, practical implementation and safety concerns experienced with the existing roller. The benefits of having continuous recorded data as a function of position from a construction site are also significant, as recorded data may be referenced in the future as pavement performance monitoring and maintenance continues.

The truck-mounted system developed during the course of this project was prepared by Kessler Soils Engineering (KSE) during the Task 3 and Task 4 portions of the project. Similar products can be purchased through KSE, and Mn/DOT is currently working with KSE to obtain several additional systems for continuing implementation. The prototype system includes the following, components of which are shown in Figure 6.1:

- GPS capability (white antenna and cable on top left of Figure 6.1)
- Microprocessor (in data collection unit on right of Figure 6.1)
- Deflection measurement devices (two sensors shown in mounting brackets in front of Figure 6.1)
- Power cable to cigarette lighter power supply
- Software code for data collection, storage and presentation
- X, Y, ΔZ deflection data in tabular format

Figure 6.1. Hardware Components of the Prototype Test Roller System.

Once the original system had been developed, the project team brought the prototype to Minnesota (August 2008) to demonstrate the equipment. To conclude Task 4, a summary report was prepared for Mn/DOT to show the components of the system, the user interface of the software, and the results of the testing of the new equipment at the sites visited on that occasion (Mn/ROAD demonstration and Waseca near TH 14 project). This task report (Task 4) has been modified for inclusion as an appendix in the final report to create a self-standing user manual for the developed system, which may be referenced in the construction specification.

During the course of and subsequent to that initial demonstration and evaluation, several modifications to the system were recommended by Mn/DOT and project personnel and changes to the system were implemented in the prototype during the winter and spring (2008-2009). Several changes in the text and output in the user interface, modifications to the data collection frequency and algorithm, and other recommendations were incorporated into the prototype.

During the following construction season (summer 2009), arrangements were made for using the test roller at three sites; Highway 14 expansion near Waseca (Susan Museus), Cottonwood County (Ron Gregg) and Scott County (Mitch Rasmussen). It was desired to test multiple sites with several soil subgrades in order to ensure that the modified system functioned as intended and desired, along with allowing the deflection model to be validated.

The system was used effectively on the TH 14 expansion project. Results from that project are included in this document in Section 6.2. However, the two additional projects were delayed (due to a combination of contracting delays and adverse weather conditions) until the following (2010) construction season. The hardware and software have been shown to be primarily acceptable with the validation to date. Additional opportunities to validate the deflection model were pursued during the 2010 construction season. While several previously identified projects did not implement the new test roller system, the implementation was successful on a project with Olmsted County County State Aid Highway (CSAH) 10 reconstruction. This implementation will be given in Section 6.3.

6.2 Prototype and Deflection Model Validation

Development of a prototype test roller system involved both the development of the hardware needed to obtain the necessary data and also the software needed for data collection, analysis and output. Specifications relating to hardware and software, as discussed and required by Mn/DOT, were provided in the Task 3 Summary Report. The Task 4 Summary Report provided the details of the prototype as a final product, including some of the data collected during the development process. This task report is intended to confirm the functionality of the final prototype based on the validations performed to date.

6.2.1 Original Prototype

The original prototype of the test roller system was found to be functional and for the most part met Mn/DOT expectations. A number of minor modifications to the user interface were suggested and implemented (for example, changing "RWD" to "Test Rolling"), but these changes were minimal. Other changes were made to the data collection code to improve the efficiency of the output, which was made possible when a new processor became available. Overall, the original prototype and the modified prototype are very comparable and each would meet the expectations of the test roller development project. Figure 6.2 shows several pictures of the prototype being connected to a Mn/DOT truck during the prototype development.

Figure 6.2. Sensors Mounted to Front Axle of Mn/DOT Plow Truck.

6.2.2 Modified Prototype Used on Trunk Highway 14 Project near Waseca

As mentioned, the modified prototype was used on the Highway 14 expansion project near Waseca, Minnesota in September 2009. Mn/DOT's local maintenance shed provided a plow truck for the day, which worked nicely on the test rolling section. Prior to test rolling, the truck was loaded with fill material to the maximum gross weight allowed for the truck. The truck was driven to a local truck scale to obtain the front axle weight. (This may be done in the future using portable scales to be included in the test rolling package.) Once the front axle weight was obtained, the truck returned to the project site. When approaching the site, the operator performed a "rolling zero" reading on smooth pavement as the truck approached the project site. This rolling zero was discussed in the Task 4 report, but essentially provides the opportunity to tare the sensors by obtaining an average sensor reading while the truck rolls, at test rolling speed, along a smooth section of asphalt or concrete pavement. Having this average distance from the sensor to the "rigid" pavement as a tare value, deflections measured on soil subgrade can accurately show the deflection of the soil.

Table 6.1 shows a portion of the data collected on one of the runs at Waseca. The complete set of data from four of the runs has been included in the Appendix. Figure 6.3 shows an Excel plot of the data from one run as a function of the data point. This plot can be replicated given only the raw data without difficulty. Figure 6.4 shows the same data plotted as a function of the distance from the start station. While this requires some calculations (to convert GPS coordinates to a distance along the rolling path), this can be done quickly by the engineer or inspector as soon as the data file is opened.

Table 6.1. Sample Test Roller Data for TH 14 Expansion (First 28 Data Points Included).

Project:	HWY 14 TEST RUN			
Date/Time:	9/30/2009 19:00			
Operator:	AARON BUDGE RUN			
TRUCK SETUP				
Left Wheel Load lbs:	6500			
Right Wheel Load lbs:	6500			
Left Tire Pressure PSI:	125			
Right Tire Pressure PSI:	125			
Left Tire Manufacture:	GOODYEAR			
Right Tire Manufacture:	GOODYEAR			
Left Tire Model Number:	P156V5678			
Right Tire Model Number:	P156V5678			
DEFLECTION MONITORING SYSTEM				
Control Unit Serial Number:	1234			
Control Unit Calibration Date:	2/17/2008			
Left Deflection Sensor Serial Number:	1234			
Right Deflection Sensor Serial Number:	1235			
Left Deflection Sensor Tare Time Stamp:	5/6/2008 13:25			
Right Deflection Sensor Tare Time Stamp:	5/6/2008 13:25			
Right Deflection Sensor Tare Value (mm):	200			
Right Deflection Sensor Tare Value (mm):	200			
SURVEY SETUP				
Start Station:	555+00			
Offset (ft):	RIGHT 0.5			
Material Type:	PLASTIC			
Depth from Final Grade (in):	0			
Data Collection Rate(Hz):	2			
SURVEY DATA				
LINE	DEFLECTION LEFT	DEFLECTION RIGHT	GPS	
	(mm)	(mm)	Latitude	Longitude
0	4	-16	4403.5118	9326.423
1	13	-11	4403.5117	9326.4238
2	4	-19	4403.5117	9326.4245
3	1	-16	4403.5116	9326.4252
4	14	-13	4403.5115	9326.4259
5	2	-20	4403.5115	9326.4266
6	2	-19	4403.5114	9326.4274
7	-3	-21	4403.5114	9326.4281
8	-5	-13	4403.5113	9326.4289
9	-6	-17	4403.5112	9326.4296
10	-10	-22	4403.5112	9326.4303
11	-16	-11	4403.5111	9326.4311
12	-10	-15	4403.511	9326.4318
13	-16	-7	4403.511	9326.4325
14	-13	2	4403.5109	9326.4332
15	-17	-4	4403.5108	9326.4339
16	-16	0	4403.5108	9326.4346
17	-7	-5	4403.5107	9326.4353
18	-8	1	4403.5106	9326.4361
19	-1	-3	4403.5105	9326.4368
20	-4	-4	4403.5104	9326.4375
21	1	-5	4403.5104	9326.4383
22	-3	2	4403.5103	9326.439
23	-4	7	4403.5102	9326.4397
24	-3	6	4403.5101	9326.4404
25	1	4	4403.5101	9326.4411
26	5	5	4403.51	9326.4418
27	-1	5	4403.5099	9326.4425
28	0	-9	4403.5098	9326.4432
29	4	-11	4403.5097	9326.4439
30	8	-21	4403.5096	9326.4446
31	10	8	4403.5096	9326.4454
32	6	1	4403.5094	9326.4461

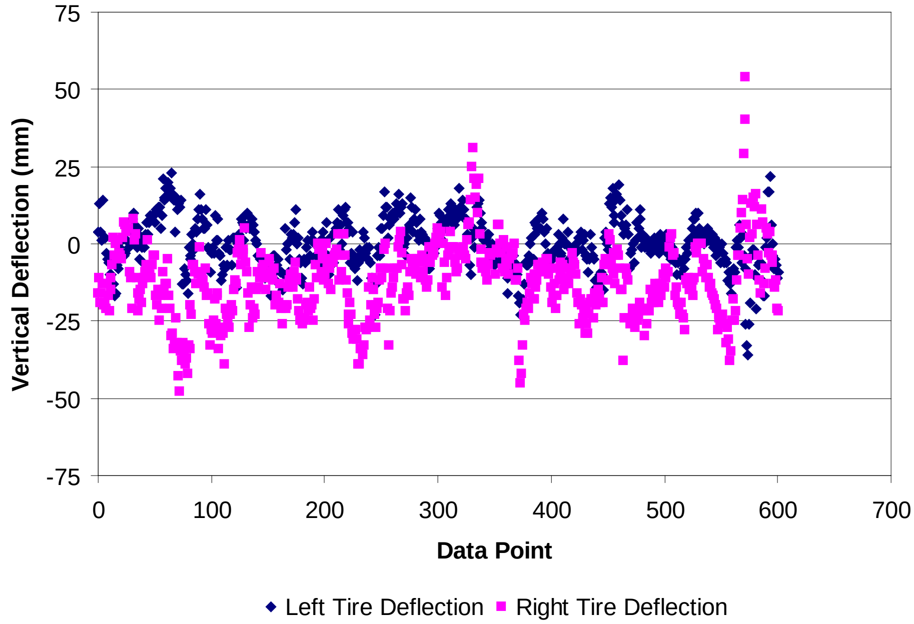

Figure 6.3. Sample Modified Test Roller Data from TH 14 as a Function of Data Point Number.

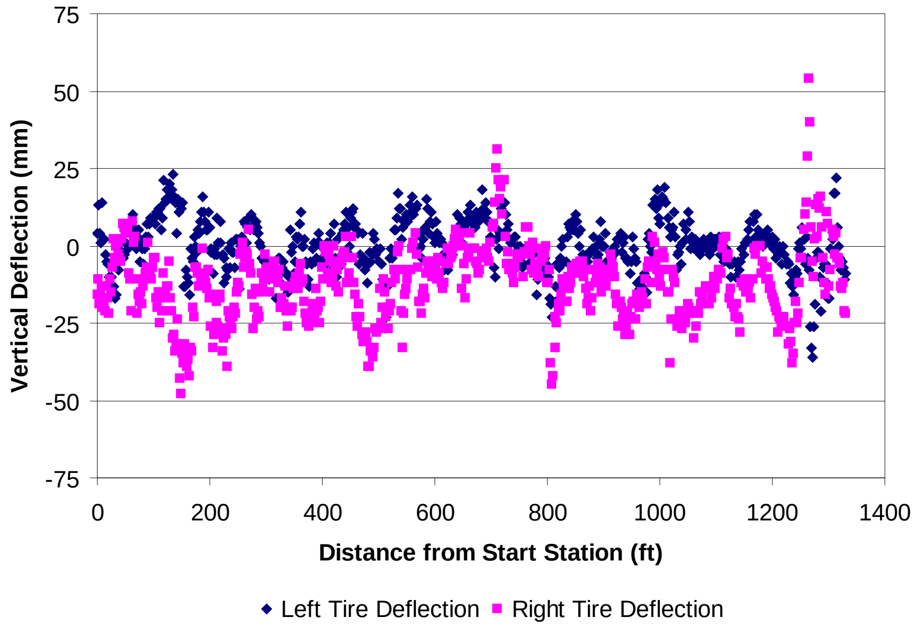

Figure 6.4. Sample Modified Test Roller Data from TH 14 as a Function of Distance from Start Station.

As seen in this data, measured deflections at each tire were frequently less than one inch (25 mm), with a few places showing deflections in excess of one inch. Given the wheel load and soil type present at the site (wheel load 6,500 lb (30 kN), plastic soil with estimated cohesion of 1,000 psf (50 kPa) and friction angle between 10 and 15 degrees), using these estimated soil parameters the deflection model developed by the University of Minnesota would indicate an acceptable deflection ranging from 0.6 inches to 1.2 inches (15 mm to 29 mm). Since no soil strength data were obtained from soils at the immediate site (plastic soil samples were recovered from a location near the site, but not immediately at the tested site), there may be some variation in the actual allowable deflection. The soil samples obtained from the project were tested in the laboratory and found to have a cohesive strength of 2000 psf (100 kPa) and a friction angle of 14 degrees when compacted to maximum dry density at the optimum water content. However, the cohesion of the soil tested dropped to around 1000 psf (50 kPa) at water contents 4% above and 4% below optimum. While such a deviation from optimum water content is not anticipated in the field, if the site was compacted slightly above or below optimum water content, the cohesion would change noticeably. For the soils tested in the laboratory, the University of Minnesota model would predict less than 0.2 inches (5 mm) of deflection, which is much less than witnessed at the site with the modified test roller system. This has been addressed further during the course of Task 7.

Based on the standard test rolling also performed at the site and discussions with project personnel on site, it would appear that a deflection criterion of 1.5 inches (40 mm) would be appropriate at this site for the loading given. There was only a short section of the section tested using the modified roller system which had not passed when tested with the traditional roller and acceptance criterion (2 inches or 50 mm) earlier that day. While this spot was also apparent for the modified roller runs, the criterion given above (1.5 inches or 40 mm) would be needed to indicate failure for these soils. For subsequent projects, it is suggested that soil samples from the immediate site be obtained to provide more accurate strength values to appropriately validate the soil and identify an appropriate maximum deflection. As seen in both Figure 6.3 and Figure 6.4, only a few very short sections had deflections exceeding 1.5 inches (40 mm). This was also seen in the response of the traditional test roller, where only a few very limited lengths exceeded the deflection criterion, such that the subgrade was accepted at the site.

6.3 Additional Field Implementation and Validation

As mentioned, several projects were postponed during the first construction season for which the modified test roller prototype was available, which limited the number of projects for which validation was possible. The validation conducted at TH 14 near Waseca was the only data collected during 2009. This project showed that the hardware and software worked reasonably well, but the ability to evaluate the deflection model was limited and for that site the deflection model did not mimic the standard test roller acceptance criterion. Field observation of failed sections allowed a deflection three times greater than that proposed by the University of Minnesota's deflection model for the soil properties assumed. Additional projects were needed to validate the model and also provide insight in developing the construction specification for the new roller system.

Technical Advisory Panel (TAP) members announced the new roller system and the need for validation projects to various groups in an effort to establish potential validation projects.

Several contacts were made with various groups on various projects, but in multiple cases there was difficulty in making use of the modified test roller system when such utilization had not been included in the original project contracts. However, due to difficulties in implementing Intelligent Compaction as a method of quality assurance on Olmsted County Highway 10, project personnel were open to using the modified test roller system on this project in order to move things forward while the IC issues were resolved. Several meetings were held to discuss the system and provide training for implementation, and Minnesota State Mankato and Mn/DOT personnel visited the site on several occasions to help with data collection and evaluation. After these initial visits, Olmsted County personnel kept the equipment and continued to use it on the project until the end of the construction season. All of the data collected by Olmsted County will not be provided at this time, but additional data can be obtained/provided, if desired.

Figure 6.5 shows several pictures of the system as implemented by Olmsted County personnel.

Figure 6.5. Modified Test Roller System as Implemented by Olmsted County (Photographs courtesy of Curt Bolles and Kent Haugen from Olmsted County.).

Rebecca Embacher, from the Grading and Base unit of the Mn/DOT Materials Office, developed a user-friendly/automated spreadsheet based on the initial spreadsheet created by Minnesota State University personnel. This spreadsheet takes the output data from the data collection system of the modified test roller system and performs several calculations in order to plot the deflection data collected at a site as a function of the station. Also shown are the deflection limits proposed for the project to indicate passing/non-passing subgrades. Deflections exceeding the criteria required the contractor to rework that section and retest for approval. Deflections less than the criteria were considered to be acceptable.

Figure 6.6 shows the graphical output from the original spreadsheet developed by MSU Mankato personnel. The spreadsheet takes the recorded GPS coordinates, converts those coordinates to relative distances from the start station and allows a plot of deflection as a function of stationing to be created. Figure 6.6 plots the deflection readings for each of the two sensors as a function of the stationing. The oval shows an area of concern where the measured deflections exceeded the allowable deflections and where the contractor was required to rework the subgrade prior to continuing with construction.

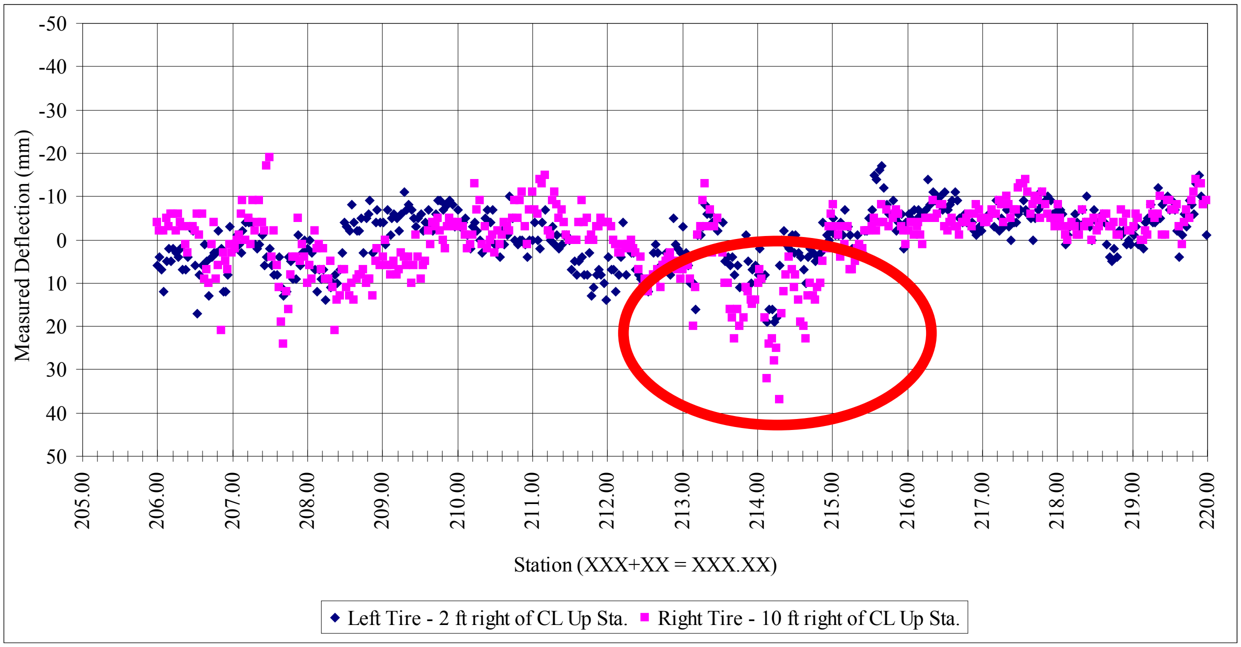

Figure 6.6. Graphical Output from Original Spreadsheet.

Figure 6.7 shows graphical output from the modified spreadsheet developed by Embacher and utilized by Olmsted County personnel for the project. This spreadsheet essentially automates the development of the graphical output and the associated calculations required for this output. The addition of the deflection criteria on the plot was greatly beneficial, allowing immediate visualization of sections where the compacted subgrade did not meet expectations for the project.

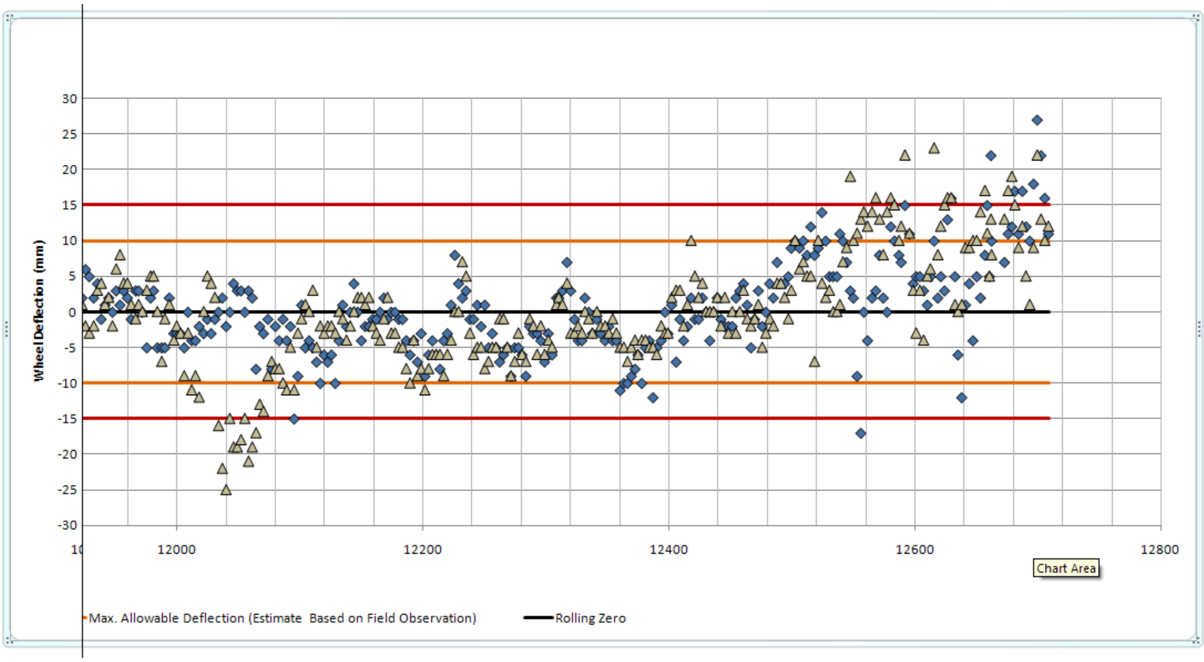

Figure 6.7. Screenshot of Graphical Output from Modified Spreadsheet by Embacher.

In addition to developing the modified spreadsheet to automate the data analysis process, Embacher also utilized GIS software to plot the data as a function of their GPS coordinates. Several plots of deflection as a function of location are provided in Figure 6.8. Data points shown in green show deflections less than the deflection criteria indicated (+/- 10 mm or +/- 0.4 in). Points shown in yellow have deflections between 10 and 15 mm (0.4 and 0.6 in), indicating points of concern. Points shown in red have deflections exceeding +/- 15 mm (0.6 in), indicating that these sections clearly failed the deflection criteria for the project. These criteria were determined by field evaluation of the performance of the subgrade during test rolling.

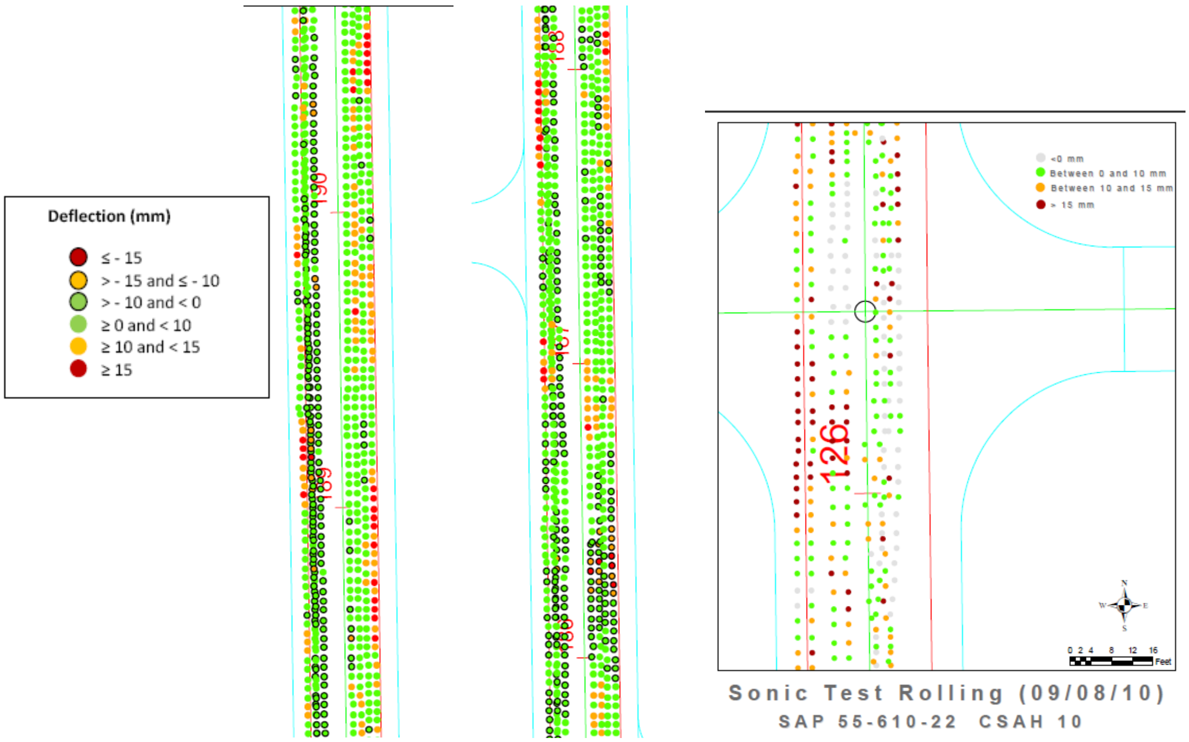

Figure 6.8. Graphical Output from GIS Software (prepared by Embacher).

In the section shown two passes were made in each direction for coverage from slightly right of centerline to the shoulder. Much of the subgrade in the traffic lanes was compacted adequately, but as seen in Figure 6.8, the material near the shoulder had deflections in excess of 10 mm (0.4 in), causing concern. Several of these sections required additional compaction before construction was allowed to proceed.

6.4 Items of Note in Subsequent Hardware Modifications

During the course of the piloting program, a number of issues have been brought forward that can be addressed in continuing implementation of the new test roller system and specification. The Grading and Base unit has compiled a list of items for consideration, as provided in Table 6.2, and distributed by Rebecca Embacher. Each is briefly addressed in this section and was discussed with the Technical Advisory Panel members at the final project TAP meeting.

Table 6.2. Synopsis of Concerns/Issues with Test Roller System to be Addressed.
(Software Development Items are Shaded in Gray.)

Item Added	Comment	Comments	Complete (Y/N/NA)
08/31/10	1. Program software to export GPS X & Y coordinates as decimal degrees.	The current system exports as degrees and minutes written as one number which adds additional steps/conversions when importing data into other software platforms (e.g., ArcGIS, etc.). Additionally, it is a step that can be easily missed (i.e., converting the last digits from minutes to degrees).	
	2. Determine precision and range of the sonic sensors	This is important to know as it will help with determining the tolerance(s) required for pass/fail values.	
	3. If not already addressed, address how one would calibrate these sensors (i.e., internally, or do they need to be sent back to the manufacturer).		
	4. Include the following GPS coordinates in ASCII output: • GPS coordinates directly from GPS unit (*done – already exported*). • Estimated GPS coordinates for the left and right sensor.	This is needed in order to plot the data on plan view. Therefore, it is also important to know the placement of the GPS unit on the truck and locations of the sensors (offset distance of the GPS unit from each sensor).	
	5. Collect static and rolling tare values (zeros) for sonic and GPS sensors on Concrete and Asphalt. This would include repeating the measurements in the testing mode to allow for review of data. The static data would also be used to review for the presence floating values with the sonic sensor.	• The objective is to find the distance between the sensors and the testing surface without deflections present. • Measurements are taken outside of the deformation area of the tire. • Concrete would be the desired medium. • Would the effects of a static wheel vs. rolling be significant on PCC? • Is a rolling value really needed? Concrete slabs are always available and present in the storage shops.	
	6. Clarify whether positive limits are only needed.	It appears that for different scenarios a negative limit is also needed. This would help ensure that the contractor ensures a smooth surface for testing. Additionally, there are scenarios where depending upon the wheel/sensor location (divots / high spots) the calculations would not be accurately reflected in the pos./neg. reading.	
	7. Increase the buffer on the data collection system to a minimum	This would allow for a maximum distance of 2 ft when driving $\leq$.5 mph	

	of 3.5 Hz.		
	8. Fix ASCII output text. There are 2 "right deflection sensor tare value" headers.	Row 23 is supposed to be for the left sensor.	
	9. Create a different text format for the exported file names.	• The current generic, consecutive order format (i.e., MNRWD***) could potentially be copied over as additional data is collected on other dates or projects. • A simple date and time stamp as the file name would eliminate this problem.	
	10. Fix the data modified for the file exports.	The date modified for each exported text file is always "12/20/2004 12:00 AM". This needs to be corrected to make it easier for our inspectors to find files and also as a secondary means to ensure no tampering has occurred in the raw files by either the Agency or Contractor.	
Item Added	**Comment**	**Comments**	**Complete (Y/N/NA)**
09/13/10	11. Sudden large distance between data points. See Figures 6.9 and 6.11.	The example shown, would have required the speed to spike at 9 mph. Some are as long as 10 ft between points.	
	12. Instant/sudden 'jags' to GPS coordinates (longitudinal direction). See Figures 6.9 – 6.11.	There are quite a few instances where there is a lateral shift in 2 consecutive GPS coordinates from east to west. Why does this happen?	

	13. Significant difference between sonic sensor measurements of left and right tire of passes in the same direction, when tire location is fairly close. Instances of 15 mm differences, etc. (See Figure 6.12 for an example).	• Is this a concern??
		
		• Could be attributed to sub-meter GPS accuracy or rough estimate of sensor locations without knowing correct offset distance.
		
		• Are the left and right sensors calibrated accurately?
		
		• Is one able to do a quick test to verify that they do not require calibration?
		
		• How often do they require calibration?
		
		• It could be attributed to the rolling zeros being used for each sensor, sensor precision, noise, etc.
		
		• Recommend running some type of validation/repeatability matrix at Mn/ROAD. For instance,
		
		    • Run truck in the same direction (e.g., WB) for all passes.
		
		    • 1st pass have left tire on centerline (or some	

		other feature that can be reproduced). • 2nd pass have right tire follow centerline (or other feature used for 1st pass). • Please note that CL joints could potentially cause a problem if concrete sections are used.	
	14. Allow data entry of X & Y offset distance (in ft) of GPS unit from LT sensor.	This is part of comment 4	
	15. Ensure the current system allows connection to base stations when available on projects.	• What would be the consequences of this action? • Could it potentially cause real-time problems trying to get the GPS to connect to a base station? • If one is unsuccessful with establishment to a base station, could one still run without use of the base station, as technical support might not be available?	
	16. Is there a maximum limit to the file size (i.e., number of data points that the data logger can store within one file)?		
09/23/10	17. Determine why stationing is not always updated in current file after data entry.	It appears that it works for the increasing stationing (pass 1 & 3), but not for 2 & 4. However, I haven't looked at a large volume of files to ensure this trend.	
	18. Export data in database form.	It would be beneficial if the data was in a dbase format, where all information is contained in a columnar format. For instance, all header information should be contained in columns with repeating information up to the number of points collected.	

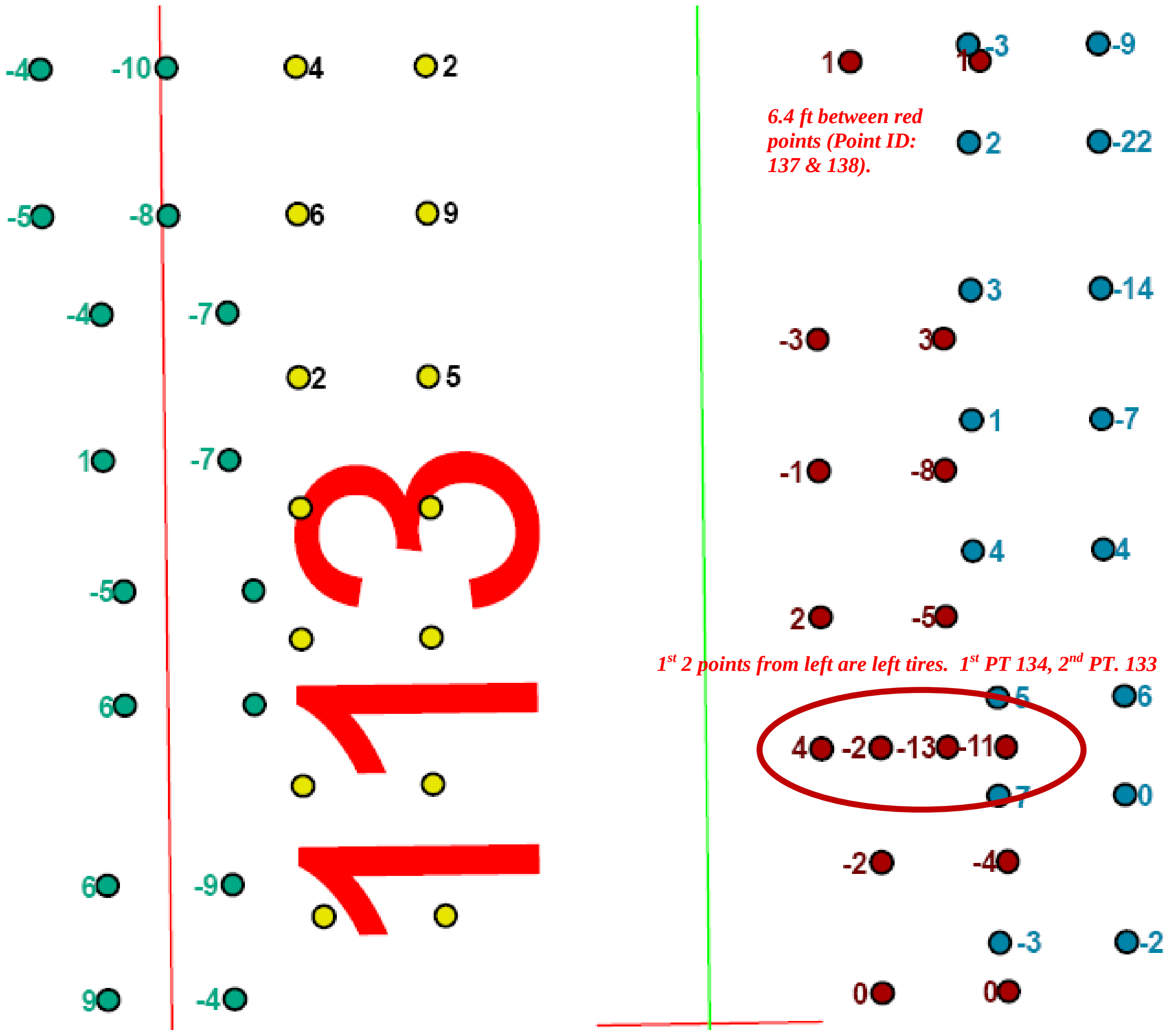

Figure 6.9. Example of Lateral Shift in GPS Coordinates and Sudden, Extended Lengths Before Next Reading (from R. Embacher).

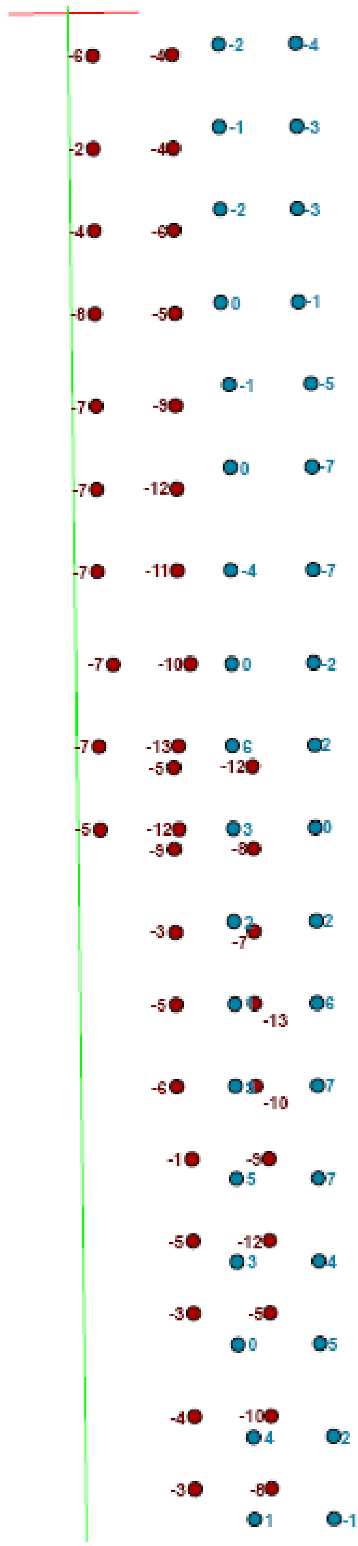

Figure 6.10. Example of Sudden Lateral Shift in Data (from R. Embacher).

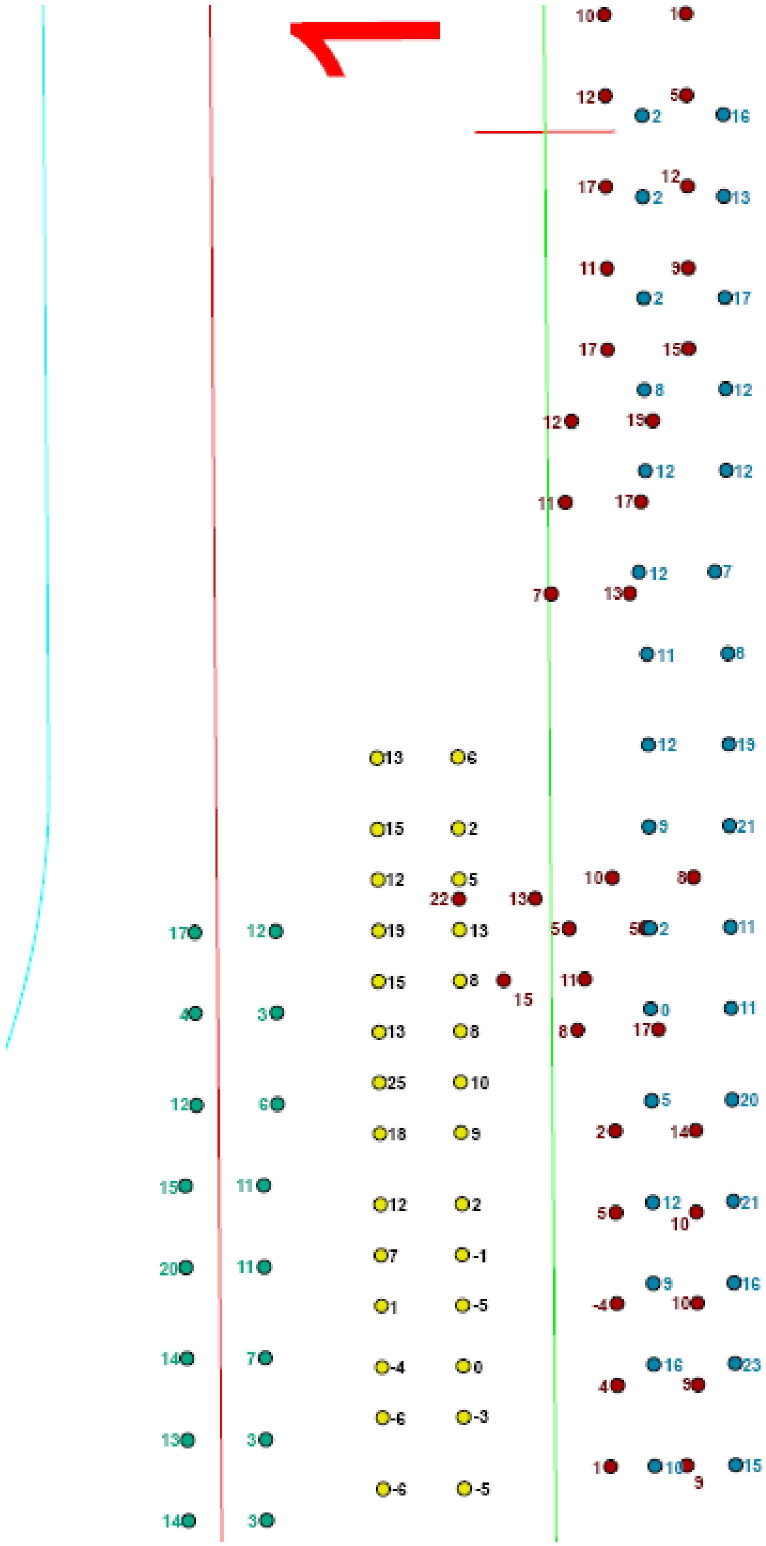

Figure 6.11. Example of Lateral Shift in GPS Coordinates and Sudden, Extended Lengths before Next Reading (10.3 ft) (from R. Embacher).

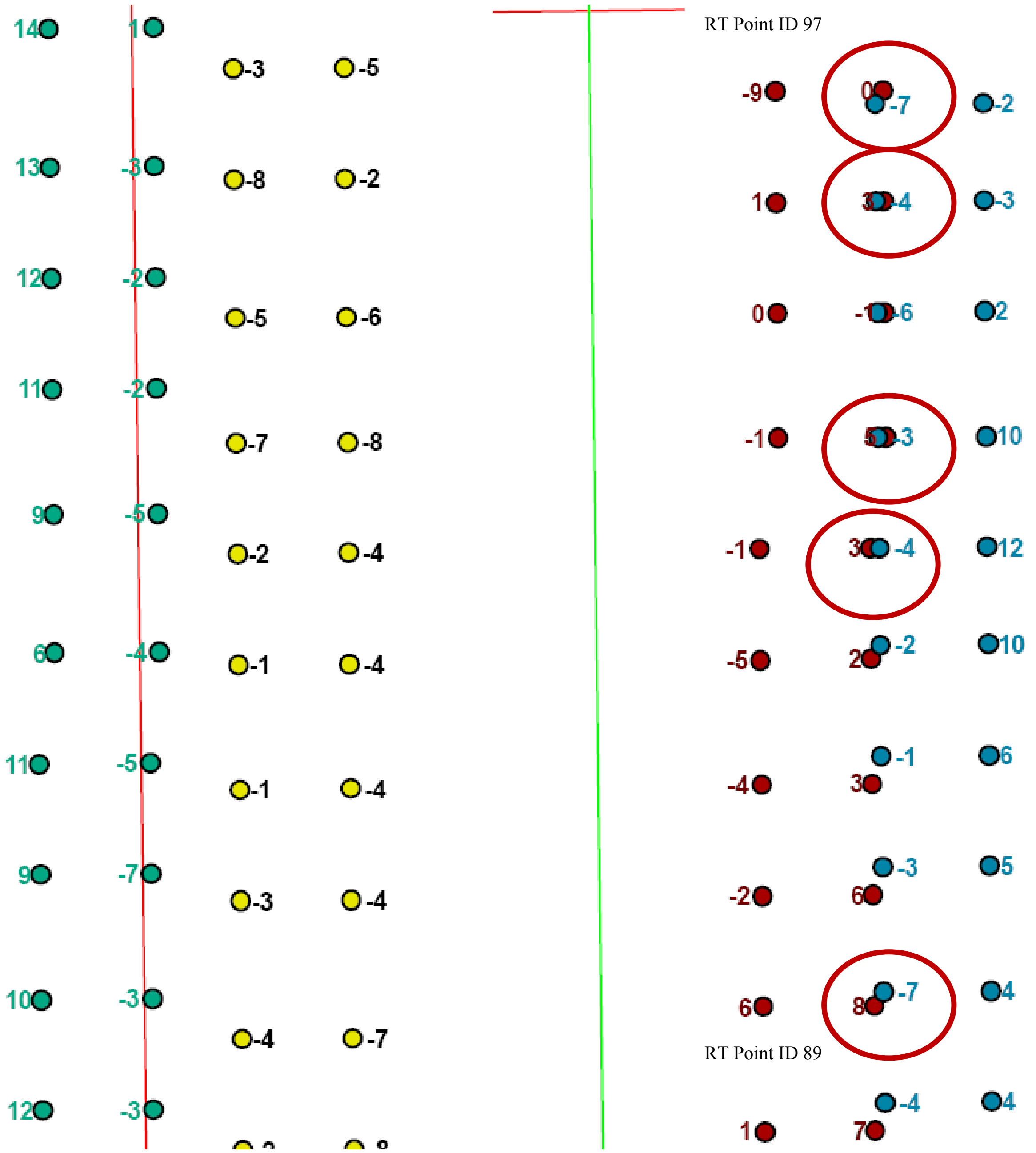

Figure 6.12. Example of Cases Where RT Sensor of 1st Pass Does Not Match Well with LT Sensor of 3rd Pass. Red Circles are 1st Pass Sensor Locations, while Blue Circles are for the 3rd Pass (from R. Embacher).

Comment 1 – Program software to export GPS X & Y coordinates as decimal degrees
This point was not recognized until the Olmsted County project, where stationing was directly compared to the output data and the GPS coordinates were shown to be output as degrees, minutes and decimal minutes rather than decimal degrees. For future software development, it is agreed that providing coordinates in decimal degree format, and clearly showing in the heading

the units used for the GPS latitude and longitude, would be very useful. This step will not be done for the current project. Knowing that the output for the prototype provides coordinates in the format mentioned, the output can be converted into decimal degrees (and distances can be calculated based on the converted position coordinates) with relatively simple calculations. However, having the decimal degree data from the raw output would be much more practical and would not require significant modification to the data collection program.

Comment 2 – Determine precision and range of sonic sensors
This point is valid and worth consideration. The sensors used by the prototype have a precision of +/- 1 mm as given by the manufacturer. However, when the sensor readings are monitored as the truck remains motionless (either on pavement or on soil), the readings appear to have noise of +/- 2 mm or so. Other sensors may be available (for a similar cost) which have better precision for the needs of test rolling and which may be used for future system developments. Otherwise, recognition of this level of noise will be required in implementing the construction specification.

The range of the sensors was determined to be appropriate during the prototype development phase of the project. Distances from the subgrade between 8 and 12 inches (200 to 300 mm) were expected and the sensors were selected based on this anticipated range.

Comment 3 – Sensor calibration
This is a good comment that deserves discussion and consideration. There are several potential methods of sensor calibration, either connected to the truck or separate from the truck. The sensors could be mounted to the truck axle, as per the construction specification, and the distance from the sensor to (for example) a rigid pavement could be measured. The measured value could be compared to the recorded value from the sensor (which can be shown real-time on the data collection box without performing an actual test rolling run.) Thin sheets of plywood or another material could be added, one at a time, with the new distance from the sensor to the surface recorded each time along with the output provided by the sensor. A similar method could be done without having the sensor mounted to the axle, holding it instead with another stationary frame and performing a similar calibration routine. Assuming the measured values match reasonably well with the sensor values, no additional modification would be required. If the check does not meet expectations, the sensor would likely need to be replaced or re-calibrated by the manufacturer.

Comment 4 – Estimated GPS coordinates for each sensor (or tire)
The current system outputs the GPS coordinates of the GPS receiver. Since the deflections correspond to subgrade deformation at the left and right tires, respectively, it would be nice to output the deflection data as a function of the GPS coordinates of each tire. This would require several more computations in the processing algorithm and an offset of the antenna with respect to the tires. Assuming the antenna was mounted in the center of the roof of the truck cab, a lateral offset could be implemented for each tire perpendicular to the direction of travel. While this may be implementable in the data acquisition software, it will involve several calculations (to determine direction of travel, calculate the magnitude and direction of the offset to each tire, calculate the GPS coordinates for each tire, etc.) which may increase processing time. Also, the output data file would be larger (by approximately a factor of two). Since data storage devices can accommodate large files, this may not be a problem. However, there would be more

involved in attempting to produce GPS estimates for each tire (or each sensor, if desired). This step will not be addressed at this time, but can be considered as development of options for other systems continues.

Comment 5 – Static versus rolling tare deflections
During the University of Minnesota study a different deflection model was developed for a static case compared to the rolling case. Since the rolling deflection model was to be used, it made sense to pursue a specification which accounted for obtaining a tare value using a rolling test roller system instead of a static system. Obtaining a tare value for a motionless truck would certainly be simpler than the rolling zero. Determining how much difference there is between a static tare and a rolling tare would be useful. If the difference between a rolling zero on asphalt or concrete pavement and a static zero on the floor of a storage shop (or other slab) is negligible, requiring the rolling zero may not make sense. Similarly, if substantial difference between asphalt and concrete pavements is found (either in a static or rolling tare), this should also be addressed in the specification. Such evaluation would not take a great deal of time and would be a worthwhile pursuit. Performing a static tare in the shop could reduce the time required for test rolling by the few minutes required to perform the rolling zero, especially if the only smooth pavement in the area is not conveniently located near the field site. It is recommended that the developed system be evaluated by Mn/DOT (with assistance from Minnesota State Mankato personnel, as needed) to determine the difference in static versus rolling tare values and whether this should be addressed in the construction specification.

Comment 6 – Positive and negative deflection limits required
As noticed during implementation at both Waseca and Olmsted County, the smoothness of the subgrade surface plays a significant factor in the results obtained by the test roller. If the contractor has done a nice job preparing the site for test rolling, the data is expected to be quite clean, with primarily positive deflections showing sinkage of the tires into the subgrade material. However, as seen on each project evaluated to date, not having a well-prepared surface causes problems with the data collected, since roughness (high and low spots along the grade at the position of the sensors) can be seen in the data as assumed “extreme” deflections. It is in the contractors’ best interest to have the subgrade as smooth as possible to reduce the apparent variability in deflection readings. To include both positive and negative deflection criteria would provide incentive to the contractor to spend adequate time preparing the subgrade for test rolling.

Comment 7 – Data collection frequency increased to 3.5 Hz
Having more frequent data collection (or data output) would be useful. The original idea was to have the data recording interval similar to the accuracy of the GPS system. If better precision can be achieved from GPS capabilities, it would make sense to increase the data output frequency. With respect to subsequent points (11-13), having more frequent data recording may not be beneficial given the current GPS limitations. Such potential modification can be discussed in more detail.

Comments 8, 9 and 10 – Fix output text, file naming/formatting, date modified, etc.
Points noted. These were not noticed during the earlier software development/modification. Comments could certainly be incorporated into subsequent revisions to the data acquisition system, but would formally have been addressed during the Task 4 effort.

Comments 11, 12 and 13 – GPS data gapping and near-point deflection discrepancy
The primary reason for each of these points is believed to be the sub-meter accuracy of the GPS receiver. While sub-meter accuracy can be expected with adequate satellite coverage, it seems as though gapping on the order of 10 feet (3 m) can occur. While not common, this does cause concern. During the field implementation, consecutive runs were performed with an offset of approximately one-half of the truck width (with the left wheel for the second run positioned halfway between the wheel tracks from the first run.) As seen in most of the data in the figures above, the wheel paths rarely showed this pattern. The limitations of the GPS system must be recognized and the shifting of consecutive readings by several feet will likely continue unless a more precise GPS system is incorporated or a base station can be referenced. Comparing deflection readings at the "same" GPS location is difficult. In reality, based on visual inspection of the wheel tracks, the measurements were rarely taken within the proximity indicated by several of the figures. Sensor readings were consistently 3 ft or more (1 m or more) from one another between passes, such that comparison of readings and evaluation of apparent discrepancies between sensor readings for separate passes is not justified. The recommendations made with respect to a repeatability study are warranted, more appropriately to explore the GPS repeatability than the sensor validation. This could be done during additional efforts with respect to Comment 5, given above.

Comment 14 – Data entry for X and Y offset
Noted and can be accommodated in any future software/system development, as appropriate.

Comment 15 – Base station reference
The GPS antenna requested was the alternative which met the cost limitations of the prototype envisioned. This antenna is self-contained and is not configured to reference a base station. Obtaining an antenna which has the ability to utilize a base station (where such is available) would certainly be worth consideration.

Comment 16 – Data acquisition file capacity
This question will require clarification from Kessler staff. To date we have testing runs approaching one mile in length without running into any problems, but if extended distances were anticipated, this would lead to difficulties. However, if storage for an individual file was problematic, a run could be paused briefly and a "new" run initialized at an intermediate point along the section to avoid this issue.

Comments 17 and 18 – Stationing updating and file export format
These points are certainly valid. Kessler Soils Engineering may provide insight on the reason the stationing is not always updated after entry. The recommendation to export the data in database form is worthwhile.

6.5 Conclusions from Test Roller Validation

The modified test roller system has been developed and implemented on several projects at this time. The deflection model developed by the University of Minnesota has been evaluated on a limited number of projects to date. It appears that the limits proposed by Mn/DOT in the new specification will be reasonable and applicable to the subgrade soils anticipated. Additional validation of these criteria will be needed as the roller system is implemented on additional projects with varying materials and axle weights. The prototype fabricated, while not perfect, seems to do a nice job in recording data for projects which allows quick and continuous deflection profiles for projects. This data can be stored and reviewed during the course of pavement monitoring and maintenance to identify potential points of concern where marginal subgrade response was experienced. Overall, using this or a similar tool, Mn/DOT will be able to gain much more information during the course of roadway construction that can be beneficial for many projects in the future.

7 Develop Test Roller Construction Specifications

7.1 Task Overview

This project has developed a more adaptable test roller system for use in subgrade compaction acceptance. In conjunction with this new test roller system, this task (Task 6) has developed an appropriate construction specification for this system. The new roller allows for variation in the weight applied, which will allow varying soil and site conditions to be tested. Such a system would be more appropriate for CSAH routes that are designed for less than 10 ton loads, along with other cases when thinner lifts are to be evaluated. The new test specification has been developed for the new system such that deflection criteria for a range of roller weights will be compiled for both plastic and granular soils, allowing more appropriate criteria to be addressed on a case by case basis. Overall, an improved test roller and testing specification has been developed that will improve the effectiveness and flexibility of Mn/DOT's testing program.

7.2 Initial Draft Test Roller Specification

Terry Beaudry, from the Mn/DOT Grading and Base unit, prepared an initial outline of the construction specification (specification 2111) for the modified test roller implementation. This included some of the basic components needed for the specification, with additional details to supplement that information based on i nput from the TAP group, inspectors, and others, as appropriate. This initial draft (May 2010) is included in this section, for reference.

2111

Intelligent Test Rolling – May 2010 Draft

2111.1 Description

This specification defines the equipment requirements, operating guidelines and acceptance standards used for test rolling roadbed embankments.

2111.2 Equipment

The test roller must meet the following requirements:

A. Two *(pneumatic)?* tires on a solid axle spaced at least 1.8m (6 feet) apart.

(1) Tire sizes are listed in Table ??

B. Inflate pneumatic tires to the max load rated pressure.

(1) Certify the weight on each tire immediately prior to calibration on the project.

2111.3 Construction Requirements

Surface must be within 100 mm (4 inches) of design cross section and profile.

Test roll the entire length and width of embankment to be covered by pavement and shoulders.

A. Testing Requirements

1 Calibrate the deflection measurement devices and location monitor (GPS) immediately prior to testing each area.

2 Make one pass over each test strip under an instrumented tire.

3 Roll test strips approximately three (3) feet apart.

4 Test roll at 3 (± 1) miles per hour.

5 The contractor is responsible for protection of all culverts and structures.

6 Test roll nongranular soils within 12 hours of placing, compacting and shaping the top 12 inch layer.

7 Record and submit all test data on memory devises provided by the Engineer.

a. Record the latitude and longitude of each deflection measurement point at (submeter)? accuracy.

b. Record deflection measurements in (1)? mm increments.

B. Acceptance Requirements

1. Maximum allowed deflection at the time of testing is determined in Table ?? using the soil type, wheel size and load.

2. Incomplete or altered records will require corrective action of the entire represented area and retesting.

3. All failing areas require retesting after corrective action. The engineer may waive retesting after corrective action on areas shorter than 50 feet.

2111.4 Method of Measurement

Test rolling will be measured by length when the embankment was constructed under a previous Contract.

Test rolling length will be measured separately for divided highways.

2111.5 Basis of Payment

Test rolling and corrective action to unstable areas is incidental to the embankment pay items of the contract.

Corrective action to unstable areas is paid for as Extra Work when the embankment was constructed under a previous Contract.

Item No.	**Item**	**Unit**
2111.501	**Test Rolling**	**road station (meter)**

7.3 Intermediate Draft Specification

Based on t his initial outline, several drafts and revisions were developed. T hese revisions provided additional details with respect to the equipment and testing requirements, the corrective measures, etc. The draft specification circulated in August 2010 is included here, for reference.

2XXX

Test Rolling – DRAFT – August 2010

2XXX.1 Description

This item shall consist of testing the bearing capacity of the roadbed by rolling with a standard, instrumented truck. This specification defines the equipment requirements, operating guidelines, and acceptance standards used for test rolling roadbed embankments.

2XXX.2 Equipment

The contractor shall provide a pneumatic-tired vehicle and approved test roller electronics conforming to the following requirements:

(a) The vehicle shall have a single-tire, non-drive front axle with wheels spaced not less than 6 feet (1.8 m) apart, center to center, (hereafter the "instrumented axle").

(b) Tires shall have a tread width between %%% and %%%, and a radius of between %%% and %%%. Each tire shall be inflated to its maximum load-rated pressure.

(c) The vehicle shall be loaded with a static load (prevented from shifting) so that the gross weight of the instrumented axle is not less than 5,000 lbs (2,268 kg) on each tire.

The data collection unit shall record, at a minimum, the deflection in 0.04-inch (1-mm) increments at an interval of no more than 24 inches (0.6 m); location by GPS coordinates and by station, offset, and depth below grading grade; tire pressure, individual wheel weights, and the date and time of testing.

2XXX.4 Testing Requirements

Test rolling shall be performed on the roadbed as required at a time when the grading grade is completed within 4 inches (100 mm) of the grade staked by the Engineer, and shall cover the full top width of the proposed pavement structure as defined by the bottom width of the typical subcut sections shown in the Plans, unless other specific dimensions are given. Non-granular soils shall be test rolled within 12 hours of placing, compacting, and shaping the top 12-inch (0.3-m) layer. Test rolling shall not be performed until the Engineer and Contractor mutually agree that the subgrade has been properly prepared and is acceptable for test rolling. On those portions of a Project where the Plans require treatment of the upper portion of a granular subgrade by the addition of aggregate or binder soil, the test rolling shall be performed before the treatment work is performed.

The Contractor shall take precautions to protect culverts and other structures during the test rolling. Where a culvert or other structure has, or will have, insufficient protective cover to withstand the test rolling vehicle, the test rolling may be performed prior to installing the structure or performed on the surface of any additional cover that may be provided as protection for in place structures. Any structures damaged by the test rolling shall be replaced at no expense to the Department.

A. Initial Setup

The test rolling electronic sensors shall be mounted to the instrumented axle no less than 12 inches (0.3 m) from the edge of the tire. The GPS unit shall be mounted magnetically above the center of the instrumented axle. All cabling must be secured to avoid entanglement and damage to the system.

The test rolling equipment shall be initiated immediately prior to test rolling using the following procedure.

(a) Establish a test strip on an asphalt or concrete pavement.

(b) Verify the weight of each tire on the instrumented axle on the asphalt or concrete test strip.

(c) Test roll a minimum linear distance of 100 feet (30.5 m) to establish a reference measurement for the sensors.

B. Testing

Test rolling shall be performed by making one pass over each strip covered by the width of a tire. Subsequent passes shall be centered between the wheel paths of the previous pass. The test roller shall be operated at a constant speed of 3±1 mph (4.8±1.6 kph) and in a pattern approved by the Engineer. The maximum allowable deflection is selected from Table %%% for the appropriate soil type, wheel size, and wheel load.

C. Reporting

The Contractor shall submit all data collected by the test roller on a memory device provided by the Engineer. Material placement on the next lift or layer shall not commence until the data has been received and reviewed by the Engineer. The roadbed will be considered to be unstable if, under the operation of the roller, either of the following conditions are met, as computed by the Test Roller Analysis spreadsheet.

(a) The surface shows yielding or rutting (at the time the roller passes over the grade) of more than the maximum value given in Table %%%, as measured by the test rolling device, in more than 30 ft (9.1 m) in any 100-ft (30.5 m) segment, for an individual wheel path.

(b) The standard deviation of all deflection measurements in any 200-foot (61.0-m) distance exceeds 20% of the mean value for the same measurements.

2XXX.5 Corrective Action

If, on a roadbed constructed by the Contractor under the same Contract, test rolling shows any sections of the roadbed to be unstable, the Contractor shall, at no expense to the Department, scarify the roadbed and aerate or add moisture to the material as necessary, and recompact the material to the extent that it will be stable when retested by rolling. However, where test failure occurs on an isolated section of roadbed less than 50 ft (15.2 m) in length, retesting of that section by rolling will not be required if the Engineer is satisfied that the corrective measures taken have eliminated the cause of failure and have produced acceptable stability as evidenced by density tests or visual inspection.

Where test failure occurs on a roadbed not constructed by the Contractor under the same Contract, the unstable sections shall be repaired by the Contractor, as directed by the Engineer, at the Department's expense.

Incomplete records, or records showing evidence of alteration will require corrective action and retesting on the affected areas.

2XXX.6 Method of Measurement

If the roadbed tested was constructed under a previous Contract, and only then, test rolling (together with any retesting required by the Engineer after unstable sections have been repaired) will be measured by length where such work is performed. The work on each separate roadbed, in the case of divided highways, will be measured separately. If the Engineer orders testing on any portion of the roadbed to an extent less than the full width specified, the measurement will be in proportion to the width tested.

2XXX.7 Basis of Payment

If the roadbed tested was constructed by the Contractor under the same Contract, the Contractor shall perform test rolling (including all corrective actions to unstable sections and retesting) as incidental work with no direct compensation. Corrective action to unstable areas, and associated retesting, will be paid by road station if the roadbed tested was constructed under a previous contract.

7.4 Final Draft Specification

The Grading and Base Unit eventually decided to combine the modified test roller specification and the original test roller specification into one document, which is currently under consideration. The most recent version of this specification (circulated March 2011) is included here, for reference.

S-xx **(2111) Test Rolling**

(12/09/10)

The provisions of Mn/DOT 2111 are modified with the following:

S-xx.1 Description

This work consists of providing and operating equipment to test roll roadway embankments. See test procedures in Grading and Base Manual.

S-xx.2 Definitions

(A) "*Strip*" is the area covered by the rolling tire.

S-xx.3 Equipment

(A) Provide test rolling equipment meeting the requirements of Table 1.

TABLE 2111-1		
EQUIPMENT REQUIREMENTS		
Requirement	**Type of Test Roller**	
	Standard	**Sonic**
Tire Spacing	6 ft (1.8 m) apart, center to center	
Tire Size	18 × 24 or 18 × 25	22.5 ± 1 in unloaded radius 20 ± 1 in loaded radius
Tire Pressure	95 psi (650 kPa)	Maximum Load Rated Pressure
Load Per Tire	29,800 to 30,200 lb (13,500 to 13,700 kg)	5,800 to 6,200 lb (2,630 to 2,800 kg) 7,300 to 7,700 lb (3,300 to 3,500 kg) 8,800 to 9,200 lb (4,000 to 4,200 kg) (Notes 1 and 2)
Vehicle Type	Trailer	Truck Gross Weights ≥ 54,000 lb (24,500 kg)
Layer Thickness	≥ 30 in (762 mm)	≥ 12 in (300 mm) ≤ 24 in (600 mm)

NOTE 1: Load truck to **maximum allowable load**. Ensure this loading is within one of the load ranges provided in Table 2111-1.

NOTE 2: Keep tire loads within 200 lb (90 kg) of each other.

(B) Deflection Measurement

(1) Standard Roller

(a) Center the approved deflection measurement devices over the axle and offset from each tire to mark the failing areas. The Engineer may allow alternate deflection recording devices.

(2) Sonic Roller

(a) Provide the data acquisition components specified in Table 2111-2.

TABLE 2111-2		
SONIC TEST ROLLING ELECTRONIC REQUIREMENTS		
System	**Quantity**	**Accuracy**
Global Positioning System	1	Sub-meter or better in the X and Y Direction (± 2 ft or less)
Sonic Sensors	2	± 1 mm (± **0.04 in**) at a nominal distance of 250 mm (10 in) from the subgrade surface, capable of data collection at a minimum of 2 Hz.
Data Collection Unit	1	Buffer Rate ≥ 3.5 Hz ASCII *dbase Output 2 Channels + GPS input
Inclinometer	1	

(b) Measurement Pass Data Files

Record and store the following data which is exportable in ASCII *dbase format.

(i) File Name

(ii) Date Stamp

(ii) Time Stamp

(iv) Location Description

(v) Starting Station

(vi) Target Deflection Value

(vii) Offset Distance of GPS unit from Left Sensor

(viii) XYZ Coordinates in NAD 1983 HARN Adjusted County Coordinates (ft) (or WGS84)

(a) XYZ Coordinates for both the Left and Right Sonic Sensor

(iv) Station at each test point

(x) Vehicle Speed (mph)

(xi) Left and Right Sonic Sensor Deflection Measurements prior to adjustment for tare value.

(xii) Left and Right Sensor Tare Values

(xiii) Adjusted left and right sensor measurements with tare values.

(c) Mount sonic sensors, on front axle of truck, no less than 12 inches from the inside edge of each tire.

(d) Mount GPS unit near the center of the instrumented axle.

S-xx.3 Testing Requirements

(A) Prepare the embankment surface within 4 in (100 mm) of the design cross section and profile.

(B) Test roll the entire length and width of embankment from shoulder point of intersection to shoulder point of intersection or the width of the subcut. .

(C) Protect all structures from damage caused by the test roller.

(D) Operate the test roller at a speed of 3 to 5 mph (5 to 8 km/h).

(E) Standard Test Rolling

(1) Keep roller parallel to grade.

(2) Test roll each strip with two overlapping passes.

(3) Roll subsequent strips no further than 12 in (300 mm) apart.

(F) Sonic Test Rolling

(a) Perform testing within 12 hours of completion of the embankment.

(b) Test roll each strip with one pass.

(c) Roll subsequent passes centered between the wheel paths of the previous pass.

(G) Acceptance Requirements

(1) Passing deflections are listed in Table 2111-3.

(2) Correct areas exceeding allowable deflection.

TABLE 2111-3			
ACCEPTANCE CRITERIA			
Roller Type	**Tire Load**	**Allowable Deflection (Note 1)**	
		Granular to be Covered by Stabilizing Aggregate	**All Other Materials**
Standard	29,800 to 30,200 lb (13,500 to 13,700 kg)	3 in (75 mm)	2 in (50 mm)
Sonic (Note 2)	5,800 to 6,200 lb (2,630 to 2,800 kg)	0.6 in (15 mm)	0.4 in (10 mm)
	7,300 to 7,700 lb (3,300 to 3,500 kg)	0.75 in (19 mm)	0.5 in (13 mm)
	8,800 to 9,200 lb (4,000 to 4,200 kg)	0.9 in (23 mm)	0.6 in (15 mm)

Note 1: Deflection is measured while rolling.

Note 2: Choose load rating closest to actual tire load.

(H) Corrected Areas

(1) Repeat testing after all failing areas are repaired.

(2) The Engineer may waive repeat testing on corrected areas less than 200 ft (60 m).

S-xx.4 Method of Measurement

(A) The Engineer will measure test rolling by length when listed as a bid item under the current contract.

(B) The Engineer will separately measure test rolling on each roadbed for divided highways.

S-xx.5 Basis of Payment

(A) Test rolling on embankment constructed under this contract is incidental to the embankment pay item, unless it is listed as a separate pay item.

Item No.:	**Item:**	**Unit:**
2111.501	Test Rolling	road station [meter]

The Acceptance Criteria values for Allowable Deflection as given in Table 2111-3 were initially derived from scaling the acceptable deflections from the original standard test roller to the wheel loads expected from the sonic test roller system. As shown in the section relating to the relationship between test roller deflection and pavement performance, these proposed criteria are in the range of deflections anticipated for soils anticipated in the field. However, as noted in Table 3.2 in Chapter 3, soils with varying strength values will have different acceptable deflections based on the University of Minnesota model. The values included in Table 2111-3 are a good starting point for the construction specification, but as implementation of the specification and the new roller system moves forward, there will need to be some flexibility in the acceptable values based on the judgment of the project engineer. As additional data is collected to confirm the deflection model's accuracy, the specification can be appropriately refined by adjusting the acceptable deflections (if appropriate.) These values, while an understandably quick estimate based on the past equipment and specification, fit within the range of values acceptable for anticipated subgrade soils based on the University of Minnesota model as obtained in this study. Continued effort will be needed to confirm these values.

8 Conclusions and Recommendations

The overall purpose of this implementation project was to develop a new test rolling system and an associated construction test specification that can be utilized by Mn/DOT to approve compacted subgrades on construction projects. This development has been accomplished and a functional system and specification have been produced.

The initial task associated with this project was to implement the critical findings of the study conducted by the University of Minnesota in product and specification development. This review was provided in Chapter 2. Hambleton and Drescher (2008) came to the following conclusions appropriate to this implementation project, in addition to a number of additional conclusions:

- Test rolling has the potential to be a very successful tool for characterizing mechanical properties of soils with a continuous record of measurement.
- Both analytic and numerical models were developed to relate test roller wheel sinkage to wheel load as a function of soil strength parameters and the test roller wheel geometry.
- The scaled model studies performed support the analytic model developed.
- Since much of the deformation induced by a test roller is permanent, this deformation is to be associated with soil failure rather than elastic compression. The conclusion of the authors was that test rolling should not be used to evaluate elastic parameters such as resilient modulus. However, test rolling was perceived to be a practical way of obtaining continuous strength properties.
- Inference of strength properties can be done in either a cohesionless or purely cohesive material, but not by a soil with combined strength properties, without additional effort. If wheels of two different sizes are used to evaluate the soil, or if the same wheel is used with two separate wheel loads, strength values can be deduced.
- The influence depth for the existing test roller system varies from 2 ft to 4 ft.
- The larger the magnitude of the wheel load, the greater the sensitivity of the sinkage to small changes in the soil strength. For smaller wheel loads, small strength changes will not lead to significant changes in sinkage.
- Wheel flexibility can influence sinkage significantly and should be taken into account in the analytic (and/or numerical) model(s).
- Validation of the models should ultimately be done using well-controlled field tests of a test rolling system.

The Hambleton and Drescher study (2008) also included a number of recommendations. These may be summarized as follows:

- Light weight deflectometers and/or intelligent compaction systems should be used to determine elastic properties rather than test rolling.
- The models developed should be considered to be approximate until they can be validated with experimental data.
- Test rollers with different weights and wheel configurations can give similar results. A heavy wheel load with a large wheel contact area can yield results similar to a small load

on a smaller wheel area. The influence depth will be less, however, for the smaller wheel/load combination.

- Rigid wheels would be preferred to flexible wheels for test rolling applications. A stiff pneumatic tire with appropriate inflation pressure can approximate a rigid wheel.
- A towed wheel is recommended over a driven wheel, and the models developed apply to a towed wheel only.
- A test roller wheel should travel ahead of the driving wheels, as when using the front axle of a standard dump truck as a test rolling device.

Based on the Hambleton and Drescher (2008) study and using the analytic model developed therein, sinkage was estimated for the prototype test rolling system for the expected wheel geometry and wheel loads anticipated for various soil strengths. Assuming the wheel flexibility coefficient of 3.5 inches per ton (0.01 m/kN) as estimated for the existing test rollers also applies to a standard wheel on a dump truck, and using a density of 20 kN/m^3 and wheel dimensions for a 385/65R22.5 tire (overall diameter = 1.072 m and overall width = 0.379 m), the initial table given in Chapter 2 and revised in Chapter 3 provides the sinkage expected for soil strengths as shown for the wheel loads listed.

Chapter 3 included an effort to correlate the sinkage of the new test roller vehicle's tire to eventual pavement performance after the entire pavement is constructed, an evaluation of the effects of inadequate subgrade compaction on pavement performance, and an application of these results to the development of the new test roller equipment and the updated test rolling specification.

The analysis contained in this report relative to the correlation of tire sinkage and pavement performance indicated that while such a correlation may be possible, it can be very difficult and requires field testing to determine the "soil sinkage parameters" as described in this report. As a result, the concept of correlating tire sinkage to soil strength and stiffness properties and thence to pavement performance was divided into two analyses – allowable sinkage and the correlation between soil properties and pavement performance.

The draft construction specifications contained in this report, and developed by the project team and Office of Grading and Base, indicates a maximum allowable sinkage of 0.6 to 0.9 inch for granular material to be covered by stabilizing aggregate, and 0.4 to 0.6 inch for all other materials. These are the values shown in Table 3. and in Chapter 7. The results of the analysis utilizing the results of research by Hambleton and Drescher (2008a) are shown in Table 3. For reasonable soil properties and tire loads, the actual expected sinkage values are estimated to be somewhat lower for granular materials (and ranging from lower to somewhat higher for other materials) than those allowed in the specification. For granular materials, then, the specification will allow slightly more sinkage than expected, to compensate for variability in subgrade soils, and in acceptable levels of compaction.

The analysis of effects of compaction on pavement performance had greater success, and multiple models were combined with the MnPAVE software to conduct pavement performance computations. The results of this analysis include a model relating the resilient modulus ratio (as-constructed / as-designed) and the subgrade's R value to the expected increase in pavement rutting damage. This model was given in Equation 3.36, and repeated below.

$$D_{MR} = \ln\left(M_{R-r}\right)^{\left[-0.141\cdot\ln(R)-0.4068\right]}$$

where:

D_{MR} = subgrade R-value,

$M_{R\text{-}r}$ = resilient modulus ratio, and

R = subgrade R-value.

The relative impact on pavement performance was not correlated with the levels of ESALs for which a pavement is designed nearly as much as with the R-value of the subgrade and the combination of other soil properties which make up the resilient modulus ratio component. In general, as the ratio of as-constructed to as-designed resilient modulus decreases, the expected increase in rutting damage increases almost linearly. In addition, soils with a higher R-value will experience a steeper relationship between modulus ratio and increased rutting damage. These impacts are shown in Figures 3.4 and 3.5.

The analyses conducted as part of this project are important in relating the new test roller equipment to the revised construction specifications and in providing a meaningful understanding of the pavement performance expected for a given subgrade density. Although other construction specifications require certain levels of compaction and soil density, the density-performance relationship developed as part of this project provides an important link between the components of design, construction, and performance.

With the new test roller equipment, field engineers and contractors are able to test roll the subgrade more often and at lower cost in both time and money. At each test interval, a comparison can be made to the allowable sinkage (and effects on pavement performance related to compaction and density). Thus, intermediate lifts can be tested more easily and problem areas can potentially be identified earlier than by testing at the final elevation of the grading grade. The correlation of soil type, wheel load, and wheel dimensions helps Mn/DOT be more comfortable in the levels of allowable sinkage required by the revised specification. Although additional verification and validation should be conducted on future grading projects, and the allowable sinkage levels may need to be adjusted, the basic theory and analysis are sound, and will support modification suggested by additional field testing.

Since initial discussions of this project began, several possible systems were discussed. The final consensus of the TAP group was to develop a truck-mounted system having two ultrasonic sensors mounted to the front axle of a dump truck to measure displacement. A GPS antenna is part of the system so displacements measured can be associated with GPS coordinate positions to sub-meter accuracy. A data acquisition system allows data entry to provide site and test roller/truck identification. A "rolling zero" of the system can be performed on a smooth, "rigid" (bituminous or concrete pavement) material to initialize the system. After this zeroing of the system, the roller can be used to test the section of interest. Once test rolling is complete, the data can be stored and uploaded by a USB connection to identify problem areas based on the failure criteria appropriate for the site, material, and roller conditions.

This modified test roller system has been developed and implemented on several projects at this time. The deflection model developed by the University of Minnesota has been evaluated on a limited number of projects to date. It appears that the limits proposed in the draft specification included in Chapter 7 will be reasonable and applicable to the subgrade soils anticipated. Additional validation of these criteria will be needed as the roller system is implemented on additional projects with varying materials and axle weights. The prototype fabricated, while not perfect, seems to do a nice job in recording data for projects which allows quick and continuous deflection profiles for projects. This data can be stored and reviewed during the course of pavement monitoring and maintenance to identify potential points of concern where marginal subgrade response was experienced. Recommendations to improve future versions of the system were also included in Chapter 7. Overall, using this or a similar tool, Mn/DOT will be able to gain much more information during the course of roadway construction that can be beneficial for many projects in the future.

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Appendix A: Specification Draft and Meeting Minutes

TO: Aaron Budge, Minnesota State Univ. Program Manager

FROM: Garry Aicken, Kessler Soils Engr, Inc. (KSE), Subcontract Program Manager

Meeting Minutes

1. **Purpose:** To document the items discussed at the following meeting pursuant to Contract between Mn/DOT and Minnesota State University, Mankato (MSU):

   1.1 Meeting hosted by Mn/DOT at the Materials Testing Lab in Maplewood, MN 09:00 – 12:30 on 20 March 2008.

   1.2 Attendees:

   1.2.1 Tim Anderson, Mn/DOT Technical Liaison

   1.2.2 Cary Efta, Mn/DOT, Grading and Base Office

   1.2.3 Bruce Holdhusen, Mn/DOT, Representing the Administrative Liaison (Clark Moe)

   1.2.4 Aaron Budge, MSU. Principal Investigator

   1.2.5 Jim Wilde, MSU. Co-Principal Investigator

   1.2.6 Garry Aicken, KSE., Subcontract Program Manager

   1.2.7 Jay Schabelski, Romus, Inc., Engineer for KSE

   1.2.8 Ken Kessler, KSE General Manager

2. **Discussion:**

   2.1 Aaron Budge reviewed each task and scope of work in each task.

   2.2 Garry Aicken solicited input on desired output from the Test Roller and suggested possible specification and design for the instrumentation (Attachment 1, Power Point slides).

   2.3 Tim Anderson indicated the Test Roller was for subgrade only and should be able to detect dissimilar layers. The study should identify maximum layer to be tested as basis for design. Location should be in Latitude/Longitude and Stations (xxxx.xx) with up-station centerline offset distance.

   2.4 Cary Efta suggested possible use of tire pressure sensors, leveling devices/inclinometers, and rental by project. Integrity of data should be maintained by safeguarding against unauthorized data manipulation.

2.5 Jay Schabelski explained the GPS data collection instruments KSE had displayed at the meeting. He explained how two ultrasound sensors on the front axle of a truck could be connected to the GPS system to obtain X, Y, Z (WGS 84). The vertical distance below the front axle and the ground would be used to determine the deflections caused by the front wheels. He drew a diagram (Attachment 2) of a proposed electronics configuration.

2.6 Ken Kessler pointed out the GPS supplier had not yet been able to access the Mn/DOT cell phone RTK (Real Time Kinematics) system to obtain 2 cm accuracy. It was also pointed out that northern MN does not have RTK coverage. It was agreed that a 2 foot radial accuracy (circular probable error) should suffice.

2.7 Jim Wilde is to determine the actual spacing required by researching the deflection caused by the wheel as a function of the various layers in the subgrade. He estimated this would take several weeks.

2.8 Garry Aicken noted (Attachment 3) the specification for the Test Roller instrumentation that would meet the requirements stated at the meeting.

2.9 Bruce Holdhusen noted that the timeline of tasks being discussed were not consistent with the contract. Dates were changed as follows:

2.9.1 Task #3 Basis of design 5/1/08

2.9.2 Task #4 Demo of instrumentation 6/1/08

2.9.3 Task #5 Field test 8/1/08

3 Recommendations:

3.1 That MSU Program manager send Attachment 3 to Mn/DOT Technical Liaison and TAP Committee for verification/approval so KSE can design and procure GPS and sensor equipment.

3.2 That MSU provide KSE with desired spacing between data points so programming can proceed.

Garry Aicken

KSE Program Manager

Attachment 1: Power Point slide of guidance need for Test Roller specification

Attachment 2: Diagram of proposed Test Roller instrument configuration

Attachment 3: Test Roller instrument configuration and operational requirements from this meeting.

Attachment 1: Power Point slides used to gather input for the draft Test Roller specification

Slide 1

RWD Operations

- Step 1 - Set-Up Phase
  - Install Instrumentation on Truck
  - Weigh Truck Axle
  - Zero the sensors
- Step 2 - Data Collection Phase
  - Enter start station & offset information into controller
  - Drive truck test section
  - End test: stop data collection
- Step 3 – Store Data
  - Print output to receipt printer
  - Download to USB

Slide 2:

RWD Design Parameters

- Input Attributes
  - Project #
  - Date
  - Weight of truck axle with sensors
  - Tire pressure (left & right)
  - Operator or Inspector name
  - Type of sub-grade/base material
  - Lift Thickness

Attachment 1: Power Point slides used to gather input for the draft Test Roller specification

Slide 3:

RWD Design Parameters

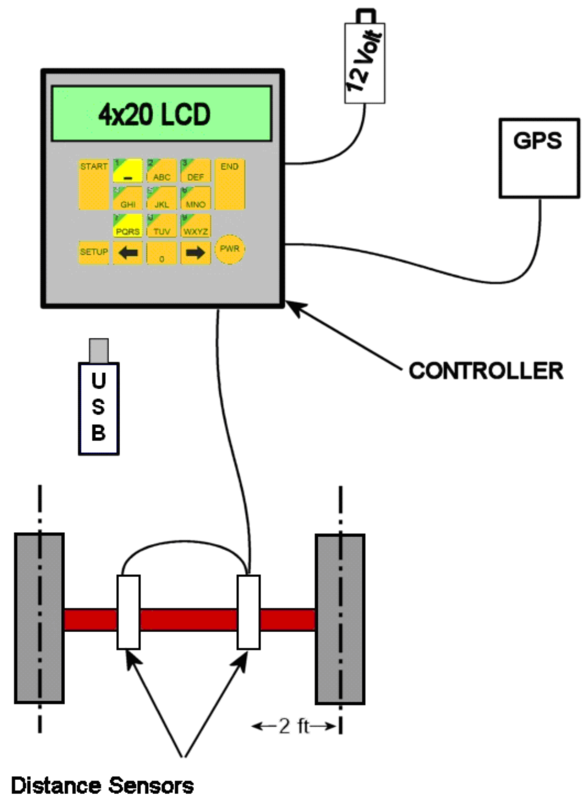
- Collection Attributes
  - Location (X & Y)
  - Median Deflection (Z) over range length
  - Rate (speed of truck)
  - Centerline Offset (left/right facing up station)
  - Direction of Test (up station/down station)

Slide 4:

RWD Next Steps

- Today – Develop Parameters
  - » Need Truck Configuration
- Next Month – Assemble & Demo of Proto-type
- Field Validation Tests
  - When
  - Where

Attachment 2: Diagram of proposed Test Roller instrument configuration



Attachment 3: Draft Test Roller instrument configuration and operational specification

1. **Purpose:**

To outline specification for the Test Roller prototype that is being developed by Minnesota State University, Mankato for the Minnesota Department of Transportation. The intent of this document is to provide a physical and functional description that will be used to develop the prototype instrument.

2. **Description:**

The instrument is designed to be used in conjunction with a large over the road straight body truck where the instrumentation can be attached to the front axle. The instrument will collect data that represents the distance between the truck axle and the surface. The truck should be of a straight body type with a sufficient gross load to produce a front axle load of approximately 24,000 lbs. The axle used for the mounting of the instrumentation should be front steering with two nondriven flotation tires. The instrument also requires the attachment of the GPS receiving antennae onto the truck mirror frame. The truck should have a 12 volt DC 5 amp power source to power Test Roller instrumentation.

2.1. Configuration:

The instrument as shown in Attachment 2 is comprised of the following items:

1. The deflection sensors shall consist of a noncontact ultrasonic ranging device. These devices are mounted to the front truck axle, approximately 24 inches from the center line of each wheel. The devices shall be mounted to the axle with a clamping mechanism that shall not interfere with the normal operations of the truck. From these two sensors a single cable will interface with the control unit located in the cab of the truck. The ultrasonic sensors shall compensate for the effects of temperature and surface irregularities and be sealed from the environment.
2. One GPS receiver capable of locating the truck with a precision of plus/minus 2 feet;
3. A processor box that contains the electronics that convert the signals from the GPS receiver, ultrasonic sensors, and the input data from the control pane; and
4. A control panel to allow input of identifying parameters such as project, truck, and test information. The control panel will also have a USB data port in order to export the information. The control panel will have an LCD display with soft touch alpha/numeric keys similar to a cellular phone. The display will have 4 rows and 25 characters columns. It will be backlit.

3. Operation:

3.1. Set Up Phase:

In the Set up Phase, the instrumentation is attached to the truck which is loaded to its survey weight and is prepared for Data Collection. During this phase the Data Input listed below is typed into the control panel. The truck front axle will be weighed using portable scales or other methods during this phase. The final step of the Set up Phase involves driving the truck over a ‘hard’ section of smooth pavement in order to calibrate the sensors to a baseline elevation by setting the sensors to a rolling zero similar to the tare function of an electronic balance.

3.2. Data Collection Phase:

The Data Collection Phase begins with the truck at the beginning station; the operator then uses the control unit to enter in the following information: the station that the truck is at, the offset from centerline, and the direction that the truck is facing (up station vs. down station.) Also, the control unit stores the date, time, and location automatically from the GPS unit. Now the data collection operator presses the START button. Then the truck driver drives the truck down the roadway at 2 to 5 MPH. While the truck is in motion, a set of data is collected at a preselected interval of 2 to 5 feet. This dataset shall contain speed, heading, GPS location, right and left wheel deflections. At the end of the roadway being tested, the control unit operator presses the END button. By pressing the END button, data collection stops and is stored internally. The truck is turned around and the process is repeated until all required data is collected. Data will be collected in the following manner:

3.2.1. Each sensor will collect a weighted average deflection value between the sensor head and the ground. It is calculated over the area of the sensor’s beam which is approximately a 6 inch diameter circle.

3.2.2. The weighted average deflection value at each sensor will be sampled every millimeter of travel distance; then the two sensors deflection value sample will be averaged together to form a single sample value. Then over a range of 2 to 5 feet of travel, the samples will be averaged again and this value will be stored as the data point.

3.3. Data Storage Phase:

Once the testing is completed, the data can be downloaded to a USB flash drive. The data files written shall be in two formats; tab separated values and a proprietary binary format. The binary format shall be made resistant to data manipulation and tampering. To decode the binary file, a program that can run within a Web browser shall be provided. This decoder program shall be written to the USB drive as the data is stored to it.

4. Data Input Capabilities:

The prototype Test Roller will be able to accept the data input listed in this section. The input is required to identify the data that is collected in the following section for use after testing. The table below shows the inputs and their attributes

Input Title (as shown on control panel display)	Input Format	Description
Project Number	Alpha/Numeric	20 character capability
Date	Numeric	MM/DD/YYYY
Weight of Truck	Numeric	XX,XXX LBS
Tire Pressure	Numeric	Left Tire = XX PSI; Right Tire = XX PSI
Distance between sensor and hard surface for calibration, Left and Right	Numeric	Left, XXX mm Right, XXX mm
Tire Size	Alpha/Numeric	20 character capability
Inspector Name	Alpha	20 character capability
Operator Name	Alpha	20 character capability
Type of Material	Alpha	XX – such as CL, CH etc.
Depth from Grading Grade	Numeric	+/- XX.X FT such as -25.2 FT
Start Station	Numeric	Station XXXX+XX such as Station 0125+20
Center Line Offset, Up-station	Alpha/Numeric	Right (+)or left |(-)of CL – such +/- XX.X FT, such as -25.2 FT
Test Roller Serial Number & the 2 Sensor Serial Numbers	Alpha/Numeric	20 character capability

5. Data Collection Capabilities:

The prototype Test Roller will be able to collect the data listed in this section. The input is required to identify the data that is collected in the following section for use after testing. Metric and English units will be available for the collected data. The table below shows the inputs and their attributes

Collected Data as shown on control panel display	Output Format	Description
Location X Direction **(From GPS Receiver)**	Numeric	Longitude (WGS84) Station XXXX+XX such as Station 0125+20
Location Y Direction **(From GPS Receiver)**	Numeric	Latitude (WGS84) Offset Distance from centerline of road such as +/- XX.X FT such as -25.2 FT
Location Z Direction **(From GPS Receiver)**	Numeric	Elevation above sea level such as +/- XXX FT such as -25 FT (WGS84)
Deflection (From Ultrasonic Sensors)	Numeric	Distance from sensor on front axle to ground surface. Measurement will be in millimeters such as XXX mm
Speed of the Truck **(Calculated from GPS)**	Numeric	Speed of the truck will be presented as feet per second such as XX FT/SEC and also MPH such as XX MPH

6. Sample Data Format:

Data Output Format Specification:

Project:{TAB}<*TEXT 20 CHAR*>{CR}{LF}

Date:{TAB}<*MM*>:<*DD*>:<*YYYY*>{CR}{LF}

Time:{TAB}<*HH*>:<*MM*>:<*SS*>{CR}{LF}

Operator:{TAB}<*TEXT 20 CHAR*>{CR}{LF}

{CR}{LF}

TRUCK SETUP{CR}{LF}

Front Axle Weight lbs:{TAB}<*INTEGER*>{CR}{LF}

Right Tire Pressure PSI:{TAB}<*INTEGER*>{CR}{LF}

Left Tire Pressure PSI:{TAB}<*INTEGER*>{CR}{LF}

Tire Size:{TAB}}<*TEXT 20 CHAR*>{CR}{LF}

{CR}{LF}

DEFLECTION MONITORING SYSTEM{CR}{LF}

Control Unit Serial Number:{TAB}<*INTEGER*>{CR}{LF}

Control Unit Calibration Date:{TAB}<*TEXT*>{CR}{LF}

Right Deflection Sensor Serial Number:{TAB}<*INTEGER*>{CR}{LF}

Left Deflection Sensor Serial Number:{TAB}<*INTEGER*>{CR}{LF}

Right Deflection Sensor Tare Value:{TAB}<*INTEGER*>.<*INTEGER*>{CR}{LF}

Left Deflection Sensor Tare Value:{TAB}<*INTEGER*>.<*INTEGER*>{CR}{LF}

Right Deflection Sensor Tare Time Stamp:{TAB}<*TEXT*>{CR}{LF}

Left Deflection Sensor Tare Time Stamp:{TAB}<*TEXT*>{CR}{LF}

GPS Status:{TAB}<*TEXT*>{CR}{LF}

{CR}{LF}

SURVEY SETUP{CR}{LF}

Start Station:{TAB}<*TEXT*>CR}{LF}

Offset:{TAB}<*INTEGER*>.<*INTEGER*>{CR}{LF}

Direction:{TAB}<*TEXT*>CR}{LF}

Material Type:{TAB}<*TEXT*>CR}{LF}

Depth from Final Grade:{TAB}<*INTEGER*>{CR}{LF}

{CR}{LF}

SURVEY DATA{CR}{LF}

STATION{TAB}SPEED{TAB}DEFLECTION RIGHT{TAB} DEFLECTION LEFT{TAB}GPS DATA{CR}{LF}

<*TEXT*>{TAB}<*INTEGER*>{TAB}<*INTEGER*>{TAB}<*INTEGER*>{TAB}<*TEXT*>{CR}{LF}