APPENDIX A
PROCEDURES FOR FORENSIC STUDY OF DISTRESS OF HOT MIX ASPHALT AND PORTLAND CEMENT CONCRETE

A.1 Introduction

This section covers the procedure for evaluating premature distress of Hot Mix Asphalt (HMA), Stone Matrix Asphalt (SMA) and Portland Cement Concrete Pavement (PCCP). The procedure calls for reviewing the type of distress with a visual analysis and recommending a sampling and testing program; this could be called a forensic study. Finally, the cause, potential solution, and recommendation for rehabilitation will be reported.

A.2 Formation of and Evaluation Team

A team will be established to perform the evaluation. The Region Materials Engineer, in consultation with all potential team participants, will make the final determination as to the level of investigation required. The team may include members from the following areas or disciplines:

- Materials and Geotechnical Branch
- Project Development Branch
- Region Materials
- Region Design
- Region Construction (Project Engineer/Resident Engineer)
- Region Maintenance (Maintenance Superintendent/Supervisor)
- Industry
- National Experts

Contractor participation should be dependent on the status of the project; closed or not.

A.3 Levels of Investigation

Based on the degree of complexity, severity of the pavement distress, and the urgency of the required response, the following three-tiered investigation levels are recommended:

A.3.1 Level I (CDOT Region)

The team may consist of Region personnel with expertise in various areas of disciplines including materials, design, construction, and maintenance. Based upon preliminary information and data, the pavement distress is determined to have a low degree of complexity and severity. Preliminary survey indicates if the cause can be easily identified. The investigation should include at least a visual analysis, investigational requirements, and required core samples and testing. The designer should complete the final report if the problem is resolved. If further information is needed, the investigation should proceed to Level II.

A.3.2 Level II (CDOT Statewide)

The team may consist of individuals from **Section A.3.1 Level I (CDOT Region)** along with personnel from CDOT Materials and Geotechnical Branch, Project Development Branch, FHWA, and industry representation (ACPA, Asphalt Institute, CAPA, etc.). Findings from the first level of investigation will be re-evaluated. If the pavement distress is concluded to have a moderate degree of complexity and severity and re-evaluation of initial findings indicates the cause is difficult to ascertain, then the investigation should include at least the following:

- Visual analysis
- Investigational requirements
- Required core samples and testing
- Pavement slab samples may be obtained for further testing
- Deflection analysis may also be conducted

The designer should complete the final report if the problem is resolved. If not, the investigation will proceed to Level III.

A.3.3 Level III (National Effort)

The team will consist of individuals from **Sections A.3.1 Level I (CDOT Region)** and **A.3.2 Level II (CDOT Statewide)** along with national experts from FHWA, AASHTO, and other state DOTs, or government entities. Findings from the first and second levels of investigation will be re-evaluated again. The pavement distress is concluded to have a high degree of complexity and severity. The cause of the pavement distress is determined to be highly complex. The investigation should include at least the following steps:

- Visual analysis
- Investigational requirements
- Required core samples and testing
- Pavement slab samples may be obtained for further testing
- Deflection analysis may also be conducted
- Other tests as necessary

A.4 Site Investigation

A.4.1 Visual Analysis

The first step in investigating the pavement distress is to perform a complete and comprehensive visual analysis of the entire project. Emphasis will be placed on the distressed areas. Refer to **Figure A.1 Pavement Condition Evaluation Checklist (Rigid)** and **Figure A.2 Pavement Condition Evaluation Checklist (Flexible)** for pavement evaluation checklists. These figures are restatements of **Figure 8.2 Pavement Condition Evaluation Checklist (Flexible)** and **Figure 9.2 Pavement Condition Evaluation Checklist (Rigid).** Guidelines on how to perform the visual distress survey can be found in the *Distress Identification Manual for the Long-Term Pavement*

Performance Program. This FHWA publication (1) includes a comprehensive breakdown of common distresses for both flexible and rigid pavements. Information gathered should include:

- Date
- Reviewers
- Project location and size
- Traffic data
- Weather information
- Extent of distress
- Detailed information concerning each distressed area
- Photographs of the typical distress on the project will be included
- Any other problems that are visible (drainage, frost problems, dips or swells, etc.) should be recorded

In general, each individual distress type should be rated for severity and the extent (amount) of the distress noted. When determining severity, each distress type can be rated as low, medium (or moderate), or high. This will not apply for some distresses, such as bleeding, which will be characterized in terms of number of occurrences.

When measuring and recording the extent or amount of a certain distress, each should be rated consistent with the type of distress. For example, alligator cracking is normally measured in terms of affected area. As a result, the overall amount of alligator cracking is recorded in terms of total square feet of distress. Alternatively, for quick surveys, the overall amount of alligator cracking can be recorded as a percentage of the overall area (i.e. 10%).

Other distresses, such as cracking, are recorded as the total number of cracks or number of cracks per mile, and the overall length of the cracks. For example, for transverse or reflection cracking it is appropriate to record the amount of distress in terms of the number of cracks per mile (for each severity level), while for longitudinal cracks it is appropriate to record the total length recorded. Any assumptions made during the investigation should also be noted.

The decision to use the Falling Weight Deflectometer (FWD) will be determined based upon visual analysis. When the decision has been made to use FWD, the following steps will be followed:

- Deflection tests will be taken throughout the problem areas to determine the extent of the distress.
- Normal deflection testing frequency is ten sites per mile. However, within an area of concern, a minimum of 30 testing sites will need to be selected.
- For comparison and control purposes, it is recommended to perform a minimum of 10 tests outside each end of the area of concern, per lane segment.
- For the control segment, a 200-foot interval between FWD test sites will be used.
- The deflection analysis will be reviewed for an elastic modulus of each layer to determine the in-place strength.
- The required design overlay thickness analysis will then be performed.

PAVEMENT EVALUATION CHECKLIST (RIGID)

PROJECT NO.: ________________________ LOCATION: _______________________________
PROJECT CODE (SA #): ________________ DIRECTION: _______ MP _____ TO MP ______
DATE: ________________________________ BY: _______________________________________
TITLE: ________________________________

TRAFFIC
- Existing ____________________18k ESAL/YR
- Design ____________________18k ESAL

EXISTING PAVEMENT DATA
- Subgrade (AASHTO)
- Base (type/thickness)
- Pavement Thickness
- Soil Strength (R/M_R)
- Swelling Soil (yes/no)
- Roadway Drainage Condition
  (good, fair, poor)
- Shoulder Condition
  (good, fair, poor)
- Joint Sealant Condition
  (good, fair, poor)
- Lane Shoulder Separation
  (good, fair, poor)

DISTRESS EVALUATION SURVEY

Type	Distress Severity*	Distress Amount*
Blowup		
Corner Break		
Depression		
Faulting		
Longitudinal Cracking		
Pumping		
Reactive Aggregate		
Rutting		
Spalling		
Transverse and Diagonal Cracks		
OTHER		

* Distress Identification Manual for the Long-Term Pavement Performance Program, U.S. Department of Transportation, Federal Highway Administration, Publication No. FHWA-RD-03-031, June 2003.

Figure A.1 Pavement Condition Evaluation Checklist (Rigid)

PAVEMENT EVALUATION CHECKLIST (FLEXIBLE)

PROJECT NO.: ________________________ LOCATION: ______________________________
PROJECT CODE (SA #): _______________ DIRECTION: _______ MP _____ TO MP ______
DATE: ________________________________ BY: _____________________________________
TITLE: _______________________________

TRAFFIC
- Existing ____________________18k ESAL/YR
- Design ____________________18k ESAL

EXISTING PAVEMENT DATA
- Subgrade (AASHTO)
- Base (type/thickness)
- Soil Strength (R/M_R)
- Roadway Drainage Condition (good, fair, poor)
- Shoulder Condition (good, fair, poor)

DISTRESS EVALUATION SURVEY

Type	Distress Severity*	Distress Amount*
Alligator (Fatigue) Cracking		
Bleeding		
Block Cracking		
Corrugation		
Depression		
Joint Reflection Cracking (from PCC Slab)		
Lane/Shoulder Joint Separation		
Longitudinal Cracking		
Transverse Cracking		
Patch Deterioration		
Polished Aggregate		
Potholes		
Raveling/Weathering		
Rutting		
Slippage Cracking		
OTHER		

* Distress Identification Manual for the Long-Term Pavement Performance Program, U.S. Department of Transportation, Federal Highway Administration, Publication No. FHWA-RD-03-031, June 2003.

Figure A.2 Pavement Condition Evaluation Checklist (Flexible)

A.4.2 Review of Construction Documents

Pertinent information from the mix design, binder tests, mixture tests, QC/QA results, and project diary should be reviewed.

A.4.3 Investigational Requirements

After the visual analysis report has been evaluated, the second step of this procedure requires the determination of the investigational requirements. The requirements will depend on the type and extent of the pavement failure. It is recommended to obtain samples of the pavement adjacent to the distress area for comparison and control purposes. A minimum of 5 samples per lane is required outside each end of the distress area. A list of investigational requirements may include:

- Core sampling and testing plan
- Slab sampling of pavement for testing and evaluation
- Base and subgrade sampling and testing
- Deflection analysis
- Transverse cracking in concrete slab

A.4.4 Required Core Samples and Testing

Samples of materials at the pavement distress location shall be taken so tests can be performed to evaluate the problem areas. For reporting purposes, the core location should be as accurate as possible. The samples shall be submitted to the Materials and Geotechnical Branch for testing unless otherwise specified.

A.4.5 Core Samples from Hot Mix Asphalt and PCCP

Samples shall be taken of each HMA, SMA or PCCP layer with at least five 4-inch cores from all locations (bad area, a shoulder next to the bad area, and a good area). Larger cores are preferred. Each layer of HMA, SMA or PCCP should be tested separately. Contact the Materials and Geotechnical Branch for sampling and removal processes and procedures. In some cases, slab samples may indicate distresses not usually seen in core samples.

A.4.6 Base and Subgrade Samples

When obtaining samples of the base and subgrade materials, a sufficient area of HMA, SMA or PCCP should be removed for adequate testing and sampling of each layer of material. Testing shall include but not limited to:

- Applicable Colorado, AASHTO and ASTM test procedures
- Nuclear gauge density and moisture determination
- Soil classification
- R-value
- Proctor testing

A.5 Final Report

A summary of the tests and other investigational requirements will be submitted to the Materials Advisory Council (MAC) upon the completion of all testing and analysis. The final report will be catalogued in the Technology Transfer Library and copies will be available for loan. The report should include some or all of the following items as applicable:

- **Project Overview**:
  - Type of pavement (HMA, SMA or PCCP)
  - Location and size of project
  - Traffic data
  - Weather conditions
  - When distress developed
  - Historical distresses

- **Visual Inspection**:
  - Type, extent and location of distress
  - Photographs

- **Summary of Construction Records**:
  - Mix design
  - Central laboratory check tests (stability, Lottman, binder tests, compacted specimen tests, concrete compressive/flexural strength and chemical tests)
  - Quality control test results (density, gradation, asphalt and portland cement)
  - Project diaries

- **Core Sampling and Testing Results**:
  - Core location and thickness
  - Density and air voids
  - Asphalt content
  - Gradation
  - Vacuum extraction and asphalt cement penetration
  - Geologic analysis of aggregates
  - Portland cement chemical tests
  - Petrographic analysis
  - Alkali-Silica Reactivity (ASR) tests
  - Modulus of elasticity
  - Resilient modulus
- **Slab Sample**:
  - Thickness
  - Areas of deformation
  - Stripping
  - Determination of subsurface deformation
  - Any other items of note

- **Results of Sampling and Testing of Base and Subgrade**:

  - R-value
  - Gradation
  - Classification testing
  - Moisture and density
  - Proctor results

- **Deflection Analysis**:
  - Overlay thickness required
  - Comparison to original overlay thickness
  - Comparison with component analysis

- **Conclusions and Recommendations**:
  - Apparent cause of failure
  - Potential solutions to prevent future problems with other pavements
  - Recommendations for rehabilitation of the distress location

A.6 Funding Sources

Funds for an investigation may come from the Regions and/or Staff Branches depending on the level of investigation. The Research Branch annually allocates funds for experimental and implementation programs. Therefore, if a situation arises one should submit a request for assistance to the Research Implementation Council (RIC) as soon as deemed appropriate.

Reference

1. *Distress Identification Manual for the Long-Term Pavement Performance Program*, U.S. Department of Transportation, Federal Highway Administration, Publication No. FHWA-RD-03-031, June 2003.

APPENDIX B
FORMS

The Colorado Department of Transportation (CDOT) uses the following forms:

COLORADO DEPARTMENT OF TRANSPORTATION **DESIGN DATA** ❑ Metric ❑ English Page 1 of 2	Orig. date: Rev. date: Revision # Region #	Project code # (SA#)	STIP #
Status: ❑ Preliminary ❑ Final ❑ Revised		Project #	
Prepared by:	Revised by:	PE project code	PE project #
Date:	Date:	Project description	
Submited by Project Manager:	Approved by Preconstruction Engineer:	County1 / County2 / County3	
Date:		Municipality	
		System code: ❑ IM ❑ NHS ❑ STP ❑ Other	
		Oversight by: ❑ CDOT ❑ FHWA ❑ Other	
		Planned length:	

Geographic location

Type of terrain ❑ level ❑ plains ❑ rolling ❑ urban ❑ mountainous

Description of proposed construction/improvement (attach map showing site location)

1 Traffic (Note: use columns A, B, and/or C to identify facility described below)

Facility	Current year:_______ ADT	DHV	DHV % trucks	Future year:_______ ADT	DHV	Facility location: Industrial	Commercial	Residential	Other
A						❑	❑	❑	❑
B						❑	❑	❑	❑
C						❑	❑	❑	❑

2 Rdwy class

	Route	Refpt	Endrefpt	Functional classification	Facility type	Rural code
1.						
2.						
3.						

3 Design standards (identify substandard items with an * in 1st column & clarify in remarks)

	A= Standard	Existing	Proposed	Ultimate	B= Standard	Existing	Proposed	Ultimate	C= Standard	Existing	Proposed	Ultimate
Surface type												
Typical section type												
# of travel lanes												
Width of travel lanes												
Shoulder width lt./median												
Shoulder width rt./outside												
Side slope dist. ("z")												
Median width												
Posted speed												
Design speed												
Max. superelevation												
Min. radius												
Min. horizontal SSD												
Min. vertical SSD												
Max grade												

Project under ❑ 1R ❑ 3R ❑ 4R ❑ Other:______________________________criteria

❑ Variance in minimum design standards required
❑ Justification attached ❑ Request to be submitted
❑ Bridge (see item 4) ❑ See remarks

❑ Safety project
not all standards addressed

❑ Stage construction (explain in remarks)

Resurfacing projects
❑ Recommendations concerning safety aspects attached

Existing guardrail meets current standards: ❑ yes ❑ no
Comments:

CDOT Form #463 12/03

Figure B.1 Design Data (Page 1 of 2) (CDOT Form 463 12/03)

Page 2 of 2	Project code # (SA#)	Project #	Revise date

4 Major structures S= to stay, R= to be removed, P= proposed new structure

Structure ID#	▼	Length	Ref. point	Feature intersected	Standard width	Structure Rdwy	load	Horizontal clearance	Vertical clearance	Year built

Proposed treatment of bridges to remain in place (address bridge rail, capacity, and allowable surfacing thickness)

5 Project characteristics (proposed)

❑ Lighting ❑ Handicap ramps
❑ Curb and gutter ❑ Curb only
❑ Sidwalk width= ❑ Bikeway width=
❑ Parking lane width= ❑ Detours
❑ Landscaping requirements: (description)

Median (type): ❑ depressed ❑ painted ❑ raised ❑ none
❑ Traffic control signals ❑ Striping
❑ Left-turn slots ❑ continuous width=
❑ Right-turn slots ❑ continuous width=
Signing ❑ construction ❑ permanent
❑ Other: (description)

6 Right of Way

	Yes	No	Est. #
ROW &/or perm. easement required:	❑	❑	________
Relocation required:	❑	❑	________
Temp. easement required:	❑	❑	________
Changes in access:	❑	❑	________
Changes to connecting roads:	❑	❑	________

7 Utilities (list names of known utility companies)

8 Railroad crossings # of crossings:

Recommendations

9 Environmental	Type:	Approved on:	under Project Code:	Project #

Comments

10 Coordination

❑ Withdrawn lands (power sites, reservoirs, etc.) cleared thru BLM or forest service office Irrigation ditch name:
❑ New traffic ordinance required ❑ Modify schedule of existing ordinance Municipality:
Other:

11 Construction method

Advertised by: ❑ State ❑ Local ❑ None

noAd Reason: ❑ Design ❑ Local F/A ❑ P.O. ❑ RR F/A ❑ Study ❑ Utility F/A ❑ CDOT F/A ❑ Miscellaneous

Entity/Agency contact name:

Phone #:

12 Remarks (include additional pages if needed)

Original to Central Files - **Copies to**: Region Files, Region Environmental Program Manager, Staff ROW, Staff Bridge or other when appropriate.

Figure B.2 Design Data (Page 2 of 2) (CDOT Form 463 12/03)

COLORADO DEPARTMENT OF TRANSPORTATION
Maintenance Project Request Form
Form 463 M(revised)

Today's Date: xx/xx/20xx	**Proposed Ad Date:** xx/xx/20xx	**Proposed Completion Date:** xx/xx/20xx
Requestor Name: xxx	**Phone:** xxx-xxx-xxxx	**E-Mail Address:** xxx.xxx @dot.state.co.us

Region No.: X	**Main. Sect. No.:** X	**Project Type:** Type of Project	**FY:** XX	**Budget:** $ XXX,XXX.00
State Hwy No.: XXX	**MP Limits:** MP xxx.xx **to** xxx.xx	**County(ies):** Xxxxxx		**City(ies):** Xxxxxx

Maintenance Superintendent/Resident Engineer: XX		**Phone:** XXX-XXX-XXXX
Design Project Manager: XX	**Phone:** XXX-XXX-XXXX	**Cell:** XXX-XXX-XXXX
Construction Project Engineer: XX	**Phone:** XXX-XXX-XXXX	**Cell:** XXX-XXX-XXXX

SAP CODING INFORMATION

****SAP Work Order #:** XXXXXXXXXX	****SAP Purchase Requisition #:** XXXXXXXXX

****Requires Release by Business Office and Maintenance Superintendent prior to Advertisement**

Cost Center	Approp Code	Sub. Obj.	N/P	Report Category
XXXX	XXX	X	N or P	XXXX
Fund Number	**Funds Center**	**Functional Area**	**GL Account**	**WBS Element**
XXX	RXXXX-XXX	XXXX	XXXXXXXXXX	RXXXXXXXX

SCOPE AND PROJECT DETAILS

(Please provide as much detail as possible regarding Scope of Work) Roadway widths, project limits, preliminary quantities, repair/treatment type (Class of repair, type of surface treatment), temporary/permanent pavement marking, excavation and drainage considerations, Contract Time (Milestone, Working/Calendar Day) and Estimated Construction Duration; ADA Requirements (1.5 inch depth or greater).

XX

Material Requirements: Pavement treatment types and recommendations; Structure material considerations; Testing/Inspection requirements; Pavement Marking Types; Project Special Provisions.

xxx

Traffic Control Requirements: Regional Lane Closure Policy (Variance Considerations); Posted Speed/Reductions; Working Hour Restrictions (Night, Day, Special Events); Public Information; Pedestrian/Bicycle Considerations, Flagging; Signage, Preliminary Quantities.

xxx

CLEARANCES

(See M-Project Manual, ROW, Utilities and Environmental Sections for more information regarding clearances)

REGION ROW

1. Existing ROW Boundaries Determined **and Confirmed**? Y/N
2. All project requirements constructed within boundary of existing ROW? Y/N
3. Are Railroad or Temporary Easements Required? Y/N explain
4. Is work in vicinity of National Forest, BLM, US Army Corps of Engineer Property? Y/N explain

Notes: xxx

REGION UTILITIES

Note any known or observable utility/railroad facilities within project limits: xxx

Are utility relocations anticipated? Y/N explain

REGION ENVIRONMENTAL/STORM WATER MANAGEENT PLAN (SWMP)

Environmental Clearance Form 128 from the respective Region Environmental Manager. **SAP Approval Required**
SWMP/ Estimated Preliminary Items, Quantities and Force Accounts: xxx
Additional Clearance/Considerations may include: Historical Clearance, Noise Variance, Hazardous Materials Testing (Lead, Asbestos, etc.), Army Corps of Engineers Permit, Habitat Protection (Swallows, Prairie Dogs, Preble Mouse, etc.), Dewatering Treatment.

Information for Project Number and Project Definition obtained from SAP	**M-Proj Number:** RXXXX-XXX	**M-Proj Definition:** XXXXX

CDOT FORM # 463M Rev-4/10

Figure B.3 Maintenance Project – Request Form (CDOT Form 463M Rev 4/10)

APPENDIX C
DEFLECTION TESTING AND BACKCALCULATION

C.1 Introduction

Deflection testing is the measurement of the structural strength of the roadway. CDOT has utilized many devices to evaluate the strength of the existing road: the Falling Weight Deflectometer (FWD), the Dynaflect, the Benkelman Beam, and the heel of the Engineer's shoe. CDOT has owned a FWD since April 19, 1988. The FWD is a device capable of applying dynamic loads to the pavement surface, similar in magnitude and duration to that of a single heavy moving wheel. Tests show the response of the pavement system measured in terms of vertical deformation, or deflection, over a given area using seismometers (geophones). Deflection testing devices are considered non-destructive testing (NDT) devices. The FWD as a NDT device should never apply a load to the pavement so great that it will not rebound fully.

FHWA (LTPP) approached CDOT in 2002 to become a Regional Calibration Center, and the MAC discussed the topic in 2003. CDOT agreed to become a national calibration center in 2003 taking the program over from Nevada DOT. The SHRP/LTPP FWD Calibration Protocol was implemented in 1992 and since then, hundreds of calibrations have been performed in the U.S. Since that time the experience gained calibrating FWDs has shed light on opportunities for improving the calibration process, however changes in computer technology have rendered some calibration equipment obsolete. Many State Highway Agencies, including CDOT, had expressed interest in updating the FWD calibration software and equipment and establish a long term plan for support of the calibration facilities and their services. A Transportation Pooled Fund Study TPF-5(039) entitled "*Falling Weight Deflectometer (FWD) Calibration Center and Operational Improvements*" was conducted over several years and revised the calibration protocol, updated the equipment, and produced new calibration software. CDOT was extensively involved in the pooled fund study in developing and testing the new calibration procedures and software.Details can be found at http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=729.

The CDOT FWD will be calibrated annually using the CDOT FWD calibration center. Any consultant engineering company that performs design work for CDOT requiring FWD data shall schedule the CDOT FWD to perform the FWD testing. If the CDOT FWD is not available to collect the data, the consultant engineering company may hire a consultant FWD. The consultant's FWD shall be calibrated at an approved FWD calibration center not more than one year prior to performing the FWD data collection. For more information on FWD test protocols, consult with the Concrete and Physical Properties Program (CPPP) Unit of the CDOT Materials and Geotechnical Branch.

The most cost effective strategy will most likely involve maximum utilization of resources. The existing pavement should be considered as a resource that is already in place. The structural value of the existing pavement needs to be thoroughly investigated and determined. Deflection measurements and analysis will yield structural values of in-place pavements and identify weak zones. During the pavement analysis portion of the thickness design, the designer should compare the information obtained from the deflection data against that noted in the distress survey. Deflection readings do not always address the total scope of corrective action needed, especially in areas with substantial distress present. It is recommended the designer use a profile plot of distress and deflection to identify areas requiring additional consideration. In areas of high distress, verifying the deflection analysis with a component analysis may be desirable.

Deflection testing and backcalculations are most highly recommended to obtain a k-value of a soil. This method is suitable for analyzing existing pavements to obtain a k-value. Sometimes a design of similar pavements in the same general location on the same type of subgrade may be appropriate, i.e. at an interchange location.

A procedure is outline in the 1998 AASHTO Supplement to compute the dynamic k-value using FWD. The dynamic k-value must be converted to the initial static k-value and dividing the mean dynamic k-value by two (2) to estimate the mean static k-value for design.

Several software tools are available for production data processing and analysis. The purpose of this section is to provide guidelines for engineers to follow when setting up FWD testing and analyzing the results. CDOT recommends using the software MODTAG.

MODTAG is a software tool that allows an engineer to analyze FWD data quickly and efficiently using empirical (Appendix L of the *AASHTO Guide for Design of Pavement Structures – 1993*) and mechanistic-empirical (MODCOMP) methods and procedures. MODTAG is an in-house software tool developed in cooperation by Virginia DOT and Cornell University's Local Roads Program. MODTAG operates in US Customary and Metric Units, however, some of the routines are not available when a metric analysis is selected. MODTAG is being provided without technical/engineering or software support to users outside Virginia DOT. Additional information on analyzing the testing results can be found in the document titled *MODTAG Users Manual* in the software MODTAG.

This appendix is based on CDOT's truck mounted JILS-20T FWD with on board JTEST™ software. If other FWD owners use this appendix, they should follow the manufacturers' recommendations. For example, the one drop setting and drop weight is associated with CDOT's FWD, refer to **Figure C.1 Depiction of FWD Load Distribution Through Pavement**.

C.2 FWD Testing: Flexible Pavements

For flexible pavements, FWD testing is used to assess the structural capacity of the pavement and estimate the strength of subgrade soils. The elastic modulus for the surface, base and subbase layers can also be determined.

C.2.1 FWD Testing Pattern: Flexible Pavement

The FWD testing pattern selected for a project should relate to the project's size and layout. The Pavement Engineer should consider the number of lanes to be tested, total length of the project, and any unusual circumstances that would require a change in the testing pattern.

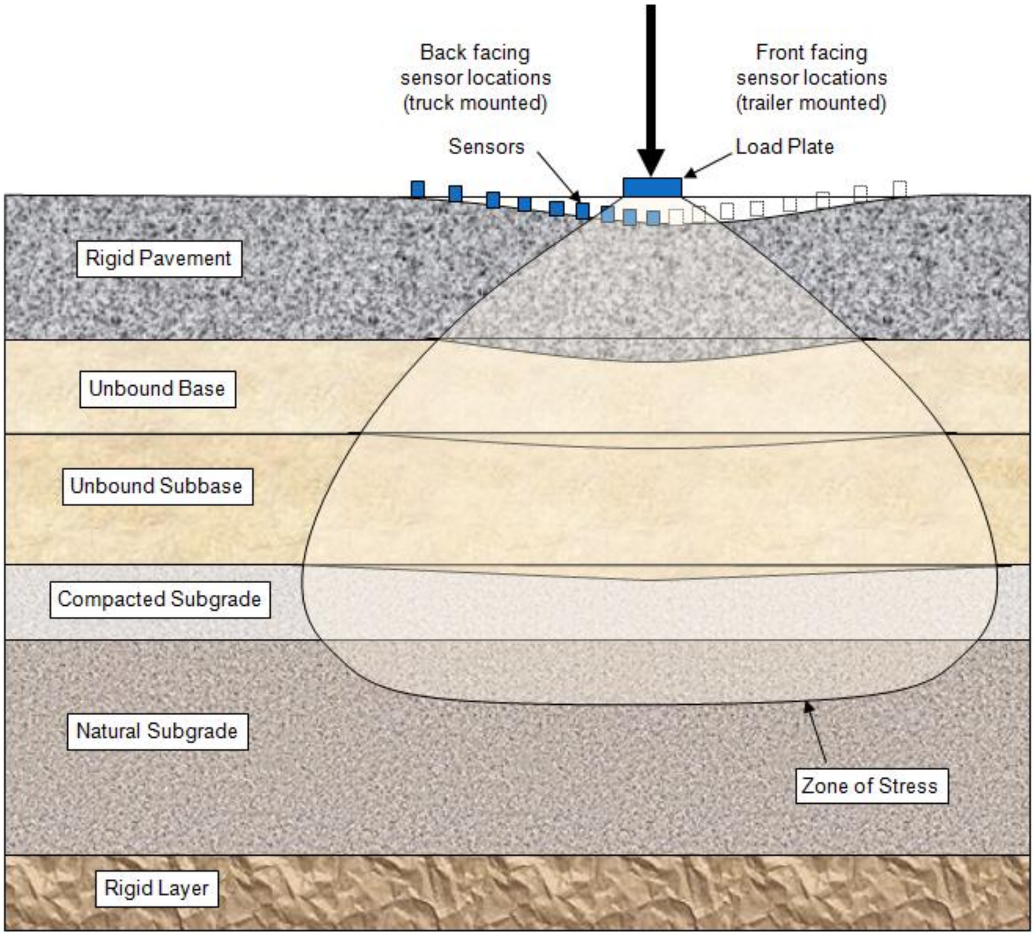


Figure C.1 Depiction of FWD Load Distribution Through Pavement

- **Project Layout:** The project layout will influence the FWD testing pattern. For projects where the pavement is to be repaired in each direction, the travel lanes in each direction should be tested. Typically, this should be the outside travel lane. For projects where only one direction will be repaired and more than two lanes exist, then testing should be conducted on the outside lane and possibly the inside lane. The inside lane should be tested if:

    - Pavement structure is different from the outside lane
    - More load related distress is present as compared to the outside lane
    - Heavy truck traffic uses the lane (lane is prior to a left exit)

  For projects that contain multiple intersections, FWD testing may not be possible due to traffic. However, testing should be conducted at approaches and departures to an intersection.

- **Project Size:** The project size is determined by the directional length of pavement to be repaired, not necessarily the centerline length and will influence the test spacing.

For example, a project with a centerline distance of one mile to be repaired in two directions has a directional length of two miles. Therefore, the test spacing should be based on two miles. **Table C.1 Flexible Pavement Test Spacing Guidelines** contains guidelines based on project size, test spacing, and estimated testing days.

- **Testing Days**: **Table C.1 Flexible Pavement Test Spacing Guidelines** shows the approximate testing days of doing the drop testing. Additional time must be allotted for traffic control setup and travel time to the test site. The project may also require a pre-testing meeting with the Pavement Engineer.

Table C.1 Flexible Pavement Test Spacing Guidelines

Project Size (miles)	Test Spacing (feet)	Approximate Number of Tests	Testing Days
0 – 0.5	25	75	½ day
0.5 – 1.0	50	90	½ day
1.0 – 2.0	50	175	1 day
2.0 – 4.0	100	175	1 day
4.0 – 8.0	150	200	1 to 1 ½ days
> 8.0	200	>200	> 1 ½ days
Note: A testing day is defined as 200 locations tested.			

For two or three lane bi-directional roadways not separated by a median, the testing should be staggered by one-half the test spacing. See **Figure C.2 Flexible Staggered Testing Patten** for clarification. For projects separated by a median, a staggered testing pattern is not required.

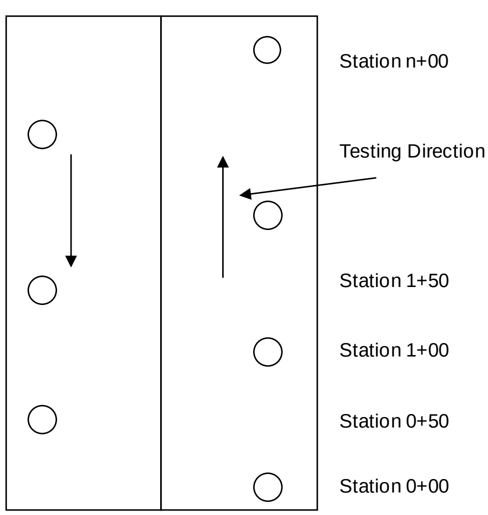


Figure C.2 Flexible Pavement Staggered Testing Pattern

- **Basin Testing Location**: For flexible pavements, FWD testing should be conducted in the wheel path closest to the nearest shoulder. This type of testing is known as basin testing since deflection measurements from all sensors may be used (see **Figure C.1 Depiction of FWD Load Distribution Through Pavement).** The purpose of this testing is to characterize the structural condition of the pavement where damage from truck loading should be the greatest. For the outside lanes, testing should be conducted in the right wheel path; for inside lanes, testing should be conducted in the left wheel path.

C.2.2 FWD Drop Sequence: Flexible Pavement

Drop sequences vary based on pavement type and the type of information being gathered. A drop sequence is defined as the order in which impulse loads are applied to the pavement. This includes the "seating drops" and the recorded impulse loads. Below is the recommended drop sequence for basin testing on flexible pavements:

- Two seating drops at 6,000 pounds
- Three recorded drops at 6,000 pounds
- Three recorded drops at 9,000 pounds
- Three recorded drops at 12,000 pounds
- Three recorded drops at 16,000 pounds

Therefore, at each test location the FWD will perform 14 drops and record four sets of deflection/impulse load data. By performing multiple drops at a location, the pavement will react as a homogeneous structure and reduce errors in measurement. Additionally, recording and analyzing data from four different load levels, the Pavement Engineer can determine if materials on the project are stress sensitive (non-linearly elastic), if a hard bottom (water table, bedrock or extremely stiff layer) is present, and/or if compaction/liquefaction is occurring in the subgrade.

C.2.3 FWD Sensor Spacing: Flexible Pavement

FWD sensor spacing to record pavement deflection data is dependent on the pavement type, and the testing purpose (load transfer testing vs. basin testing). For basin testing on flexible pavements, the recommended spacing from the center of the load plate is given below:

0, 8, 12, 18, 24, 36, 48, 60, and 72 (inches)

C.2.4 Surface Temperature Measurement: Flexible Pavement

Ideally, the pavement temperature will be recorded directly from temperature holes at each test location as the test is being performed. While this is the preferred approach for research projects, it is not practical for production level testing (maintenance and rehabilitation projects). Therefore, for production level testing the economic and practical approach is by measuring the surface temperature at each test location using an infrared thermometer. The FWD can automatically measure and record the pavement surface temperature to the FWD file. If the FWD is not equipped with an infrared thermometer, the operator can use a hand held thermometer and record the temperature to a file. By measuring and monitoring the surface temperature during testing, the FWD operator can suspend testing if the pavement becomes too hot.

C.3 FWD Testing: Rigid Jointed Plain Concrete Pavements

For rigid pavements, FWD testing is used to assess the structural capacity of the pavement, estimate the strength of subgrade soils, assess load transfer at joints, and detect voids at joints. In addition to the structural capacity, the elastic modulus of the surface, base and sub-base layers can be determined.

C.3.1 FWD Testing Pattern: Rigid Pavement

The FWD testing pattern selected for a jointed concrete pavement project should be related to the project's layout, project size, and slab length. The Pavement Engineer should consider the number of lanes to be tested, total number of slabs, length of the project, and any unusual circumstances that would require a change in the testing pattern.

- **Project Layout**: The project layout will influence the FWD testing pattern. For projects where the pavement is to be repaired in each direction, the travel lanes in each direction should be tested. Typically, this should be the outside travel lane. For projects where only one direction will be repaired and more than two lanes exist, then testing should be conducted on the outside lane and possibly the inside lane. The inside lane should be tested if:

  - Pavement structure is different from the outside lane
  - More load related distress is present as compared to the outside lane
  - Heavy truck traffic uses the lane (lane is prior to a left exit)

  Due to traffic, FWD testing may not be possible for projects with multiple intersections, however, where possible testing should be conducted at approaches and departures to an intersection.

- **Slab Length and Project Size:** The number of jointed concrete slabs in a project will determine test spacing. For projects with short slab lengths, it may not be practical to test every slab (basin and joint testing). In addition to slab length, the size of a project will influence the test spacing. The project size is determined by the directional length of pavement to be repaired, not necessarily the centerline length. For example, a project with a centerline distance of 1 mile and will be repaired in two directions has a directional length of 2 miles. Therefore, the test spacing should be based on two miles. **Table C.2 Jointed Plain Concrete Pavement Test Spacing Guidelines** contains guidelines based on project size, approximate slab length, test spacing, and estimated testing days. A testing day is defined as 175 locations tested (joints, corners and basins).

- **Testing Days**: **Table C.2 Jointed Plain Concrete Pavement Test Spacing Guidelines** shows the approximate testing days of actually doing the drop testing. Additional time must be allotted for traffic control setup and travel time to the test site. It may also be required to have a pre-testing meeting with the Pavement Engineer.

- **Rigid and Composite Basin Testing:** The standard procedure will be basin testing only. If additional testing of joint and corner testing is required, a special request is to be submitted.

- **Testing Location:** For jointed concrete pavements, three types of FWD testing are generally conducted; and basin, joint, and slab corner testing. Each test provides information on the structural integrity of the pavement.

- **Basin Testing**: F jointed concrete pavement basin testing should be conducted near the center of the slab (see **Figure C.3 JPCP Testing Pattern**). Testing provides information on the elastic modulus of the PCC and strength of base materials and subgrade soils.

- **Joint Testing:** For jointed concrete pavements, joint testing should be conducted in the wheel path closest to the free edge of the slab (see **Figure C.3 JPCP Testing Pattern**). Typically, for the outside lanes, testing will be conducted in the right wheel path. For inside lanes, testing should be conducted in the left wheel path. If more than two lanes exist and the middle lanes are to be tested, then the nearest free edge must be determined. This testing provides information on joint load transfer; how well a joint through either aggregate interlock and/or dowel bars can transfer a wheel load from one slab to an adjacent slab.

- **Corner Testing:** For jointed concrete pavements, corner testing should be conducted at the slab's free edge corner (see **Figure C.3 JPCP Testing Pattern**). Typically, for the outside lanes, testing will be conducted in the right corner edge of the slab. For inside lanes, testing should be conducted in the left corner edge of the slab. If more than two lanes exist, then the middle lanes should only be tested if pumping is suspected in the middle lanes. The Pavement Engineer will determine if pumping is present and if testing should be conducted. Unless otherwise directed by the Pavement Engineer, corner testing shall be conducted on the leave side of the joint where voids are typically located. This testing provides information on the possibility of the presence of voids under a slab corner.

Table C.2 Jointed Plain Concrete Pavement Test Spacing Guidelines

Project Size (miles)	Slab Length (feet)	Basin Test Spacing (no. of slabs)	Joint/Corner Spacing (no. of slabs)	Approximate Number of Tests	Testing Days
0 - 0.5	< 20	every 6th slab	every 2nd J/C	115	1 day
0.5 – 1.0	< 20	every 9th slab	every 3rd J/C	180	1 day
1.0 – 2.0	< 20	every 12th slab	every 4th J/C	250	1 – 2 days
2.0 – 4.0	< 20	every 15th slab	every 5th J/C	380	1½ - 3 days
4.0 – 8.0	< 20	every 20th slab	every 10th J/C	220	1½ - 3 days
> 8.0	< 20	every 20th slab	every 10th J/C	450	> 3 days
Note: Basin testing using spacings of every 20th slab is more applicable to network than project testing.					

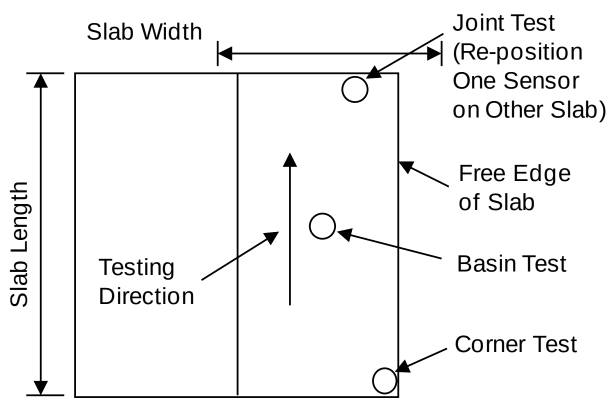


Figure C.3 JPCP Testing Pattern

C.3.2 FWD Drop Sequence – Rigid Pavement

When collecting pavement structure data, the correct drop sequence is required. Drop sequences vary based on pavement type and information being gathered. A drop sequence is defined as the order in which impulse loads are applied to the pavement. This includes the “seating drops” and the recorded impulse loads.

- **Basin Testing:** Below is the recommended drop sequence for basin testing on jointed concrete pavements:
  - Two seating drops at 6,000 pounds
  - Three recorded drops at 6,000 pounds
  - Three recorded drops at 9,000 pounds
  - Three recorded drops at 12,000 pounds
  - Three recorded drops at 16,000 pounds

Therefore, at each test location the FWD will perform 14 drops and record four sets of deflection and impulse load data. By performing multiple drops at a location, the pavement will react as a homogeneous structure, as well as, reduce the errors in measurement. Additionally, by recording and analyzing data from four different load levels, the Pavement Engineer can determine if the materials on the project are stress sensitive (non-linearly elastic), if a hard bottom (water table, bedrock or extremely stiff layer), and if compaction/liquefaction is occurring in the subgrade.

- **Joint Testing:** Below is the recommended drop sequence for joint testing on jointed concrete pavements:

  - Two seating drops at 6,000 pounds
  - Three recorded drops at 6,000 pounds
  - Three recorded drops at 9,000 pounds
  - Three recorded drops at 12,000 pounds
  - Three recorded drops at 16,000 pounds

  Therefore, at each test location the FWD will perform 14 drops and record four sets of deflection and impulse load data. Two sensors are needed for the analysis, the sensor at the load and the second sensor on the other side of the joint.

- **Corner Testing:** Below is the recommended drop sequence for corner testing on jointed concrete pavements:

  - Two seating drop at 6,000 pounds
  - Three recorded drops at 9,000 pounds
  - Three recorded drops at 12,000 pounds
  - Three recorded drops at 16,000 pounds

  In order to use the AASHTO procedure for the detection of voids, three different load levels are required. Thus, at each test location the FWD will need to perform 10 drops and record three sets of deflection and impulse load data. Only one sensor is needed in the analysis, the sensor at the load.

C.3.3 FWD Sensor Spacing – Rigid Pavement

FWD sensor spacing to record pavement deflection data is dependent on the pavement type and the type of testing. For jointed concrete pavements, three types of testing are performed - joint, corner and basin.

- **Basin Testing**: For basin testing on jointed concrete pavements, below is the recommended spacing:

  0, 8, 12, 18, 24, 36, 48, 60, and 72 (inches)

- **Joint Testing**: For joint testing on jointed concrete pavements, only two sensors are required. Below is the required spacing:

  0 and 12 (inches)

  The sensors are to be placed on each side of the joint and are 6 inches from the joint (see **Figure C.4 Joint Load Transfer Testing Sensor Spacing**).

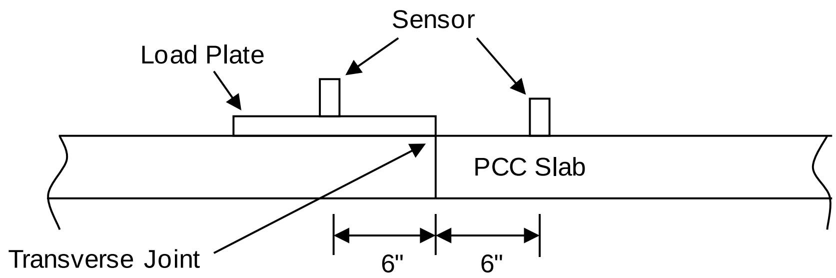


Figure C.4 Joint Transfer Testing Sensor Spacing

- **Corner Testing**: For joint testing on jointed concrete pavements, only one sensor is required. Below is the required sensor location:

  0-inches – at the load

  The sensor is to be placed on the leave side of the joint, 6 inches from the joint (**Figure C.5 Corner Testing Sensor Location**).

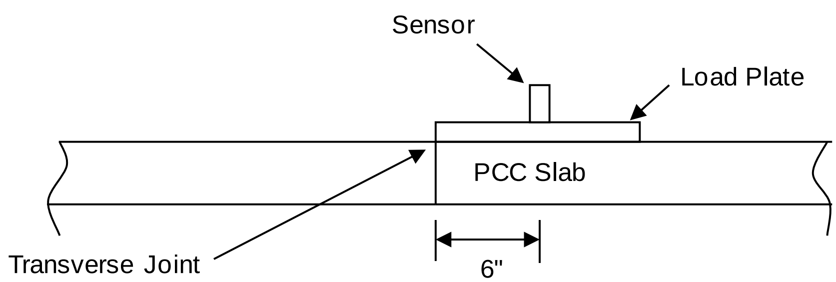


Figure C.5 Corner Testing Sensor Location

C.3.4 Surface Temperature Measurement: Rigid Pavement

Ideally, the pavement temperature will be recorded directly from temperature holes at each test location as the FWD test is being performed. While this is the preferred approach for research projects, it is not practical for production level testing (network level or maintenance and rehabilitation projects). Therefore, for production level testing the economic and practical approach is by measuring the surface temperature at each test location. This can be easily done using an infrared thermometer. The FWD can automatically measure and record the pavement surface temperature to the FWD file. If the FWD is not equipped with an Infrared thermometer, then the FWD operator can use a hand held thermometer and record the temperature to a file. By measuring and monitoring the surface temperature during testing, the FWD operator can suspend testing if the pavement becomes too hot. **Note**: Pavement temperature is recorded for joint and corner testing only.

C.4 FWD Testing: Composite Pavement

The FWD testing pattern selected for a project should be related to the project's size and layout. The Pavement Engineer should consider the number of lanes to be tested, total length of the project, and any unusual circumstances that would require a change in the testing pattern. In addition, the AC overlay thickness should be considered. If the thickness is less than four inches, then the load transfer of the underlying PCC joints may be performed.

- **Project Layout**: The project layout will influence the FWD testing pattern. For projects where the pavement is to be repaired in each direction, the travel lanes in each direction should be tested. Typically, this should be the outside travel lane. For projects where only one direction will be repaired and more than two lanes exist, then testing should be conducted on the outside lane and possibly the inside lane. The inside lane should be tested if:

  - Pavement structure is different from the outside lane
  - More load related distress is present as compared to the outside lane
  - Heavy truck traffic uses the lane (lane is prior to a left exit)

  For projects that contain multiple intersections, FWD testing may not be possible due to traffic. However, testing should be conducted at approaches and departures to an intersection.

- **Project Size**: The project size is determined by the directional length of pavement to be repaired, not necessarily the centerline length will influence the test spacing. For example, a project with a centerline distance of 1 mile and to be repaired in two directions has a directional length of 2 miles. Therefore, the test spacing should be based on two miles. **Table C.3 Composite Pavement Test Spacing Guidelines** contains guidelines based on project size, test spacing, and estimated testing days if load transfer testing is not performed. If load transfer testing is desired, then the appropriate spacing should be determined in the field. As a guideline, please refer to Joint/Corner Spacing column in **Table C.2 Jointed Plain Concrete Pavement Test Spacing Guidelines**. A testing day is defined as 200 locations tested.

- **Testing Days: Table C.3 Composite Pavement Test Spacing Guidelines** shows the approximate testing days of actually doing the drop testing. Additional time must be allotted for traffic control setup and travel time to the test site. It may also be required to have a pre-testing meeting with the Pavement Engineer.

- **Composite Basin Testing**: The standard procedure will be basin testing only. If additional testing of joint testing is required, a special request is to be submitted.

Table C.3 Composite Pavement Test Spacing Guidelines

Project Size (miles)	Test Spacing (feet)	Approximate Number of Tests	Testing Days
0 – 0.5	25	75	½ day
0.5 – 1.0	50	90	½ day
1.0 – 2.0	50	175	1 day
2.0 – 4.0	100	175	1 day
4.0 – 8.0	150	200	1 to 1½ days
> 8.0	200	> 200	> 1½ days

For two or three lane bi-directional roadways not separated by a median, the testing should be staggered by one-half the test spacing. Refer to **Figure C.6 Staggered Testing Pattern** for clarification. For projects that are separated by a median, a staggered testing pattern is not required.

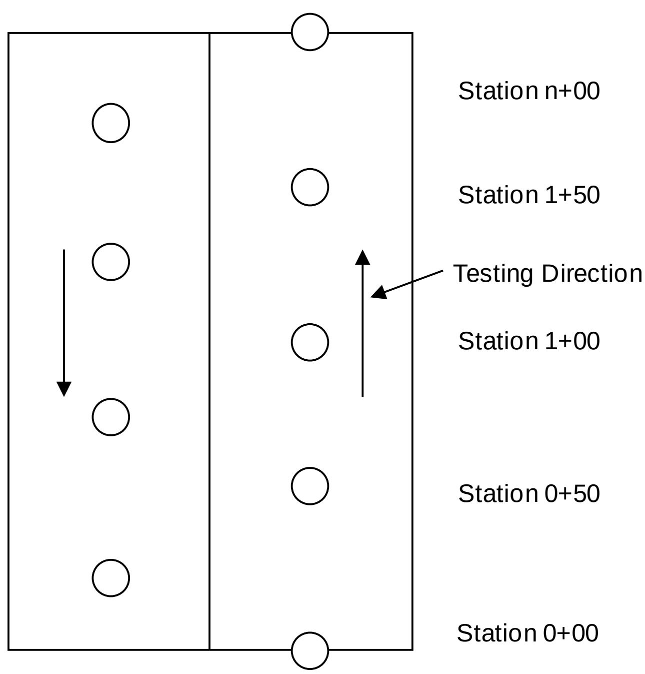


Figure C.6 Staggered Testing Pattern

- **Testing Locations:** For composite pavements, two types of FWD testing are generally conducted, basin and joint. Each test provides information on the structural integrity of the pavement.

- **Basin Testing:** For composite pavements, basin testing should be conducted in the middle of the lane or near the center of the slab. This testing provides information on the elastic modulus of the AC, PCC and strength of base materials and subgrade soils.

- **Joint Testing:** For composite pavements, joint testing should be conducted in the wheel path closest to the free edge of the slab (see **Figure C.6 Staggered Testing Pattern**). Typically, for the outside lanes, testing will be conducted in the right wheel path. For inside lanes, testing should be conducted in the left wheel path. If more than two lanes exist and the middle lanes are to be tested, then the nearest free edge must be determined. This testing provides information on joint load transfer; how well a joint, through either aggregate interlock and/or dowel bars, can transfer a wheel load from one slab to an adjacent slab.

C.4.1 FWD Drop Sequence: Composite Pavement

When collecting pavement structure data, the correct drop sequence is required. Drop sequences vary based on pavement type and information being gathered. A drop sequence is defined as the order in which impulse loads are applied to the pavement. This includes the "seating drops" and the recorded impulse loads.

- **Basin Testing** - below is the recommended drop sequence for basin testing on composite pavements:

  - Two seating drops at 6,000 pounds
  - Three recorded drops at 6,000 pounds
  - Three recorded drops at 9,000 pounds
  - Three recorded drops at 12,000 pounds
  - Three recorded drops at 16,000 pounds

Therefore, at each test location the FWD will perform 14 drops and record four sets of deflection and impulse load data. By performing multiple drops at a location, the pavement will react as a homogeneous structure as well as reduce the errors in measurement. Additionally, by recording and analyzing data from four different load levels, the Pavement Engineer can determine if the materials on the project are stress sensitive (non-linearly elastic), if a hard bottom (water table, bedrock or extremely stiff layer), and if compaction/liquefaction is occurring in the subgrade.

- **Joint Testing** - below is the recommended drop sequence for joint testing on composite pavements:

  - Two seating drops at 6,000 pounds
  - Three recorded drops at 6,000 pounds

- Three recorded drops at 9,000 pounds
- Three recorded drops at 12,000 pounds
- Three recorded drops at 16,000 pounds

Therefore, at each test location the FWD will perform 14 drops and record four sets of deflection and impulse load data. Two sensors are needed for the analysis, the sensor at the load and the second sensor on the other side of the joint.

C.4.2 FWD Sensor Spacing: Composite Pavement

FWD sensor spacing to record pavement deflection data is dependent on the pavement type, and the type of testing. For composite pavements, two types of testing are performed; joint and basin.

- **Basin Testing**: For basin testing on composite pavements, below is the recommended spacing:

  0, 8, 12, 18, 24, 36, 48, 60, and 72 (inches)

- **Joint Testing:** For joint testing on composite pavements, only two sensors are required. Below is the required spacing:

  0 and 12 (inches)

The sensors are to be placed on each side of the joint and 6 inches from the joint (see **Figure C.7 Joint Load Transfer Testing Sensor Spacing**).

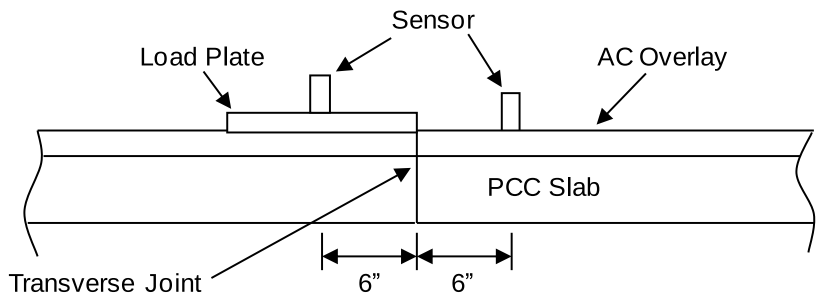


Figure C.7 Joint Load Transfer Testing Sensor Spacing

C.4.3 Pavement Temperature Readings: Composite Pavement

Ideally, the pavement temperature will be recorded directly from temperature holes at each test location as the FWD test is being performed. While this is the preferred approach for research projects, it is not practical for production level testing (network level or maintenance and rehabilitation projects). Therefore, for production level testing the economic and practical approach to determine the mid-depth pavement temperature is by measuring the surface temperature at each test location using an infrared thermometer. The FWD can automatically measure and record the pavement surface temperature to the FWD file. If the FWD is not equipped with an infrared thermometer, the FWD operator can use a hand held thermometer and record the temperature to a file. Using temperature correlation models such as the BELLS3 equation, the mid-depth AC material temperature can be estimated.

C.5 Field Test Report

Besides the FWD drop file, additional documentation of the FWD project is necessary. A suggested Field Test Report is presented in **Figure C.8 Field Test Report**. A log entry should only be made for special conditions, such as a test location skipped because it was on a bridge. The FWD operator does not test for frost depth.

C.6 FWD Data Processing

CDOT uses AASHTO PDDX file format in its FWD files. The following is an example of data collected at a test site:

```
**********************
[Test Location 1]
TestLocation = 45.592
TestLane = 1
TestTemperatures = 93.5,105.1
TestComment = 13:01
NumberOfDrops = 3
DropData_1 = 9120.00, 18.32, 12.43, 9.69, 6.95, 5.37, 3.32, 2.43
DropData_2 = 9040.00, 17.98, 12.24, 9.57, 6.90, 5.42, 3.30, 2.43
DropData_3 = 8990.00, 17.91, 12.18, 9.56, 6.92, 5.36, 3.31, 2.46
   ↓
   ↓
**********************
```

On the "*Test Temperatures = 93.5,105.1*" line, the first value of 93.5 is the air temperature and the second value of 105.1 is the pavement surface temperature.

The "Test Comment = 13:01" indicates the time of the test is 1:01 PM. The time uses the 24 hour format.

In order to process FWD data, many steps are required. These steps include gathering information on the pavement's surface condition, conducting a preliminary analysis on the deflection data, performing pavement coring and subgrade boring operations, processing of all the data collected, and analyzing, interpreting and reporting on the data results. Each one of these steps has numerous tasks associated with them. These steps are detailed in the following sections.

COLORADO DEPARTMENT OF TRANSPORTATION
FALLING WEIGHT DEFLECTOMETER FIELD TEST REPORT

Project Number		Test Date	
Project Description		Test Start Time	
Project Code		Test End Time	
		Pavement Type	
File Name		Test Type	
Route Number		Purpose of Testing	
Beginning MP		Season	
Beginning MP Description		Weather	
Ending MP		FWD Operator	
Ending MP Description		FWD Serial Number	
Requestor		FWD Company	
Phone Number		FWD Calibration Date	

Test Location Remarks

Use this to indicate abnormal test results, skipped test locations, or other items the Pavement Engineer should be made aware of

FWD Test #	Station	Lane	Direction	Remarks

FWD - Field Test Report.xls

Figure C.8 Field Test Report

C.6.1 Pre-Analysis

Once FWD data are collected, it is important to perform a preliminary analysis on the deflection data. Please refer to the *MODTAG Users Manual* for further instruction on pre-analysis.

C.6.2 Pavement Surface Condition Survey

Prior to collecting any FWD data, the engineer should conduct a detailed pavement condition and patching survey. These surveys will help the engineer establish possible problem areas with the pavement and set-up the appropriate FWD testing plan. Testing could be concentrated in specific areas while other areas could be avoided completely. Refer to **Section 8.2.5 Non-Destructive Testing, Coring and Material Testing Program** and **Section 9.2.4 Non-Destructive Testing.** Once these data are collected, the engineer can plot the results on a straight-line diagram. This will be extremely beneficial when other data are collected and analyzed.

C.6.3 Pavement Coring and Subgrade Boring

In order to conduct an analysis of FWD data, the exact pavement structure must be known. For most roadways, the exact structure is not known; therefore, pavement coring is required. Coring provides thicknesses to be used as seed values for backcalculation analysis. Cores should be retained for further evaluation in the laboratory. Pavement cores identify layer types and conditions to help validate surface course moduli. In addition, while the engineer may know what type of subgrade soils exists in the project area, they cannot be sure without boring the subgrade and extracting samples. These materials collected in field can be analyzed in the lab, to validate FWD data analysis results.

The thickness of the existing pavement layers must be known. Cores must be taken at a minimum of one core per mile for pavement layer and base layer thickness measurements. When pavement length is less than one mile, a minimum of one core will be taken. If a review of the as built plans from previous projects indicates there are locations with varying thicknesses, more cores will be taken to verify the existing pavement thickness.

For the materials above the subgrade, the coring and boring crew should record:

- **Layer Materials:** asphalt, PCC, granular, cement treated, etc
- **Layer Thickness:** thickness for each different layer
- **Layer Condition:** AC material stripped, PCC deteriorated, granular material contaminated, etc.
- **Material Types:** For AC materials, identify various layer types

For the subgrade and base materials refer to **Section 4.2 Soil Survey Investigation** for three steps that are necessary to conduct a subgrade and base investigation. One should document findings and test results on CDOT Forms #554 (Soil Survey Field Report) and #555 (Preliminary Soil Survey). Refer to **Figure C.9 Coring Log Example**.

C.6.4 Full Data Processing

Once pavement condition and materials data are collected, then the engineer can perform the data processing. The type of data processing depends on 1) pavement type; flexible, rigid or composite, and 2) testing performed; basin, joint load transfer, or corner void. Please refer to the *MODTAG Users Manual* for further instructions.

C.6.5 Data Analysis, Interpretation and Reporting

Except for operating the FWD processing programs, the data analysis and interpretation is the most difficult portion. Once the analysis and interpretation is complete, the results must be presented in such a manner to be used in the pavement design programs. Please refer to the *MODTAG Users Manual* for further information.

COLORADO DEPARTMENT OF TRANSPORTATION

PRELIMINARY PAVEMENT STRUCTURE INVESTIGATION

Date: 4/13/06 Page: 1 of 2 NOTE: If samples are submitted leave sieve analysis section blank.

LOCATION: I-76, US 85 to Burlington Canal
PROJECT NO.
SUBACCOUNT: 15361

STATION AND LOG	TEST NO.	DESCRIPTION	PERCENT PASSING 1"	3/4"	1/2"	3/8"	#4	#8	#16	#50	#200	LIQUID LIMIT	PLASTIC INDEX	CLASSIFICATION AND GROUP INDEX	MOISTURE %	Mr P.S.I.
I-76, US 85 to Burlington Canal																
Eastbnd. @ MP 12.5, Lane #2																
0-4.5"	1	HBP	Lift Thickness: 0-1.5", 1.5-2.5", 2.5-4.5" (New 1/2" mix)													
4.5-12"		PCCP	Lift Thickness: 4.5-12"													
12-28"		Roadbase		100	99	97	90	78	66	39	18.5			Class 3		
Eastbnd. @ MP 13, Lane #2																
0-4.5"	2	HBP	Lift Thickness: 0-1.5", 1.5-2", 2-4.5" (New 1/2" mix)													
4.5-12.75"		PCCP	Lift Thickness: 4.5-12.75"													
12.75+"		Roadbase similar as #1														
Eastbnd. @ MP 13.5, Lane #2																
0-4.25"	3	HBP	Lift Thickness: 0-1.5", 1.5-2", 2-4.25" (New 1/2" mix)													
4.25+"		PCCP	Did not core PCCP because of similar depths													
Eastbnd. @ MP 13.5, Shoulder																
0-6.75"	4	HBP	Lift Thickness: 0-1.5", 1.5-2.25", 2.25-3", 3-4.25" (New 1/2" mix), 4.25-6.75" (Old 1/2" mix) highly visible air voids													
6.75-12+"		Roadbase		100	96	92	77	58	38	15	6.2			Class 2		
Eastbnd. @ MP 14.5, Lane #2																
0-4"	5	HBP	Lift Thickness: 0-1", 1-1.75", 1.75-4" (New 1/2" mix)													
4-12.25"		PCCP	Lift Thickness: 4-12.25"													
12.25-16"		Roadbase	100	100	99	97	92	87	81	58	27.8					
16+"		Soil														
Eastbnd. @ MP 16, Lane #2																
0-4.5"	6	HBP	Lift Thickness: 0-2", 2-4.5" (New 1/2" mix)													
4.5+"		PCCP	Did not core PCCP because of similar depths													
Eastbnd. @ MP 16, Shoulder																
0-6.5"	7	HBP	Lift Thickness: 0-1.75" (New 1/2" mix), 1.75-2.5" (Chip Seal), 2.5-4.5", 4.5-6.5" (New 1/2" mix)													
6.5+"		Roadbase similar as #4														

REGION DESIGN
REGION MATERIALS ENGINEER

C.D.O.T. FORM #555
1/92

Figure C.9 Coring Log Example

C.6.6 Results Reporting – Flexible Pavements

FWD Analysis results are used to report on the condition of the existing pavement and to provide information for use in future pavement designs. For flexible pavements, the existing conditions and pavement design information should be reported and include:

- Effective structural number (if designing with software prior to M-E Design)
- Subgrade resilient modulus
- Remaining life or condition factor

C.6.7 Results Reporting – Jointed and Composite Pavements

FWD Analysis results are used to report the condition of the existing pavement and provide information for use in future pavement designs. For jointed and composite pavements, the existing conditions and pavement design information should be reported and include: :

- Elastic modulus of the concrete
- Composite modulus of subgrade reaction (k-value) (if designing with software prior to M-E Design)
- Load transfer efficiency and J-factor
- Corners with possible voids

C.6.8 Data Analysis and Interpretation – Jointed and Composite Pavements

More than one analysis approach should be used to minimize errors in interpretation. By using multiple approaches, the engineer can determine if the results correlate between programs or are vastly different. Once results are obtained, then engineering judgment must be employed to see if the results are reasonable.

References

1. *Chapter VI - Pavement Evaluation and Design*, Virginia Department of Transportation, 1401 Broad Street, Richmond, VA 23219, January 2004.

2. *MODTAG Users Manual Version 4*, Virginia Department of Transportation and Cornell University, Virginia Department of Transportation, 1401 Broad Street, Richmond, VA 23219, June 2006.

3. *Instructional Guide for Back-Calculation and the Use of MODCOMP3*, Version 3.6, CLRP Publication No. 94-10, by Dr. Lynne H. Irwin, Cornell University, Local Roads Program, March 1994.

4. ModTag Analyser, Version 4.0.6, Software.

APPENDIX D
LOW VOLUME ROAD PAVEMENT MAINTENANCE

D.1 Introduction

The New Economy: Materials and Pavement Options and Considerations is a finalized white paper, written by Colorado Department of Transportation (CDOT) Materials Advisory Committee on January 16, 2007. The white paper is important document and is included in this manual as guidance for the pavement engineer. The authors and members of the Materials Advisory Committee at the time of the issuance were:

Tim Aschenbrener, CDOT Materials and Geotechnical Branch
Bill Schiebel, Region 1 Materials
Richard Zamora, Region 2 Materials
Rex Goodrich, Region 3 Materials
Gary DeWitt, Region 4 Materials
Mike Coggins, Region 5 Materials
Masoud Ghaeli, Region 6 Materials
Glenn Frieler, Concrete Pavement Program Manager
Jay Goldbaum, Pavement Design Program Manager
Roy Guevara, Asphalt Pavement Program Manager
Corey Stewart, Pavement Management Program Manager

D.2 White Paper: The New Economy

Introduction

There is a new economy relative to petroleum products. National prices set records in 2006 for crude oil (over $70 per barrel) and gasoline (over $3 per gallon). In the Rocky Mountain West there has been an increase in the use of cokers at asphalt refineries which has provided an additional tightening of the supply of asphalt binder. The tighter supply has also had an impact on cost. Unmodified asphalt binder prices exceeded $450 per ton. These economic changes have been behind the recently introduced term, “new economy.” CDOT’s surface treatment program relies heavily on petroleum products, and the new economy warrants a discussion on the relative impacts and options available to CDOT.

The National Asphalt Pavement Association (NAPA) and Colorado Asphalt Pavement Association (CAPA) have concerns regarding the new economy. They have published methods to encourage owners to be more cost effective. NAPA has focused on the hot-mix asphalt (HMA) materials and pavement design with recommendations on reclaimed asphalt pavement (RAP), appropriate use of polymers, large-stone aggregate mixtures, thin-lift overlays and roofing shingles. CAPA has focused some on HMA materials and pavement design areas (RAP, specification changes, etc) but has also included the project development process (partnering, constructability reviews, etc.). The methods NAPA and CAPA have documented are valid and need to be considered. However, they do not necessarily represent a complete list of options the owner should consider.

The purpose of this white paper is to document seven strategies that should be considered by the owner in light of the new economy. Some of these are old, tried and true strategies that will now be cost effective more often than in the past. Other strategies are new ideas that can be investigated to get the most from the limited surface treatment program funds. We need to remember that the common strategies used in the past will still work and may still be cost effective; however, we need to be sure to look at a variety of options with the prices of the new economy. Automatically choosing the proven strategies of the past may not be the most cost effective solution.

Preventive Maintenance

Nationally, pavement preservation has been touted as a more cost effective process to maintain the surface condition. It represents a key component of a long-range plan to preserve and prolong the service life of the existing roadway system. Its goal is to keep the pavements that are in good and fair condition in that condition rather than let them deteriorate to a poor condition. When in a poor condition, more costly treatments are needed. States such as Georgia and Michigan have documented that for every $1 spent on maintaining and preserving roads in good to fair condition, you can save approximately $5 to $8 on major rehabilitation and reconstruction. Treating the pavements at the right time with the right maintenance treatments is very cost effective. These cost analyses were for the “old economy” so the “new economy” analyses should be even more persuasive.

Colorado Policy Memo 18 dated October 15, 2003 has started Colorado in the direction of more preventive maintenance. CDOT has committed 5% of the surface treatment program budget to be dedicated to preventive maintenance. With the new economy, it may be time to increase the amount dedicated to preventive maintenance.

<u>Strategy 1: Use more preventive maintenance treatments that have worked.</u>

Standard preventive maintenance treatments that are frequently used by CDOT have been incorporated into the draft CDOT Preventive Maintenance Manual available on the Pavement Management website.

- Chip seals are a commonly used maintenance treatment. Sometimes they are used for corrective maintenance and other times they are used for preventive maintenance. When it comes to preventive maintenance, chip seals provide the biggest bang for the buck. They dramatically slow the deterioration of the underlying asphalt by sealing out water and preventing further oxidation of the underlying asphalt, caused in part by the damaging effects of the sun. An asphalt overlay achieves the same but at a much higher cost. When the structural capacity of the pavement is adequate, a chip seal is often the best value tool in our toolbox for increasing the pavement life. It is necessary to extend the life of HMA overlay treatments as anticipated Surface Treatment budgets may not be sufficient to sustain network conditions.

A recent Region 5 chip seal project was bid at around $3/SY for 385,000 SY of roadway. A similar 3” HMA overlay project cost about $12/SY for 241,000 SY of roadway. In this example, the chip seal was approximately 1/4 the cost of a 3" overlay. Chip seals will continue to be widely used by CDOT and, considering our limited funding, are an essential tool for preserving and maintaining our roads.

Regions 4 and 5 have started doing chip seals for preventive maintenance at the 3rd to 5th year of life of an overlay. The goal is to extend the time to the next overlay from 8 to 10 years to 12 to 15 years. By placing 2 or 3 chip seals, the need for the next overlay can be delayed. The chip seals are much less costly than overlays making this strategy cost effective.

<u>Strategy 2: Examine new preventive maintenance techniques.</u>

CDOT should continue to evaluate new treatment strategies and expand upon existing treatment options. Examples of additional treatment options are as follows:

- There are 2 types of Brazier mixes. Understanding the difference is important to a successful application. The original Brazier mix is similar to an asphalt sand mix. The new generation of Brazier mix is a milled asphalt mixed with emulsion in a pug mill prior to placement. A technique called Armor Cote from Nebraska DOT, consisting of small rounded river rock mixed with emulsion, is being studied for a possible treatment.
- Further, project selection is critical. When trying these new techniques, it is important to follow the experimental feature protocol. Region 4 is experimenting with the Brazier mix.
- Cape seals are another new and potentially effective preventive maintenance treatment. Region 4 is experimenting with it. Project selection guidelines and materials and construction specifications need to be followed. The performance will be monitored to see if this is a viable new alternative.

Rehabilitation Strategies

<u>Strategy 3: Use more 100 percent recycling.</u>

There are several different types of 100 percent recycling that have been used in Colorado for many years. These options have performed very well when appropriate project selection guidelines have been used and the projects were constructed properly.

- Hot-in-place recycling has been used for many years in Colorado. Regions 3 and 5 have used the three types of hot-in-place recycling on the appropriate projects and have had very good success to date. Some of the projects that have been placed have even won awards. It is interesting to note that the City and County of Denver focuses on the heater repaving option in the major metropolitan area. Using curb line milling, the heater repaving process provides 2 inches of treatment for the cost of 1 inch of new material. The heater-remixing process provides 2 inches of treatment for less than the cost of a 1-inch overlay. Even though the fuel costs of hot-in-place recycling have increased, it is only a fraction of the increase that has been experienced for HMA pavements.

- Full-depth reclamation (FDR) is relatively new to Colorado. This is a version of foamed asphalt that was identified on a recent European scanning tour. In some cases FDR includes an additive and in other cases it does not. Region 4 has used this treatment on many projects with low traffic in the eastern part of the State. This treatment allows for a full depth treatment of the existing pavement section with the addition of just 2-6 inches of new HMA. The feedback on construction and performance to date has been very positive. Test sections in service for several years have shown no reflective cracking.
- Cold-in-place recycling has also been used for many years in Colorado. This is a tried and true method that has worked in the past. The specifications and project selection guidelines are CDOT standards. Once again, the existing pavement can have a deep treatment of up to 8 inches if specialized emulsion and equipment are used. Typical cold-in-place recycling is typically 4 inches deep and then only need 2 to 6 inches of overlay. This method should still be considered.
- Additionally, consideration should be given to performing combinations of various treatments depending on distresses observed during a project level pavement analysis.

<u>Strategy 4: Focus on cost effective wearing surfaces.</u>

- Stone matrix asphalt (SMA) shows a lot of promise. After first being introduced to the United States from a European scanning tour, SMA has shown to be a highly effective wearing surface on the high volume roadways in Colorado. Although the initial costs are higher than conventional HMA, the performance data indicates it is a cost effective choice in those locations.
- Expanding on CDOT's successful implementation of SMA, thin-lift SMA is now being studied and may even be more cost effective than SMA when only a functional overlay is required. The use of a smaller nominal maximum aggregate size (3/8-inch) and a thinner lift (1-inch) will allow for this wearing surface to be more cost effective initially. Data from other states have shown that the thin SMA performs well as a wearing course. Colorado has limited data to date, but we have learned that compaction and aggregate size are critical. Colorado will use thin-lift SMAs on several projects during the 2007 construction season. This may also be a preventative maintenance treatment.
- Micro-surfacing has been used by CDOT to correct minor rutting and to restore the skid resistance of the pavement surface. It is composed of polymer modified asphalt with crushed aggregate, mineral fillers, and field control additives. Due to the quick reaction time, an experienced Contractor is desired. Colorado has had mixed results using micro-surfacing as a wearing surface.
- When using more expensive wearing surfaces, shoulders can be treated differently. When focusing on the wearing surface, it is not necessary to treat the wider shoulders with the same premium HMA pavement that is placed on the shoulders. Consideration should be given to a more economical mix.

Strategy 5: Use more portland cement concrete pavement.

- Thin white topping is a CDOT standard. After 10 years of experimentation, the specifications and project selection guidelines have been refined to provide a product that has proven success. When examining major rehabilitations, this option should be given strong consideration.

Strategy 6: Examine new rehabilitation strategies.

- An Ultra-thin Whitetopping Overlay (UTW) is a pavement rehabilitation technique that has been marketed by the American Concrete Pavement association (ACPA). UTW projects have provided durable wearing surfaces for pavements that are not subject to frequent heavy truck loadings, and where a substantial thickness of asphalt exists. Given its success in limited applications, UTW is now being considered for a range of other applications. In fact, a few states have pilot projects using UTW as an alternative to asphalt overlays for interstate roads. There are, however, still a lot of unknowns about the process. CDOT's Pavement Design Program and Region 6 have gathered design and construction information and would be glad to share that with anyone that wants to consider this experimental feature. When there is a need to place 4-inches of HMA pavement, ultra-thin white topping may be a cost-effective alternative for pavement rehabilitation.
- Cement-treated bases and roller-compacted concrete (RCC) have been used in the past as strong bases to build up the structural layer coefficient of the pavement section. Possibilities exist for utilization of lesser quality of rock and utilization of asphalt placement equipment. A reduced quantity of HMA overlay that results from a stronger base is one motivation for considering these treatments. Colorado has not used RCC in the past, but is considering potential applications in light of the new economy. There is minimal experience nationally at this time with using RCC for highway applications, but RCC may be evaluated as a finished driving surface. Detour pavements may be the ideal location to begin evaluation of RCC pavement.
- Some geotextiles can reduce the structural layer coefficient needed for rehabilitation with an HMA overlay. Some research has shown that the use of a geo-grid can provide a structural benefit. Region 3 is reviewing this literature and is giving consideration to this treatment. If the overlay can be reduced by a nominal amount, then the use of the geo-grid may be cost effective. Region 1 is evaluating the use of high-tensile strength paving geogrids to mitigate severe crack reflection. These products are specially designed for placement within the asphalt layers. Successful performance may yield an alternative to hot and cold in-place recycling prior to overlay. Considerations need to be made for future rehabilitations that may include milling or 100% recycling options.

New Products

Strategy 7: Examine new products.

- AggCote is a product of the American Gilsonite Company that is an additive for Hot Mix Asphalt pavement that may increase the material's resistance to stripping and subsequently increases resistance to rutting. The product is a mineral called Gilsonite that is mined in Utah and works by "priming" the aggregates before the liquid asphalt is applied. The AggCote increases the bond strength between the aggregate and asphalt cement, increasing the resistance to stripping while still maintaining the flexural properties of the binder for thermal crack resistance.

Lab studies conducted by CDOT concluded that AggCote does work well in all areas that the manufacturer claims. The product consistently provides both increased durability and rut resistance over the current alternative of hydrated lime. This is all with lab mixed samples only. It is unknown if these same results can be produced with plant mixed material in the field.

AggCote is currently a more expensive alternative to lime but it is undetermined if the benefits are worth the additional costs when this product is applied in the field. Field testing may determine if AggCote's benefits outweigh the additional costs. With the price of crude oil increasing, the benefits and cost savings of using AggCote may soon surpass that of lime. AggCote can replace some asphalt cement used in the mix and does not require the aggregates to be hydrated and dried, which is another area for fuel savings.

It would be worthwhile to pilot this product on a project and do extensive field testing and comparisons of this product versus hydrated lime.

- Asphalt membranes have been an effective way to protect our bridge decks. However, they often have performance issues due to their unique nature, placement, and environment. Alternate bridge deck protection should be considered. A membrane that shows promise is Dega-deck. Region 1 has experimented with this new product. Applications where short application times are necessary have given support to the Dega-deck process.

Closure

From this discussion it can be observed that every Region within CDOT is proactively evaluating additional options because of costs in the new economy. There are many old strategies being used at increasing levels, and new ideas that are being investigated to get the most from the limited surface treatment program funds. This information is provided to encourage the continued and expanded uses of CDOT's standard products when cost effective and to encourage the exploration of innovative products.

In looking at these pavement rehabilitation and maintenance strategies, it is important to remember to do the right treatment at the right time. Be sure to use structural fixes when the structure needs it. A recently published document that provides guidance for identifying the right treatment at the right time is *Guidelines for Selection of Rehabilitation Strategies for Asphalt Pavement* report number CDOT-DTD-R-2000-08 written by Bud Brakey.

References

1. CDOT Policy Memo 18, Pavement Preventive Maintenance Initiatives, Oct.1, 2003.

2. Brakey, Bud, *Guidelines for Selection of Rehabilitation Strategies for Asphalt Pavement*, Report No. CDOT-DTD-R-2000-08, Colorado Department of Transportation, 2000.

3. American Concrete Pavement Association, Ultra Thin Whitetopping Calculator, http://www.pavement.com/Concrete_Pavement/Technical/UTW_Calculator/index.asp, (1/16/2007).

APPENDIX E
PAVEMENT TREATMENT GUIDE FOR HIGHWAY CATEGORIES

E.1 Introduction

This guide is intended to assist the Region Materials Engineers (RME) when making pavement design decisions in accordance with the hierarchical stratification of highway categories. The Transportation Commission, per Policy Directive 14, identified Interstates and NHS as having the highest standards and the highest priority when directing surface treatment funds. Other highways will have reduced funding and treatment priority in accordance with traffic volume. Surface Treatment Program investments on highways should be in accordance with the defined goals and objectives for each. This document identifies treatment parameters for each category of highway.

These guidelines do not apply to capacity related projects, realignment projects, pavement safety issues, or new construction; such projects will follow current *CDOT Pavement Design Manual* processes.

E.2 Definitions

E.2.1 Highway Categories

- **Interstate:** Any highway on the Interstate Highway System. This is the most important highway category in the State of Colorado.
- **NHS**: Any highway on the National Highway System, excluding interstates.
- **Other Highways**: Any highway not on the NHS or interstate.
- **High Volume**: A high volume highway includes segments with annual average daily traffic (AADT) greater than 4,000 or average annual daily truck traffic (AADTT) greater than 1,000.
- **Medium Volume:** A medium volume facility includes segments with AADT between 2,000 and 4,000 or AADTT between 100 and 1,000.
- **Low Volume**: A facility with Low Volume includes segments with AADT less than 2,000 and AADTT less than 100.

E.2.2 Treatment Categories

- **Reconstruction**: Complete removal, redesign, and replacement of the pavement structure (asphalt or concrete) from subgrade to surface. A minimum design life of 20 years for asphalt pavements and 30 years for concrete pavements is used for these projects.

- **Major Rehabilitation:** Heavy duty pavement treatments that improve the structural life to the highway. These are asphalt treatments typically thicker than 4 inches, and may include, but are not limited to, full depth reclamation, thin concrete overlays, deep cold-in-place recycles, and thick overlays. Concrete treatments in this category may include, but are not limited to, asphalt overlays (thicker than 4 inches), extensive slab replacements, and rubblization.

- **Minor Rehabilitation**: Moderate pavement treatments that improve the structural life to the highway. These are asphalt treatments between 2 and 4 inches thick, and may include mill and fills, shallow cold-in-place recycles, overlays, leveling courses with overlays. Concrete treatments in this category may include black toppings (thinner than 4 inches), dowel and tie bar repairs, and diamond grinding.

- **Pavement Maintenance**: Thin functional treatments $1^{1}/_{2}$ inches in thickness or less, intended to extend the life of the highway by maintaining the driving surface.

E.3 Policy and Process

CDOT's most important highway facilities are interstates. These national networks provide interconnectivity across the state and across the nation. Interstate projects shall be built, rehabilitated, and maintained in accordance with AASHTO Pavement Design Standards, ensuring that they meet Federal standards and provide reliable service to the traveling public.

The High Volume category includes NHS and other highways. These highways serve a large segment of the traveling public and provide critical routes for the transportation of goods and services across regional boundaries. These projects shall also follow AASHTO Pavement Design Standards.

Medium Volume category may contain segments on the NHS and Other Highways. These projects shall be treated primarily with minor rehabilitation and pavement maintenance treatments. Major rehabilitation can be considered when drivability is poor and project level analysis reveals a compromised pavement structure.

The Low Volume category may include segments on the NHS or other highways and are to be maintained above acceptable drivability standards with pavement maintenance treatments. Minor rehabilitation treatments can be considered when drivability is poor and project level analysis reveals a compromised pavement structure or safety issues are identified. When designing these treatments the RME will consider using reliability levels at the bottom of the range for the appropriate functional classification of the highway. The RME will also consider using lower reliability binders for thermal cracking, especially if reflective cracking is expected to occur. A pavement justification report (PJR) shall be performed for every project however; a life cycle cost analysis will not be required for these low volume projects. If the RME and the Program Engineer determines that more than a pavement maintenance treatment is needed, they will prepare a detailed PJR documenting why the selected treatment is cost effective and obtain concurrence from the Chief Engineer. The PJR will include the date that concurrence was obtained from the Chief Engineer. The Chief Engineer's decision will establish the typical remedial action for the project.

APPENDIX F
HMA MATERIALS INPUT LIBRARY

F.1 Introduction

This appendix presents the library of inputs for typical CDOT HMA mixtures. These inputs can be used in lieu of site-specific or mixture-specific data.

F.2 Mix Types and Properties

Table F.1 Properties of Typical CDOT HMA Mixtures presents the binder type, gradation, and volumetric properties of typical CDOT HMA mixtures and the selection of one typical CDOT mixture that is closest to the HMA mix to be used in the design. The following sections in this Appendix present the laboratory measured engineering properties including dynamic modulus, creep compliance, and indirect tensile strength.

F.2.1 Dynamic Modulus

Table F.2 Dynamic Modulus Values of Typical CDOT HMA Mixtures presents Level 1 dynamic modulus values of typical CDOT HMA mixtures. The dynamic modulus values were measured in accordance with the AASHTO TP 62 - Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA) protocols. **Section S.1.5.2 Asphalt Dynamic Modulus E*** presents a discussion on HMA dynamic modulus properties.

F.2.2 Asphalt Binder

Table F.3 Asphalt Binder Complex Shear Modulus (G*) and Phase Angle (δ) Values of Typical CDOT HMA Mixtures presents Level 1 complex shear modulus, G* and phase angle, δ values of typical CDOT HMA mixtures. Under this effort, binder characterization tests were not performed to measure the rheology properties of the binders used in Superpave mixtures listed in **Table F.2 Dynamic Modulus Values of Typical CDOT HMA Mixtures,** rather allow the use of lab measured E* values in the M-E Design software. G* and δ values were back calculated using the estimated E* shift factors and G*– η conversion relationships in the MEPDG. **Chapter 6, Principles of Design for Flexible Pavement** presents a discussion on HMA binder properties.

F.2.3 Creep Compliance and Indirect Tensile Strength

Table F.4 Creep Compliance Values of Typical CDOT HMA Mixtures and **Table F.5 Indirect Tensile Strength Values of Typical CDOT HMA Mixtures** present laboratory measured (Level 1) indirect tensile strength and creep compliance values of typical CDOT HMA mixtures, respectively. Testing was conducted in accordance with the AASHTO T 322 - Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device. **Section S.1.11 Tensile Creep and Strength for Hot Mix Asphalt** presents a discussion on HMA creep compliance and indirect tensile strength properties.

Table F.1 Properties of Typical CDOT HMA Mixtures

Mix ID	FS1918-9	FS1920-3	FS1938-1	FS1940-5	FS1958-5	FS1959-8	FS1919-2	FS1939-5	FS1960-2
Sample No.	United 58-28-2	#183476	#16967C	#17144B	Wolf Creek Pass	I70 Gypsum to Eagle	#181603	#194140	I25 N of SH34
Binder Grade	PG 58-28	PG 58-28	PG 64-22	PG 58-28	PG 58-34	PG 64-28	PG 76-28	PG 76-28	PG 76-28
Gradation	SX	SX	SX	SX	SX	SX	SMA	SX	SMA
Passing ¾" sieve	100	100	100	100	100	95	95	100	100
Passing ⅜" sieve	83	88	89	82	81	87	46	87	69
Passing No 4 sieve	53	62	69	56	54	65	22	62	25
Passing No. 200 sieve	6.5	7.1	6.8	5.9	5	7.1	8	6.6	8.1
Mix AC Binder	5	5.6	5.4	5.5	7	5.4	6.2	5.4	6.5
VMA (%)	16.2	17	16.3	17.2	19.6	16.4	16.9	16.3	17.1
VFA (%)	65.9	64.1	68.5	68.2	73.4	65.5	72	68.2	76.8
Air Voids (%)	5.5	6.1	5.1	5.5	5.2	5.7	4.7	5.2	4.0
Vb_{eff} (%)	10.7	10.9	11.2	11.7	14.4	10.7	12.2	11.1	13.1

Table F.2 Dynamic Modulus Values of Typical CDOT HMA Mixtures

Mix ID	Temperature (°F)	Testing Frequency			
		0.5 Hz	1 Hz	10 Hz	25 Hz
FS1918 PG 58-28 Gradation SX	14	2,067,099	2,488,999	2,785,899	2,873,299
	40	930,800	1,472,800	2,008,399	2,196,999
	70	207,600	439,600	838,700	1,039,200
	100	52,500	101,200	215,300	291,900
	130	24,100	35,400	60,900	78,900
FS1919 PG 76-28 Gradation SMA	14	1,875,400	2,299,039	2,624,309	2,726,019
	40	846,575	1,309,050	1,799,540	1,983,379
	70	230,100	427,271	753,122	918,360
	100	76,296	127,286	231,357	296,468
	130	40,803	55,308	84,229	102,895
FS1920 PG 58-28 Gradation SX	14	1,913,059	2,346,169	2,663,359	2,759,109
	40	820,000	1,323,520	1,846,660	2,037,379
	70	181,430	379,863	730,105	911,130
	100	47,935	89,742	185,976	250,629
	130	22,739	32,752	54,793	70,107
FS1938 PG 64-22 Gradation SX	14	2,333,549	2,642,179	2,861,449	2,927,779
	40	1,309,490	1,791,270	2,219,829	2,365,949
	70	379,514	695,090	1,127,310	1,318,450
	100	87,238	174,824	349,546	452,545
	130	29,326	49,265	92,795	122,034
FS1939 PG 76-28 Gradation SX	14	1,821,960	2,284,749	2,635,719	2,743,629
	40	761,414	1,245,330	1,773,800	1,972,669
	70	186,328	368,894	694,551	866,370
	100	59,960	102,426	195,476	256,712
	130	32,727	44,234	68,258	84,345
FS1940 PG 58-28 Gradation SX	14	1,989,039	2,422,519	2,730,149	2,820,819
	40	831,755	1,354,270	1,895,720	2,091,109
	70	177,386	367,904	716,158	900,206
	100	51,014	88,693	175,626	234,927
	130	27,500	36,567	56,022	69,361
FS1958 PG 58-34 Gradation SX	14	1,291,280	1,808,320	2,249,869	2,393,659
	40	424,726	794,978	1,289,510	1,499,050
	70	98,659	198,153	405,545	529,690
	100	37,405	59,422	109,288	143,776
	130	23,504	29,885	43,077	51,915
FS1959 PG 64-28 Gradation SX	14	1,687,360	2,134,249	2,493,389	2,608,869
	40	697,463	1,127,680	1,612,900	1,802,220
	70	173,403	334,774	616,373	765,125
	100	54,259	93,163	175,106	227,742
	130	27,890	38,645	60,413	74,657
FS1960 PG 76-28 Gradation SMA	14	1,860,030	2,300,499	2,637,329	2,741,889
	40	850,728	1,324,800	1,828,840	2,017,009
	70	246,113	453,444	796,133	969,276
	100	88,308	145,258	261,320	333,687
	130	49,660	66,719	100,905	123,005

Table F.3 Asphalt Binder Complex Shear Modulus (G*) and Phase Angle (δ) Values of Typical CDOT HMA Mixtures

Mix ID	Temperature (°F)	Binder G* (P_a)	Phase Angle (degree)
FS1918	136.4	2,227.6	80
PG 58-28	147.2	1,068.2	82
Gradation SX	158.0	540.1	84
FS1919	158.0	1,233	64
PG 76-28	168.8	673	66
Gradation SMA	179.6	383	68
FS1920	136.4	2,056	80
PG 58-28	147.2	985	82
Gradation SX	158.0	498	84
FS1938	147.2	1,857	81.6
PG 64-22	158.0	889	83.1
Gradation SX	168.8	451	85
FS1939	158.0	1,559	64
PG 76-28	168.8	859	66
Gradation SX	179.6	493	68
FS1940	136.4	1,758	80
PG 58-28	147.2	835	82
Gradation SX	158.0	419	84
FS1958	136.4	3,093	80
PG 58-34	147.2	1,519	82
Gradation SX	158.0	784	84
FS1959	147.2	3,051	81.6
PG 64-28	158.0	1,495	83.1
Gradation SX	168.8	772	85
FS1940	158.0	1,733	64
PG 76-28	168.8	959	66
Gradation SMA	179.6	552	68

Table F.4 Creep Compliance Values of Typical CDOT HMA Mixtures

Mix ID	Loading Time (s)	Testing Temperature		
		-4°F	14°F	32°F
FS1918 PG 58-28 Gradation SX	1	2.78E-07	3.91E-07	2.65E-07
	2	3.11E-07	4.79E-07	3.91E-07
	5	3.48E-07	5.57E-07	6.33E-07
	10	3.74E-07	6.94E-07	9.55E-07
	20	4.22E-07	8.31E-07	1.28E-06
	50	4.63E-07	1.08E-06	1.99E-06
	100	5.28E-07	1.35E-06	2.72E-06
FS1919 PG 76-28 Gradation SMA	1	4.01E-07	4.45E-07	6.88E-07
	2	4.28E-07	5.41E-07	8.96E-07
	5	4.98E-07	6.37E-07	1.27E-06
	10	5.51E-07	7.85E-07	1.69E-06
	20	6.17E-07	9.33E-07	2.23E-06
	50	7.19E-07	1.18E-06	3.14E-06
	100	7.96E-07	1.39E-06	4.01E-06
FS1920 PG 58-28 Gradation SX	1	3.38E-07	4.31E-07	5.28E-07
	2	3.66E-07	5.02E-07	7.44E-07
	5	4.1E-07	6.27E-07	1.12E-06
	10	4.53E-07	7.61E-07	1.51E-06
	20	4.92E-07	8.55E-07	1.98E-06
	50	5.53E-07	1.11E-06	3.03E-06
	100	6.02E-07	1.31E-06	4.05E-06
FS1938 PG 64-22 Gradation SX	1	3.34E-07	4.19E-07	4.99E-07
	2	3.53E-07	4.64E-07	6.19E-07
	5	3.79E-07	5.15E-07	7.49E-07
	10	4.05E-07	5.7E-07	9.08E-07
	20	4.31E-07	6.26E-07	1.08E-06
	50	4.87E-07	7.27E-07	1.43E-06
	100	5.05E-07	8.41E-07	1.79E-06
FS1939 PG 76-28 Gradation SX	1	3.46E-07	4.12E-07	7.13E-07
	2	3.83E-07	4.76E-07	9.57E-07
	5	4.34E-07	5.97E-07	1.33E-06
	10	4.85E-07	7.25E-07	1.8E-06
	20	5.29E-07	8.45E-07	2.29E-06
	50	5.99E-07	1.05E-06	3.25E-06
	100	6.87E-07	1.32E-06	4.24E-06
FS1940 PG 58-28 Gradation SX	1	3.53E-07	3.82E-07	6.92E-07
	2	3.81E-07	4.62E-07	8.61E-07
	5	4.21E-07	5.92E-07	1.23E-06
	10	4.64E-07	7.07E-07	1.69E-06
	20	5.11E-07	8.15E-07	2.21E-06
	50	5.9E-07	1.1E-06	3.22E-06
	100	6.35E-07	1.27E-06	4.47E-06

Mix ID	Loading Time (s)	Testing Temperature		
		-4°F	14°F	32°F
FS1958 PG 58-34 Gradation SX	1	4.82E-07	5.95E-07	9.61E-07
	2	5.30E-07	8.18E-07	1.48E-06
	5	6.05E-07	1.05E-06	2.18E-06
	10	6.85E-07	1.35E-06	3.14E-06
	20	7.71E-07	1.62E-06	4.19E-06
	50	8.72E-07	2.12E-06	6.23E-06
	100	1.00E-06	2.63E-06	8.74E-06
FS1959 PG 64-28 Gradation SX	1	3.61E-07	4.73E-07	7.12E-07
	2	4.04E-07	5.74E-07	9.97E-07
	5	4.51E-07	7.35E-07	1.52E-06
	10	5.11E-07	8.78E-07	1.99E-06
	20	5.67E-07	1.04E-06	2.59E-06
	50	6.57E-07	1.37E-06	3.75E-06
	100	7.68E-07	1.66E-06	4.66E-06
FS1960 PG 76-28 Gradation SMA	1	3.64E-07	4.64E-07	7.35E-07
	2	4.05E-07	5.70E-07	1.04E-06
	5	4.43E-07	7.15E-07	1.51E-06
	10	5.06E-07	8.79E-07	2.04E-06
	20	5.48E-07	1.03E-06	2.61E-06
	50	6.40E-07	1.31E-06	3.61E-06
	100	7.44E-07	1.70E-06	4.69E-06

Table F.5 Indirect Tensile Strength Values of Typical CDOT HMA Mixtures

Mix ID	Indirect Tensile Strength at 14˚F
FS1918 (PG 58-28, Gradation SX)	555.9
FS1919 (PG 76-28, Gradation SMA)	515.0
FS1920 (PG 58-28, Gradation SX)	519.0
FS1938 (PG 64-22, Gradation SX)	451.0
FS1939 (PG 76-28, Gradation SX)	595.0
FS1940 (PG 58-28, Gradation SX)	451.0
FS1958 (PG 58-34, Gradation SX)	446.0
FS1959 (PG 64-28, Gradation SX)	519.0
FS1960 (PG 76-28, Gradation SMA)	566.0

APPENDIX G
PCC MATERIALS INPUT LIBRARY

G.1 Introduction

This appendix presents the library of inputs for typical CDOT PCC mixtures. These inputs can be used in lieu of site-specific or mixture-specific data.

G.2 Mix Types

Table G.1 Properties of Typical CDOT PCC Mixtures presents the mix proportions and fresh concrete properties of typical CDOT PCC mixtures. The fresh concrete properties include slump, air content and unit weight.

The slump was documented in accordance with *ASTM C143 Standard Test Method for Slump of Portland Cement Concrete*. The air content of the concrete was tested by the pressure method according to *ASTM C231 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*. Unit weight was determined in accordance with *ASTM C138 Standard Test Method for Unit Weight, Yield and Air Content (Gravimetric) of Concrete*.

Table G.2 Materials and Sources Used in Typical CDOT PCC Mixtures presents the sources of materials used in these mixtures. Select one of these typical CDOT mixtures from the tables that is closer to the concrete mix to be used in the design. The following sections in this Appendix present their laboratory measured engineering properties including compressive strength, flexural strength, static elastic modulus, coefficient of thermal expansion and Poisson's ratio.

G.2.1 Compressive and Flexural Strength

Table G.3 Compressive Strength of Typical CDOT PCC Mixtures presents Level 1 compressive strength values of typical CDOT PCC mixtures. Testing was conducted in accordance with the *ASTM C 39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.* **Table G.4 Flexural Strength of Typical CDOT PCC Mixtures** presents Level 1 flexural strength values of typical CDOT PCC mixtures. Testing was conducted in accordance with the *ASTM C 79 Standard Test Method for Flexural Strength of Concrete.*

G.2.2 Static Elastic Modulus and Poisson's Ratio

Table G.5 Static Elastic Modulus and Poisson's Ratio of Typical CDOT PCC Mixtures presents Level 1 static elastic modulus and Poisson's ratio of typical CDOT PCC mixtures. Testing was conducted in accordance with the *ASTM C 469 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression.*

G.2.3 Coefficient of Thermal Expansion

Table G.6 CTE Values of Typical CDOT PCC Mixtures presents laboratory measured (Level 1) coefficient of thermal expansion values of typical CDOT HMA mixtures, respectively. Standard 4 inch diameter by 8 inch high cylinders were tested in accordance with *AASHTO T336 Standard Method of Test for Coefficient of Thermal Expansion of Hydraulic Cement Concrete*.

Table G.1 Properties of Typical CDOT PCC Mixtures

Mix ID	Region	Cement Type	Cement Content (lbs/yd^3)	Fly ash Content (lbs/yd^3)	Water/ Cement Ratio	Slump (in)	Air Content (%)	Unit Weight (pcf)
2008160	2	I/II	575	102	0.44	3.75	6.3	139.8
2009092	3	I/II	515	145	0.42	4.00	6.8	138.6
2009105	1, 4, 6	I/II	450	113	0.36	1.50	6.8	140.6
2008196	5	I/II	480	120	0.44	1.25	6.0	140.8

Table G.2 Materials and Sources Used in Typical CDOT PCC Mixtures

Mix ID	2008160	2009092	2009105	2008196
Region	2	3	4, 1, 6	5
Cement	GCC-Pueblo	Mountain	Cemex-Lyons	Holsim
Fly ash	Boral-Denver Terminal	SRMG – Four Corners	Headwaters-Jim Bridger	SRMG – Four Corners
Aggregates	RMMA Clevenger Pit	Soaring Eagle Pit	Aggregate Industries	SUSG Weaselskin Pit (fine aggregate) C&J Gravel Home Pit (coarse aggregate)
Water Reducer	BASF Pozzolith 200N BASF PolyHeed 1020 (mid-range)	BASF PolyHeed 997	BASF Masterpave	BASF PolyHeed 997
Air Entrainment	BASF MB AE 90	BASF Micro Air	BASF Pave-Air 90	BASF MB AE 90

Table G.3 Compressive Strength of Typical CDOT PCC Mixtures

Mix Design ID	Region	Compressive Strength (psi)				
		7-day	14-day	28-day	90-day	365-day
2008160	2	4,290	4,720	5,300	6,590	6,820
2009092	3	3,740	4,250	5,020	5,960	7,140
2009105	1, 4, 6	3,780	4,330	5,370	5,560	6,390
2008196	5	4,110	4,440	5,340	5,730	5,990

Table G.4 Flexural Strength of Typical CDOT PCC Mixtures

Mix Design ID	Region	Flexural Strength, psi				
		7-day	14-day	28-day	90-day	365-day
2008160	2	660	760	900	935	940
2009092	3	570	645	730	810	850
2009105	1, 4, 6	560	620	710	730	735
2008196	5	640	705	905	965	970

Table G.5 Static Elastic Modulus and Poisson's Ratio of Typical CDOT PCC Mixtures

Mix Design ID	Region	Elastic Modulus, ksi					Poisson's Ratio
		7-day	14-day	28-day	90-day	365-day	
2008160	2	3,140	3,260	3,550	3,970	4,240	0.21
2009092	3	3,560	3,860	4,300	4,550	4,980	0.2
2009105	1, 4, 6	3,230	3,500	4,030	4,240	4,970	0.2
2008196	5	3,280	3,510	3,930	4,170	4,210	0.21

Table G.6 CTE Values of Typical CDOT PCC Mixtures

Mix ID	Sample	CTE in/in./°C	CTE in/in./°F*10^{-6}
2008160	1	8.5	4.72
	2	8.5	4.72
2009092	1	8.8	4.89
	2	8.6	4.78
2009105	1	8.8	4.89
	2	8.7	4.83
2008196	1	8.8	4.89
	2	8.6	4.78

APPENDIX H
HISTORICAL CDOT 18,000 POUND EQUIVALENT AXLE LOAD CALCULATIONS

H.1 Introduction

The appendix documents how 18,000-pound Equivalent Single Axle Load (18-kip ESAL) calculations were defined for CDOT.

H.2 Traffic Projections

There are certain input requirements needed for 18-kip ESAL calculations. They are:

- Vehicle or truck volumes
    - Lane distributions
    - Direction distributions
    - Class distributions
    - Growth factors
- Vehicle or truck weights
    - Axle weight
    - Axle configuration (single, tandem)
- Traffic equivalence load factors

This section describes the process on obtaining or calculating 18-kip ESAL numbers.

H.2.1 Volume Counts

Volume counts are expressed as Annual Average Daily Traffic (AADT) counts. AADT is the annual average two-way daily traffic volume. It represents the total traffic on a section of roadway for the year, divided by 365. It includes both weekday and weekend traffic volumes. The count is given in vehicles per day and includes all CDOT (or FHWA) vehicle classification types.

H.2.2 Lane and Directional Distributions

The most heavily used lane is referred to as the design lane. Generally, the outside lanes are the design lanes. Traffic analysis determines a percent of all trucks traveling on the facility for the design lanes, this is also referred to as a lane distribution factor.

The percent of trucks in the design direction is applied to the two directional AADT to account for any differences to truck volumes by direction. The percent trucks in the design direction is referred to as the directional distribution factor. Generally, the directional distribution factor is a 50/50 percent split. If the number of lanes and volumes are not the same for each direction, it may be appropriate to design a different pavement structure for each direction of travel.

CDOT uses a design lane factor to account for the lane distribution and directional distribution. Both distributions are combined into one factor, the design lane factor. **Table H.1 Design Lane Factor** shows the relationship of the design lane factor and the lane and directional distributions.

Table H.1 Design Lane Factor

Type of Facility	Number of Lanes in Design Direction	CDOT Method	DARWin™ Procedure	
		Design Lane Factor	Percent of Total Trucks in the Design Lane (Outside Lane)	Directional Split (Design Direction/ Non-design Direction)
One Way	1	1.00	100	NA
2-lanes	1	0.60	100	60/40
4-lanes	2	0.45	90	50/50
6-lanes	3	0.30	60	50/50
8-lanes	4	0.25	50	50/50

Note: *Highway Capacity Manual*, 2000 (Exhibit 12-13) recommends using a default value for a directional split of 60/40 on a two-lane highway may it be rural or urban (3).

H.2.3 Vehicle Classification

CDOT uses a classification scheme of categorizing vehicles into three bins. CDOT 18-kip ESAL calculations were based on "generalized, averaged, and non-site-specific equivalency factors" using a 3-bin vehicle classification scheme. These vehicle classifications types are (1):

- Passenger vehicles, types 1to 3 and 0 to 20 feet long
- Single unit trucks, types 4 to 7 and 20 to 40 feet long
- Combination trucks, types 8 to 13 and greater than 40 feet long

A fourth bin is sometimes used and may be shown as unclassified vehicles. These bins are further broken down into 13 classes. The 13-classification scheme follows FHWA vehicle type classification. Two additional classes may be used as a fourth bin. Class 14 is for unclassifiable vehicles and Class 15 is not used at the present time. The 13 classes of FHWA are separated into groupings of whether the vehicle carries passengers or commodities. Non-passenger vehicles are subdivided by number of axles and number of units, including both power and trailer units. Exceptions may be a large camping and recreational vehicles, which crosses over into the commodities grouping. **Note**: The addition of a light trailer to a vehicle does not change the classification of the vehicle. Refer to **Figure H.1 CDOT Vehicle Classifications**. Listed are FHWA vehicle classes with definitions (2):

Class 1 - Motorcycles - All two or three-wheeled motorized vehicles. Typical vehicles in this category have saddle type seats and are steered by handlebars rather than steering wheels. This category includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheel motorcycles. This vehicle type may be reported at the option of the State.

Class 2 - Passenger Cars - All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers and including those passenger cars pulling recreational or other light trailers.

Class 3 - Other Two-Axle, Four-Tire Single Unit Vehicles - All two-axle, four-tire, vehicles, other than passenger cars. Included in this classification are pickups, panels, vans, and other vehicles such as campers, motor homes, ambulances, hearses, carryalls, and minibuses. Other two-axle, four-tire single-unit vehicles pulling recreational or other light trailers are included in this classification. Because automatic vehicle classifiers have difficulty distinguishing class 3 from class 2, these two classes may be combined into class 2.

Class 4 - Buses - All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This category includes only traditional buses (including school buses) functioning as passenger-carrying vehicles. Modified buses should be considered to be a truck and should be appropriately classified.

Note: In reporting information on trucks the following criteria should be used:

a. Truck tractor units traveling without a trailer will be considered single-unit trucks.

b. A truck tractor unit pulling other such units in a "saddle mount" configuration will be considered one single-unit truck and will be defined only by the axles on the pulling unit.

c. Vehicles are defined by the number of axles in contact with the road. Therefore, "floating" axles are counted only when in the down position.

d. The term "trailer" includes both semi- and full trailers.

Class 5 - Two-Axle, Six-Tire, Single-Unit Trucks - All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with two axles and dual rear wheels.

Class 6 - Three-Axle Single-Unit Trucks - All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with three axles.

Class 7 - Four or More Axle Single-Unit Trucks - All trucks on a single frame with four or more axles.

Class 8 - Four or Fewer Axle Single-Trailer Trucks - All vehicles with four or fewer axles consisting of two units, one of which is a tractor or straight truck power unit.

Class 9 - Five-Axle Single-Trailer Trucks - All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.

Class 10 - Six or More Axle Single-Trailer Trucks - All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.

Class 11 - Five or fewer Axle Multi-Trailer Trucks - All vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit.

Class 12 - Six-Axle Multi-Trailer Trucks - All six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.

Class 13 - Seven or More Axle Multi-Trailer Trucks - All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit.

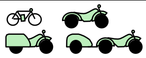
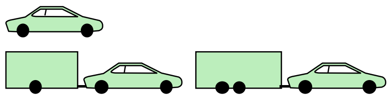
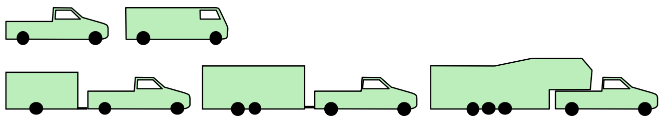
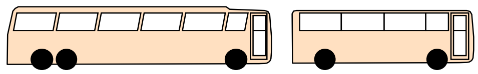
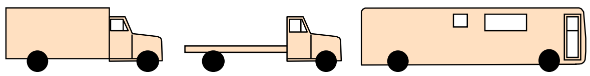
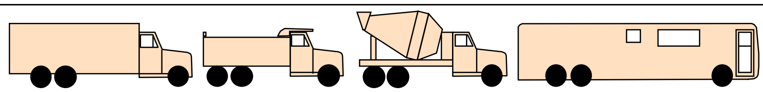
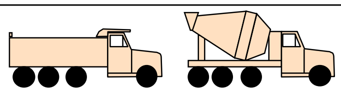
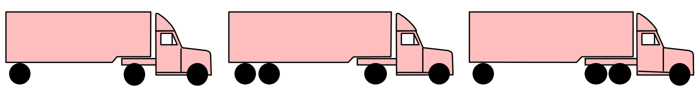
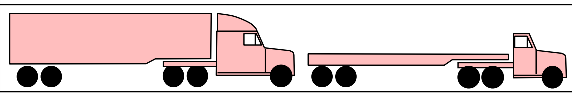
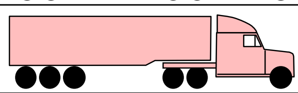
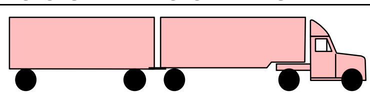
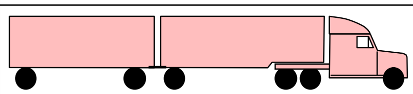
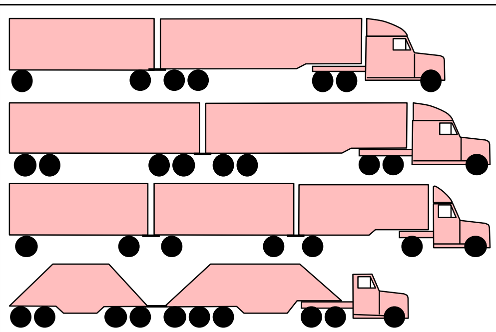
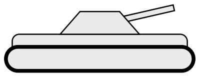
	Class	Schema	Description
Light-weight Vehicles	1		all motorcycles plus two wheel axles
	2		all cars plus one/two axle trailers
	3		all pickups and vans single/dual wheels plus one/two/three axle trailers
Single Unit Vehicles	4		buses single/dual wheels
	5		two axle, single unit single/dual wheels
	6		three axle, single unit
	7		four axle, single unit
Combination Unit Vehicles	8		four or less axles, single trailers
	9		five axles, single trailers
	10		six or more axles, single trailers
	11		five or less axles, multi-trailers
	12		six axles, multi-trailers
	13		seven or more axles, multi-trailers
Unclassified Vehicles	14		Unclassifiable vehicle
	15		Not used

Figure H.1 CDOT Vehicle Classifications

H.2.4 Growth Factors

The number of vehicles using a pavement tends to increase with time. Each roadway segment has a growth factor assigned to that segment. CDOT uses a 20-year growth factor. A simple growth rate assumes the AADT increases by the same amount each year. A compound growth rate assumes the AADT percent growth rate for any given year is applied to the volume during the preceding year. CDOT uses a compound growth rate. See **Equation H.3.**

H.2.5 Vehicle or Truck Weights

The 18,000-pound Equivalent Single Axle Load (18-kip ESAL) is a concept of converting a mixed traffic stream of different axle loads and axle configurations into a design traffic number. The 18-kip ESAL is a conversion of each expected axle load into an equivalent number of 18,000-pound single axle loads and the sum over the design period.

H.2.6 Traffic Equivalence Load Factors

The equivalence load factor is a numerical factor that expresses the relationship of a given axle load to another axle load in terms of their effect on the serviceability of a pavement structure. All axle loads are equated in terms of the equivalent number of repetitions of an 18,000-pound single axle. Using the 3-bin vehicle classification scheme, factors were assigned to each.

The damaging effect of an axle is different for a flexible pavement and a rigid pavement; therefore, there are different equivalency factors for the two types of pavement. **Table H.2 Colorado Equivalency Factors** shows the statewide equivalency factors determined by a study of Colorado traffic in 1987.

Table H.2 Colorado Equivalency Factors

3-Bin Vehicle Classification	Flexible Pavement	Rigid Pavement
Passenger Cars and Pickup Trucks	0.003	0.003
Single Unit Trucks	0.249	0.285
Combination Trucks	1.087	1.692

H.2.7 Discussion and Calculation of Traffic Load for Pavement Design

Traffic is one of the major factors influencing the loss of a pavement's serviceability. Traffic information required by the pavement designer includes axle loads, axle configurations, and number of applications. The damaging effect of the passage of an axle of any load can be represented by a number of 18-kip ESAL. The load damage factor increases as a function of the ratio of any given axle load raised to the fourth power.

> **Example**: One application of a 12,000 pound single axle will cause a damage equal to 0.2 applications of an 18,000 pound single axle load and about five applications of a 12,000-pound single axle will cause the same damage as one 18,000 pound single axle load thus,

a 20,000 pound single axle load is 8 times as damaging as the 12,000 pound single axle load.

The determination of design ESALs is an important consideration for the design of pavement structures. An approximate correlation exists between 18-kip ESAL computed using flexible pavement and rigid pavement equivalency factors. As a general rule of thumb, converting from rigid pavement 18-kip ESAL to flexible pavement 18-kip ESAL requires multiplying the rigid pavement 18-kip ESAL by 0.67.

Example: 15 million rigid pavement 18-kip ESAL is approximately equal to 10 million flexible pavement 18-kip ESALs. Five million flexible pavement 18-kip ESAL equal 7.5 million rigid pavement 18-kip ESALs.

Failure to utilize the correct type of 18-kip ESAL will result in significant errors in the design. Conversions must be made, for example, when designing an asphaltic concrete overlay of a flexible pavement (flexible 18-kip ESAL required) and when designing an alternative portland cement concrete overlay of the same flexible pavement (rigid 18-kip ESAL required). CDOT has some sites on the highway system where instruments have been placed in the roadway to measure axle loads as a vehicle passes over the site. These stations, called Weigh-in-Motion (WIM) sites, can provide accurate information for the existing traffic load. An estimate of growth over the design period will be needed to calculate the traffic load during the design period. The link http://dtdapps.coloradodot.info/Otis/TrafficData is used to access traffic load information. Traffic analysis for pavement structure design is supplied by the Division of Transportation Development (DTD) Traffic Analysis Unit. The traffic data figures to be incorporated into the design procedure are in the form of 18 kip equivalent single axle load applications (18-kip ESALs). All vehicular traffic on the design roadway is projected for the design year in the categories of passenger cars, single unit trucks, and combination trucks with various axle configurations. The actual projected traffic volumes for each category are weighted by the appropriate load equivalence factors and converted to a cumulative total 18-kip ESAL number to be entered into the flexible or rigid pavement design equation. Adjustments for directional distribution and lane distribution will be made by the DTD Traffic Analysis Unit. The number supplied will be used directly in the pavement design calculation. Recall that this 18-kip ESAL number is the cumulative yearly ESAL for the design lane in one direction. This 18-kip cumulative number must be a 20-year ESAL to be used for the asphalt mix design for SuperPave™ gyratory compaction effort (revolutions). The designer must inform the DTD Traffic Analysis Unit that the intended use of the 18-kip ESAL is for flexible or rigid pavement design (see **Table H.2 Colorado Equivalency Factors**), since different load equivalence factors apply to different pavement types. If a comparison of flexible and rigid pavements is being made, 18-kip ESAL for each pavement type must be requested.

The procedure to predict the design ESALs is to convert each expected axle load into an equivalent number of 18-kip ESAL and to sum these over the design period. Thus, a mixed traffic stream of different axle loads and configurations is converted into a number of 18-kip ESALs. See *1993 AASHTO Guide for Design of Pavement Structure* Appendix D, pages D1-28 for Conversion of Mixed Traffic to Equivalent Single Axle Loads for Pavement Design.

The DTD provides traffic projections Average Annual Daily Traffic (AADT) and ESAL. The designer must request 10, 20, and 30 year traffic projections for flexible pavements and 20 and 30 year traffic projections for rigid pavements from the Traffic Section of DTD. Requests for traffic projections should be coordinated with the appropriate personnel of DTD. The pavement designer can help ensure accurate traffic projections are provided by documenting local conditions and planned economic development that may affect future traffic loads and volumes.

DTD should be notified of special traffic situations when traffic data are requested. Some special situations may include:

- A street that is or will be a major arterial route for city buses.
- A roadway that will carry truck traffic to and from heavily used distribution or freight centers.
- A highway that will experience an increase in traffic due to a connecting major, high-traffic roadway.
- A highway that will be constructed in the near future.
- A roadway that will experience a decrease in traffic due to the future opening of a parallel roadway facility.

H.2.8 Traffic Projections

The following steps are used by CDOT to calculate ESALs:

Step 1. Determine the AADT and the number of vehicles of various classifications and sizes currently using the facility. The designer should make allowances for traffic growth, basing the growth rate on DTD information or other studies. Assuming a compound rate of growth, **Equation H.1** is used by CDOT to calculate the 20-year growth factor. The future AADT is determined by:

$$\mathbf{T_f = (1+r)^n} \qquad \textbf{Eq. H.1}$$

Where:

T_f = CDOT 20-year growth factor
r = rate of growth expressed as a fraction
n = 20 (years)

$$\mathbf{T=[((T_1 \times T_f) - T_l) / 20] \times D + T_1} \qquad \textbf{Eq. H.2}$$

Where:

T = future AADT
T_1 = current AADT
D = design period (years)
T_f = CDOT 20-year growth factor

Step 2. Determine the midpoint volume (**Equation H.3**) by adding the current and future traffic and dividing by two.

$$T_m = (T_1 + T) / 2 \qquad \textbf{Eq. H.3}$$

Where:

T_m = traffic volume at the midpoint of the design period
T_1 = current AADT

Step 3. Multiply the midpoint traffic volume by the percentage of cars, single unit trucks, and combination trucks.

Step 4. Multiply the number of vehicles in each classification by the appropriate 18-kip equivalency factor. See **Table H.2 Colorado Equivalency Factors**. Then add the numbers from each classification to yield a daily ESAL value.

Step 5. Multiply the total 18-kip ESAL for the roadway by the design lane factor that correlates to the number of lanes for each direction shown in **Table H.2 Colorado Equivalency Factors**. This will be the 18-kip ESAL for the design lane over the design period.

Example: Determine the 20-year design period ESALs for a 4-lane flexible pavement (2 lanes per direction) if the current traffic volume is 16,500 with 85% cars, 10% single unit trucks, and 5% combination trucks. The traffic using the facility grows at an annual rate of 3.5%.

$T_f = (1 + 0.035)^{20} = 1.99$
$T = [((16500 \times 1.99) – 16500) / 20] \times 20 + 16{,}500 = 32{,}835$
$T_m = (16{,}500 + 32{,}835) / 2 = 24{,}668$

Cars = 24,668 × 0.85 = 20,968
Single Unit Trucks = 24,668 × 0.10 = 2,467
Combination Trucks = 24,668 * 0.05 = 1,233

Daily ESALs for Cars = 20,968 × 0.003 = 62.9
Daily ESALs for Single Unit Trucks = 2,467 × 0.249 = 614.3
Daily ESALs for Combination Trucks = 1,233× 1.087 = 1,340.3

Total Daily ESALs = 2,017.5

Total Design Period ESALs = 2,017.5 × 365 × 20 = 14,727,750

Design lane ESALs = 14,727,750 × 0.45 = 6,627,500

References

1. *Development of Site-Specific ESAL, Final Report*, CDOT-DTD-R-2002-9, Project Manager, Ahmad Ardani, Colorado Department of Transportation and Principal Investigator, Sirous Alavi, Nichols Consulting Engineers, Chtd., July 1, 2002.

2. *Heavy Vehicle Travel Information System*, Field Manual, FHWA publication PDF version, May 2001 (revised), obtained at website, http://www.fhwa.dot.gov/ohim/tvtw/hvtis.htm

3. *Highway Capacity Manual*, Transportation Research Board, National Research Council, Washington, D.C., 2000.