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TECHNICAL MEMORANDUM

# Twenty-Year Performance Review of Long-Life Jointed Plain Concrete Pavements


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(DRISI Task 3764)

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**16. ABSTRACT**

This technical memorandum evaluates the half-life performance of three long-life jointed plain concrete pavements (JPCPs), a combined total of 260 lane-miles, that were built in Southern California in the early 2000s. The pavements were designed for a 40-year life, which was twice the standard 20-year design life used for JPCP at that time. The projects are located in or close to the Mojave Desert on heavily trafficked interstate highways with 2022 annual average daily truck traffic levels between 2,800 to 5,100. The performance of the pavements has been evaluated based on data from the Caltrans pavement management system (PMS) databases (with software system *PaveM*), including pavement condition surveys with data about lane-based cracking, transverse joint faulting, and smoothness data, and the as-built database that includes all maintenance, rehabilitation, and reconstruction activities conducted on the Caltrans road network. The PMS databases were complemented with an in-situ evaluation of the projects in 2022 that included an inertial profiler evaluation and a road closure of one mile per project for visual inspection, coring, and falling wight deflectometer testing. Overall, the performance of the projects has been excellent so far. The third-stage cracking (slabs with two or more cracks) is essentially zero in all lanes, the faulting is also essentially zero, and the smoothness as measured by the International Roughness Index has been stable since the construction of the projects. The load transfer efficiency of the doweled transverse joints was high, from 80% to 85%, and it was also very uniform along the sections, with minimal diurnal variation (morning versus afternoon). Mechanistic-empirical modeling with *AASHTOWare Pavement ME Design* (version 2.5.5) supports the excellent performance of the projects and the lack of transverse cracking, in particular. Further, none the JPCP long-life projects has required any maintenance or rehabilitation activity (e.g., individual slab replacement or grinding) since their construction. The only concern with the performance of the projects is the presence of longitudinal cracking, affecting to 4% to 7% of the slabs, in some truck lanes. The longitudinal cracking may be related to the dry environment and, potentially, the use of widened slabs in one of the projects.

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It is recommended that the impact of 2 ft. widened slab shoulders with JPCP in dry climate regions like the Desert, High Desert, and Inland Valley be investigated further and considerations of safety, maintenance, and pavement longitudinal cracking be included in any updating of design standards.

**8. RELATED DOCUMENTS**

Wu, R., Lea, J., Harvey, J.T., and Guada, I. Forthcoming. *Twenty-Year Performance Review of Asphalt Concrete Long-Life Pavements*. Davis and Berkeley, CA: University of California Pavement Research Center.

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## PROJECT OBJECTIVES

This technical memorandum was prepared as part of Partnered Pavement Research Center Project 3.58, "Continued Calibration of Mechanistic-Empirical Design Models with Pavement Management System Data." The objective of this project is to establish an efficient and repeatable procedure for updating field calibration of mechanistic-empirical design methods. This will be achieved through the following tasks:

- Task 1: Update calibration data.
- Task 2: Update *CalME* calibration.
- Task 3: Update *AASHTOWare Pavement ME Design* calibration.
- Task 4: Integrate network level mechanistic-empirical data management.
- Task 5: Prepare project documentation.

The objective of this technical memorandum is to review the half-life performance of several long-life jointed plain concrete pavements (JPCP) that were built in Southern California in the early 2000s. These pavements were designed for a 40-year life, which was twice the standard 20-year design life used for JPCP at that time. Caltrans adopted a 40-year design life for JPCP in its *Highway Design Manual* in 2007. The review presented in this technical memorandum will serve to assess design hypotheses and to provide lessons from the half-life performance of these projects. This technical memorandum is part of the completion of Task 3.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AADT | Annual average daily traffic |
| AADTT | Annual average daily truck traffic |
| AC | Asphalt concrete |
| ACI | American Concrete Institute |
| APCS | Automated pavement condition survey |
| ATPB | Asphalt treated permeable base |
| CSOL | Crack, seal, and overlay |
| EA | Expenditure authorization |
| ESAL | Equivalent single axel load |
| FWD | Falling weight deflectometer |
| HMA | Hot mix asphalt |
| IRI | International Roughness Index |
| JPCP | Jointed plain concrete pavement |
| LCCA | Life cycle cost analysis |
| LLPRS | Long-Life Pavement Rehabilitation Strategy |
| LTE | Load transfer efficiency |
| MEPDG | Mechanistic-empirical pavement design guide |
| MoE | Modulus of elasticity |
| PCC | Portland cement concrete |
| PCS | Pavement condition survey |
| PM | Post mile |
| PMS | Pavement management system |
| WIM | Weigh-in-motion |

# LIST OF TEST METHODS AND SPECIFICATIONS

| | |
|---|---|
| ASTM C39-21 | Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens |
| ASTM C469-22 | Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression |
| AASHTO R57-14 (2022) | Standard Practice for Operating Inertial Profiling Systems |

## CONVERSION FACTORS

| APPROXIMATE CONVERSIONS TO SI UNITS | | | | |
|---|---|---|---|---|
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| in. | inches | 25.40 | millimeters | mm |
| ft. | feet | 0.3048 | meters | m |
| yd. | yards | 0.9144 | meters | m |
| mi. | miles | 1.609 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.09290 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8361 | square meters | $m^2$ |
| ac. | acres | 0.4047 | hectares | ha |
| $mi^2$ | square miles | 2.590 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl. oz. | fluid ounces | 29.57 | milliliters | mL |
| gal. | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.02832 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.7646 | cubic meters | $m^3$ |
| | | **MASS** | | |
| oz. | ounces | 28.35 | grams | g |
| lb. | pounds | 0.4536 | kilograms | kg |
| T | short tons (2000 pounds) | 0.9072 | metric tons | t |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | (F-32)/1.8 | Celsius | °C |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | pound-force | 4.448 | newtons | N |
| $lbf/in^2$ | pound-force per square inch | 6.895 | kilopascals | kPa |

| APPROXIMATE CONVERSIONS FROM SI UNITS | | | | |
|---|---|---|---|---|
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| mm | millimeters | 0.03937 | inches | in. |
| m | meters | 3.281 | feet | ft. |
| m | meters | 1.094 | yards | yd. |
| km | kilometers | 0.6214 | miles | mi. |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.001550 | square inches | $in^2$ |
| $m^2$ | square meters | 10.76 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.196 | square yards | $yd^2$ |
| ha | hectares | 2.471 | acres | ac. |
| $km^2$ | square kilometers | 0.3861 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.03381 | fluid ounces | fl. oz. |
| L | liters | 0.2642 | gallons | gal. |
| $m^3$ | cubic meters | 35.31 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.308 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.03527 | ounces | oz. |
| kg | kilograms | 2.205 | pounds | lb. |
| t | metric tons | 1.102 | short tons (2000 pounds) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C + 32 | Fahrenheit | °F |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.2248 | pound-force | lbf |
| kPa | kilopascals | 0.1450 | pound-force per square inch | $lbf/in^2$ |

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised April 2021)

# 1 INTRODUCTION

The goals of improving pavement design and construction practices are to improve the cost-effectiveness of investments in road infrastructure by reducing life cycle costs and to improve the environmental performance of road infrastructure by reducing life cycle global warming potential and other priority emissions, particularly air pollution in California.

For many decades, the design life for new Caltrans concrete and asphalt pavements was 20 years and the design life for major rehabilitation was 10 years for asphalt pavement, with no standards for concrete pavement rehabilitation other than 10-year life asphalt overlays. In 1996, an internal Caltrans study was undertaken to compare the life cycle costs of rehabilitating an existing portland cement concrete (PCC) pavement using a standard 10-year asphalt concrete (AC) overlay strategy with those of using a 35-year PCC pavement. The Caltrans term for this new approach was the Long-Life Pavement Rehabilitation Strategy (LLPRS). The primary goal was to achieve fast construction and thereby reduce road user traffic delay. This goal followed up on the lessons of fast-track construction learned from reconstructing the Interstate 10 corridor in Los Angeles County after the 1994 Northridge earthquake, while also seeking longer life and less life cycle maintenance.

The study entailed a basic spreadsheet computation that compared the net present values of pavements with different lifecycle maintenance and rehabilitation costs under different traffic volume assumptions *(1)*. Data were obtained from five projects with annual average daily traffic (AADT) volumes varying from 50,000 to 220,000 vehicles per day and 10% to 20% heavy vehicles. The study found that for AADT above about 150,000 and/or truck traffic higher than about 15,000 trucks per day, user costs were dominant in strategy selection compared with agency costs and that LLPRS designs typically had lower life cycle costs than the conventional 10-year asphalt overlay designs. Additionally, Caltrans expected implementation of LLPRS to result in a decreased need for maintenance forces to be in the roadway, improving workforce and road user safety *(1)*.

The Caltrans LLPRS Task Force was commissioned in April 1997. The product Caltrans identified for the LLPRS Task Force to develop was Long-Life Pavement Rehabilitation Strategy guidelines and specifications for implementation of projects in the 1998–1999 fiscal year. The focus of the LLPRS Task Force was originally concrete pavement strategies. A separate task force was established in early 1998 for flexible pavement strategies called the Asphalt Concrete Long-Life (AC Long-Life) Task Force.

The specific goals of the LLPRS Task Force were the following:

- Have sufficient production to rehabilitate or reconstruct about six lane-kilometers (four lane-miles) within a construction window of 67 hours (10 a.m. Friday to 5 a.m. Monday), with the intent of this fast production to minimize traffic delay.
- Provide 30+ years of service life.
- Require minimal maintenance, although zero maintenance is not a stated objective *(1)*.

Both PCC and AC LLPRS were analyzed by the UCPRC, and a computer program was created called *Construction Analysis for Pavement Rehabilitation Strategies* (*CA4PRS*), which analyzed design, construction, and traffic and quantified construction productivity and traffic delay, with both deterministic and probabilistic analyses. *CA4PRS* models were populated with initial input data gathered from California concrete paving contractors, Caltrans, and academia. The models were later updated using data collected by the UCPRC on the initial PCC and AC LLPRS projects and from discussions with asphalt paving contractors.

The concrete pavement construction productivity analyses explored the effect of the following variables: pavement design profile (thickness), curing time (different opening times for concrete), number and capacity of contractor's resources (trucking, plant, paving, demolition), number of lanes to pave, type of construction scheduling (serial or parallel processes), and alternative lane closure tactics (number of lanes closed for construction and number left open to traffic) *(2)*. The asphalt pavement construction productivity analyses looked at the following variables for both crack, seat, and overlay (CSOL) and full-depth replacement approaches: rehabilitation approach (CSOL or full-depth), design profile (thickness), cooling time (time for asphalt to cool for different thicknesses and weather, calculated using MultiCool), number and capacity of construction resources (trucking, plant, paving, demolition), and alternative lane closure strategies (same as for concrete) *(3)*.

The initial PCC LLPRS project was reconstruction of part of Interstate 10 in Pomona in Los Angeles County in 1998, with additional early projects constructed in 2002 to 2004 *(4)*. The initial AC LLPRS project was reconstruction of part of Interstate 710 in Long Beach, also in Los Angeles County, in 2003, with additional projects completed from 2012 to 2014 *(5)*.

The 1996 internal Caltrans study previously mentioned was undertaken with limited data and basic life cycle cost analysis (LCCA) principles. More data became available from the initial concrete and asphalt projects, and in late 2004 Caltrans requested that a more detailed study be undertaken by the UCPRC to determine whether the 150,000 AADT/15,000 trucks figure was still appropriate. A factorial sensitivity study was completed comparing life cycle costs of long-life strategies and conventional rehabilitation strategies with more variables than were included in the 1996 study, using more appropriate data from the initial LLPRS projects and the then-new Federal Highway Administration LCCA software *RealCost*, which had just been customized for Caltrans in 2005. The 2005 LCCA sensitivity analyses made clear the need to perform life cycle cost analysis for each project using project-specific data for both agency costs and road user costs. The results of the LCCA are dependent on the following variables, which are different for each project:

- Traffic demand patterns, including hourly demand, weekday and weekend demand, directional peaks, and discretionary versus job-related travel.
- Alternative routes and modes.
- Lane and shoulder configurations and highway geometry in each direction.

- Feasibility and expected life of each rehabilitation strategy, which depend on truck traffic and existing pavement condition in each lane.
- Expected construction durations *(6)*.

The design long-life goal for all new concrete pavement and major rehabilitation was increased to 40 years in the early 2000s as experience was gained with pavement design and construction. In addition, the standard major rehabilitation design life was increased from 10 years to 20 years for all asphalt pavement and 40 years on higher traffic routes in the 2010s after design and construction of the initial AC long-life projects. The goals of decreased life cycle cost and decreased life cycle environmental impacts are made feasible by the fact that doubling of the design lives requires less than a doubling of the pavement thickness. Mechanics show that for both asphalt and concrete designs the bending resistance—which controls the tensile strain at the bottom of the asphalt layer and the tensile stress at the bottom of the concrete layer under traffic loading, both causing bottom-up fatigue cracking—diminish approximately proportionally with an increase in stiffness (E) and to the third power with increase in thickness ($h^3$) (*7-9*). This means that increasing stiffness and the third-power exponential effect of increasing thickness increase fatigue life in thick pavements at a greater than one-to-one rate.

A number of factors, together, have contributed to the idea of expanding the design life of concrete pavement beyond 20 years:

- Advancements in materials science, construction quality control/quality assurance practices, and pavement design, including the introduction of the AASHTO *Guide for Mechanistic-Empirical Pavement Design of New and Rehabilitated Pavement Structure*s, the mechanistic-empirical pavement design guide (MEPDG) in 2004 *(10)*.
- Evidence of some jointed plain concrete pavement (JPCP) performing well beyond the expected 20-year design life, and Caltrans investigations in the 1990s of the factors contributing to that performance.
- Accelerated pavement testing in the late 1990s and early 2000s that evaluated joint spacing, concrete materials, use of dowels, slab thicknesses, slab widths, and drying shrinkage effects *(9)*.
- Thinking about and attention to development of best practices contributing to longer concrete pavement lives, including materials, joint spacing, dowels, drainage, consideration of climate regions, consideration of axle load spectra, and curing, many of which were documented in a 2008 publication regarding design for 100-year concrete pavement design lives *(11)*.
- Experience gained from the initial projects built from 2002 to 2005 investigated in this report.

In 2007, the UCPRC developed a catalog of design tables using the MEPDG (version 0.8). The catalog adopted a concrete pavement design life of 40 years *(12)*. These tables were later adjusted based on a comparison with design catalogs from other states and introduced in the Caltrans *Highway Design*

*Manual* in 2007 and were updated in 2022 based on recalibration of concrete pavement performance data since 1978 *(13)*.

Around 20 years have passed since the first JPCP 40-year design projects were built in Southern California. The 20-year (half design life) performance can provide information for assessing whether these projects are on track to meet the expected life. That assessment constitutes the goal of the study presented in this technical memorandum.

While Caltrans JPCPs are now designed for 40-year lives, the term “long life” is used in this technical memorandum to refer to the first set of JPCP 40-year designs as, back in the early 2000s when they were built, their design life was twice the design life adopted by JPCP standard practice on the Caltrans road network and the rest of the United States.

### 1.1 Objective

The objective of this technical memorandum is to evaluate the half-life performance of the JPCP long-life projects that were built in Southern California in the early 2000s. The goal of the evaluation is to determine whether these pavements are on track to meet the expected life, to assess design hypotheses, and to learn lessons from the half-life performance of these pavements.

### 1.2 Methodology

The experimental data for the study presented in this technical memorandum come mainly from Caltrans pavement management system (PMS) databases, and in particular the following databases:

- **Pavement condition survey (PCS) database.** This database has data from the PCS conducted by Caltrans every one or two years, including the automated pavement condition survey (APCS) since 2011. These surveys provide per-lane condition data for the entire Caltrans road network. The last PCS included in this study was conducted in 2021. For JPCP, the PCS database includes slab cracking (quantified in different ways), transverse joint faulting (quantified as percentage of transverse joints with more than 0.15 in. faulting), and smoothness (quantified as the International Roughness Index [IRI]).
- **Pavement as-built database.** This database includes all maintenance, rehabilitation, and reconstruction activities conducted in the Caltrans road network. This database was used to find the extension of each JPCP long-life project (lanes and post mile boundaries) and the maintenance/rehabilitation activities that each JPCP long-life project had required since the construction. The pavement layers (types and thicknesses) placed in each pavement maintenance, rehabilitation, and reconstruction activity are also included in this database.
- **Traffic database.** This database includes the traffic volume, truck percentage, and truck traffic weigh-in-motion (WIM) number (1 to 5) for each highway location and lane. The WIM number, which defines the truck traffic characteristics, is used by Caltrans for pavement design and management. Each WIM is defined by the distributions of truck class, axle type,

axle weight, and hourly traffic *(14)*. The five WIMs represent truck traffic characteristics that exist on the Caltrans road network.

- **Climate database.** This database includes the climate region for each highway location. Caltrans considers nine climate regions, based on pavement surface temperature and rainfall, for pavement design and management *(15)*. The pavements included in this study are in the Desert climate region.
- **Project plans database.** This database includes the construction plans for each pavement project executed in Caltrans road network. The plans for each of the JPCP long-life projects were downloaded from the database and reviewed for this study. The slab thickness and the configuration of the base were extracted from these plans (the slab thickness was also extracted from the pavement as-built database previously discussed).

In addition to the PCS data, the present condition of the JPCP long-life projects was assessed by an in-situ evaluation conducted by the UCPRC in 2021 and 2022. The in-situ evaluation included the following:

- Laser profiler evaluation of the complete projects (all lanes) in September 2021.
- Road closure of one mile per project (located in the truck lane) in February and March 2022, which included the following activities:
    - Visual inspection.
    - Coring (the cores were used to verify slab thickness and base type and to measure compressive strength and modulus of elasticity in the laboratory).
    - Falling weight deflectometer (FWD) evaluation (the FWD data were used to determine the transverse joints load transfer efficiency [LTE]).

The assessment of the condition of the projects is based on the following factors:

- Maintenance/rehabilitation activities that each project has required since the construction.
- Comparison of measured distress levels (cracking, faulting, IRI) versus the different threshold values that trigger some type of maintenance/rehabilitation action in the Caltrans road network. These threshold values are as follows:
    - Third-stage cracking (a slab with third-stage cracking is a slab with two or more longitudinal and/or transverse cracks):
        - 3% of slabs with third-stage cracking triggers individual slab replacement.
        - 10% of slabs with third-stage cracking triggers reconstruction.
    - Faulting (% of 0.1 mi. segments with 0.15 in. faulting or more):
        - 25% of 0.1 mi. segments with 0.15 in. faulting or more triggers grinding.

- IRI:
  - 170 in./mi. triggers grinding.
- Comparison of measured transverse cracking versus the transverse cracking predicted by *AASHTOWare Pavement ME Design* (this software can only predict transverse cracking).
- In-situ evaluation of 1 mi. segment per project:
  - Visual inspection.
  - Strength of the PCC, based on the testing of the extracted cores.
  - LTE of the transverse joints, based on the FWD evaluation.

## 1.3 Overview of JPCP Long-Life Projects

The list of JPCP long-life projects is shown in Table 1.1. The table includes the construction window; the expenditure authorization (EA), a code used by Caltrans to identify each construction project; and the project postmile (PM) range. All projects are located in or close to the Mojave Desert, northeast of Los Angeles in Southern California (Figure 1.1).

**Table 1.1: List of JPCP Long-Life Projects**

| Project | Construction Window | Expenditure Authorization (EA) | Location |
|---|---|---|---|
| Interstate 15-Baker (I-15-Baker) | 2002-Sep-10 to 2004-Sep-08 | 08-4047U | Interstate 15, San Bernardino County:<br>Northbound direction, ~19 miles, PM R137.632 to 156.301 |
| Interstate 15-Victorville (I-15-Victorville) | 2002-Apr-02 to 2005-Jul-01 | 08-3555U | Interstate 15, San Bernardino County:<br>Northbound direction, ~22 miles, PM 45.855 to PM 67.768<br>Southbound direction, ~19 miles, PM 45.855 to PM 64.468 |
| Interstate 40-Ludlow (I-40-Ludlow) | 2001-Mar-14 to 2003-Feb-21 | 08-37780 | Interstate 40, San Bernardino County:<br>Eastbound direction, ~22 miles, PM R51.006 to PM R73.029<br>Westbound direction, ~22 miles, PM R51.006 to PM R73.029 |

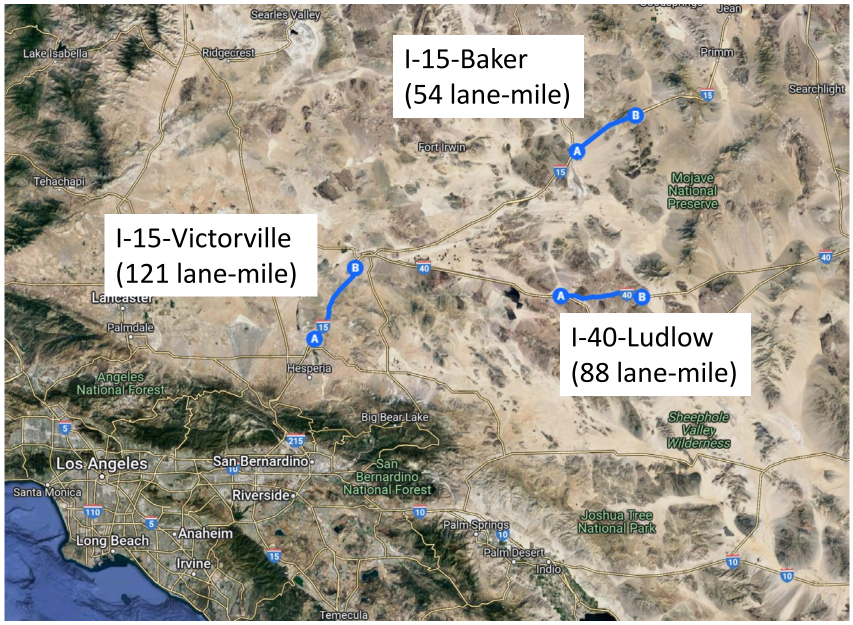
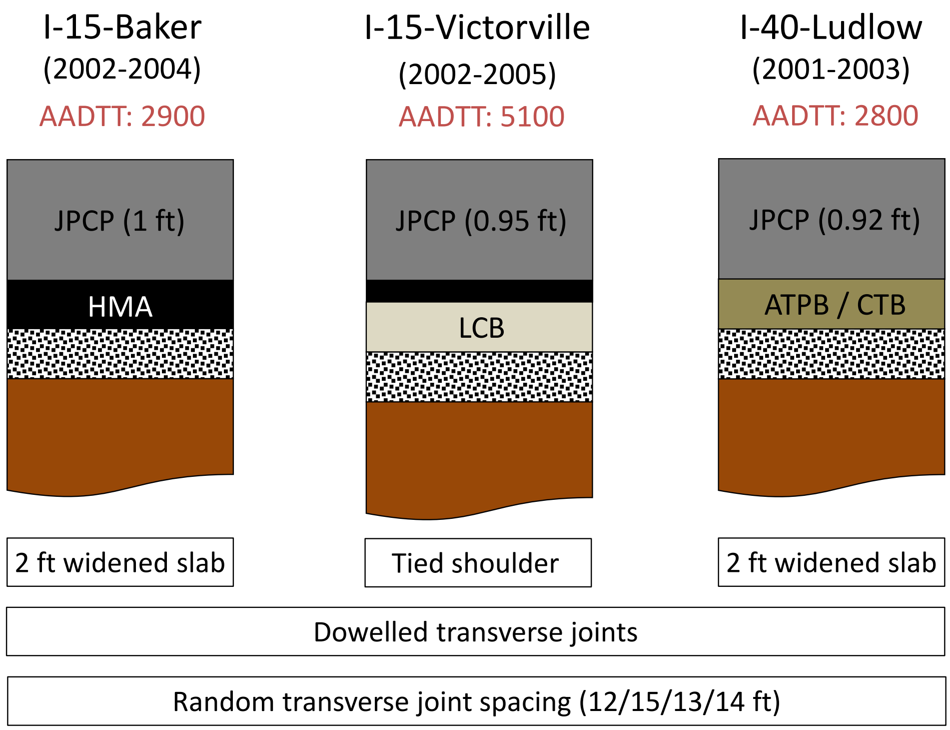



**Figure 1.1: JPCP long-life projects location.**

A fourth JPCP long-life project, referred as Interstate 15-Devore (I-15-Devore), was also built in the same area in the early 2000s, along the I-15 route close to Devore, in San Bernadino County, around PM 13 to PM 16. This project was also evaluated based on PCS data, in addition to a field evaluation that included coring, FWD testing, visual inspection, and laser profiling. Unfortunately, the FWD data indicated that the transverse joints were undoweled, contrary to what is known about the I-15-Devore project. It is believed that the highway segments that were in theory I-15-Devore did not actually correspond to this project. Consequently, the I-15-Devore project was not included in the study presented in this technical memorandum.

Figure 1.2 shows the typical pavement cross section of each project. The figure also shows the construction years, the annual average daily truck traffic (AADTT) of the truck lane, and some design features for each project. The three projects included tied longitudinal joints and doweled transverse joints. The mandatory use of dowels at the transverse joints was implemented by Caltrans in the early 2000s, when these projects were built, and the practice is still in place. The three projects have random transverse joint spacings of 12, 15, 13, and 14 ft., a practice that was discontinued by Caltrans around 2010. Current Caltrans practice for new JPCP is 14 ft. (fixed) transverse joint spacing.




**Configuration of the base of the different projects beneath the concrete**

| | |
|---|---|
| I-15-Baker | • 0.05 ft. newly placed hot mix asphalt (HMA) overlay on cold-milled asphalt pavement; or<br>• 0.50 ft. newly placed HMA on aggregate subbase, after removing existing asphalt pavement |
| I-15-Victorville | • 0.10 ft newly placed HMA overlay on 0.40 ft newly placed lean concrete base (LCB) |
| I-40-Ludlow | • 0.35 ft. newly placed asphalt treated permeable base (ATPB); or<br>• 0.50 ft. existing cement treated base (CTB) |

**Figure 1.2: JPCP long-life pavement sections and design features.**

The three JPCP projects include a total of 263 lane-miles. Project lanes and PM boundaries are shown in Table 1.2. The average AADTT and the prevalent WIM spectra of each lane are also included in the table. Figure 1.3 shows the truck volume that the truck lanes of the projects have supported between the construction and the last evaluation, conducted in 2021. Depending on the project, the truck lanes have supported between 19 and 33 million trucks. Based on the load equivalence factors estimated for the different WIM spectra in Caltrans road network *(14)*, the truck traffic is equivalent to 6 to 11 million equivalent single axel loads (ESALs), which correspond to Caltrans Traffic Index values of 11.0 to 12.0, respectively.

**Table 1.2: Boundaries and Truck Traffic of the Projects**

| Project | Lane | Dir. | Lane No.[a] | County[b] | Begin PM | End PM | Length (mi.) | Lane AADTT (2023) | WIM | ESALs/ Year |
|---|---|---|---|---|---|---|---|---|---|---|
| Interstate 15-Baker | N1 | North | 1 | SBD | R137.632 | 156.301 | 18.5 | 190 | 4 | 20,000 |
| | N2 | North | 2 | SBD | R137.632 | 156.301 | 18.5 | 1500 | 4 | 160,000 |
| | N3 | North | 3 | SBD | R138.733 | 156.301 | 17.4 | 2900 | 4 | 320,000 |
| Interstate 15-Victorville | N1 | North | 1 | SBD | 45.855 | 67.768 | 21.9 | 310 | 5 | 40,000 |
| | N2 | North | 2 | SBD | 45.855 | 67.768 | 21.9 | 2400 | 5 | 290,000 |
| | N3 | North | 3 | SBD | 45.855 | 67.768 | 21.9 | 5100 | 5 | 610,000 |
| | S1 | South | 1 | SBD | 45.855 | 64.468 | 18.6 | 310 | 5 | 40,000 |
| | S2 | South | 2 | SBD | 45.855 | 64.468 | 18.6 | 2400 | 5 | 290,000 |
| | S3 | South | 3 | SBD | 45.855 | 64.468 | 18.6 | 5000 | 5 | 600,000 |
| Interstate 40-Ludlow | E1 | East | 1 | SBD | R51.006 | R73.029 | 22.0 | 280 | 5 | 30,000 |
| | E2 | East | 2 | SBD | R51.006 | R73.029 | 22.0 | 2800 | 5 | 340,000 |
| | W1 | West | 1 | SBD | R51.006 | R73.029 | 22.0 | 280 | 5 | 30,000 |
| | W2 | West | 2 | SBD | R51.006 | R73.029 | 22.0 | 2800 | 5 | 340,000 |

[a] Lane 1 is the innermost lane.
[b] SBD: San Bernardino.

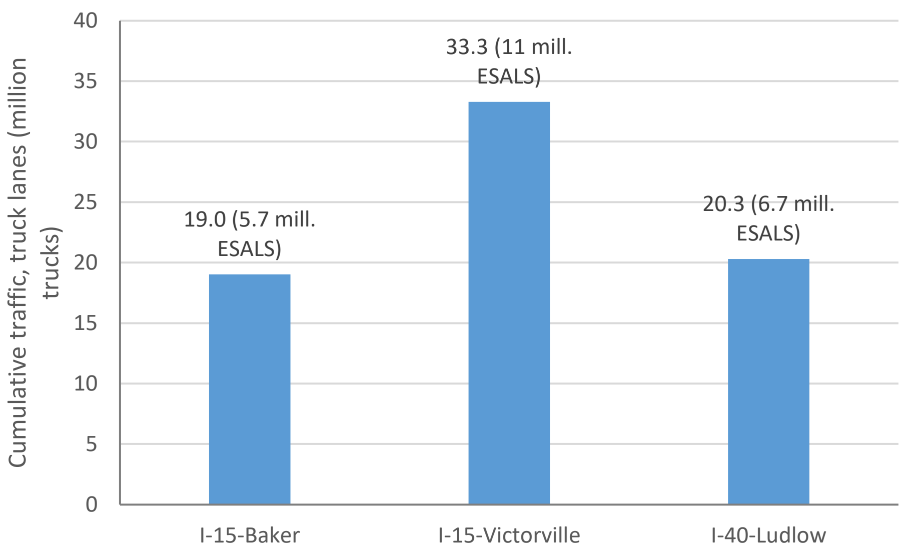



**Figure 1.3: Cumulative traffic, truck lanes (from construction to 2021).**

# 2 PERFORMANCE AND MAINTENANCE HISTORIES

The performance and maintenance histories of the three JPCP long-life projects are summarized in this chapter. Performance is summarized for different distress types included in the Caltrans PMS database that are collected by the APCS or were collected using the manual PCS prior to implementation of the APCS in 2011. The following are performance measures:

- Cracking:
  - First- and third-stage cracking:
    - First-stage cracking (1st Stg. Cr.) is a single crack, either longitudinal or transverse, in the slab. Third-stage cracking (3rd Stg. Cr.) consists of two or more longitudinal and/or transverse cracks, frequently two cracks that intersect each other and break the slab into three or more pieces (Figure 2.1). Corner cracking is not considered first-stage cracking.
  - Third-stage cracking:
    - JPCP distress conditions that trigger specific maintenance or rehabilitation activities, summarized in Caltrans "decision trees," are based on third-stage cracking, faulting, and IRI. First-stage cracking (longitudinal or transverse) is not considered by Caltrans decision trees.
- Faulting:
  - Percentage of transverse joints with more than 0.15 in. faulting.
- Smoothness:
  - IRI summarized as in./mi. IRI is collected as part of the APCS using inertial profiler data.

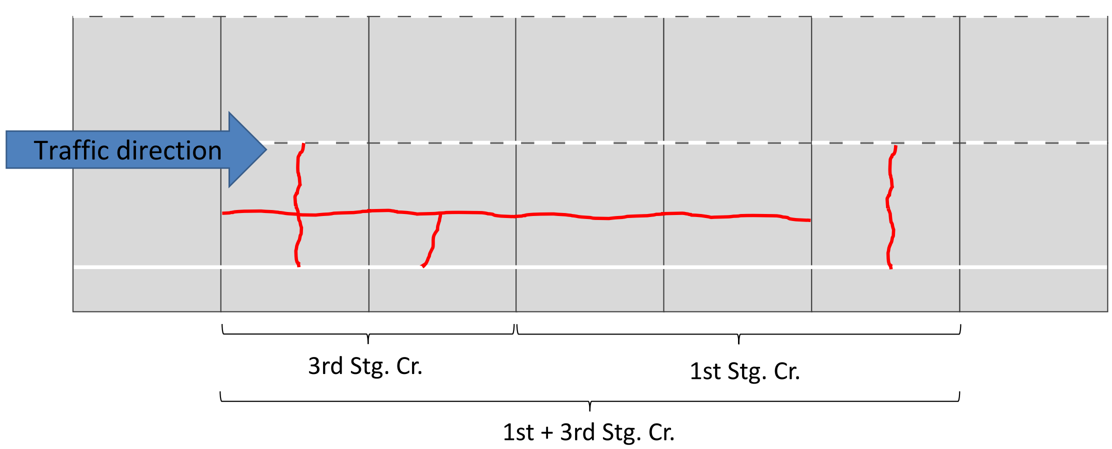



**Figure 2.1: Definition of first- and third-stage cracking.**

## 2.1 Maintenance History

None of the JPCP long-life projects has required any maintenance or rehabilitation activity (e.g., individual slab replacement or grinding) since their construction. An example Highway chart (H-chart) output from the Caltrans pavement management system (PaveM) for one of the project's lanes (I-15-Baker, Lane N3) is shown in Figure 2.2. The H-chart is a plotting tool used by Caltrans for pavement management purposes. The plot shows the highway segment boundaries on the x-axis and the timing on the y-axis for different maintenance and rehabilitation activities. The H-chart in Figure 2.2 shows the I-15-Baker project construction in 2004 (end of construction) and an HMA overlay applied on the previous pavement in 2001. No activity occurred after the JPCP long-life project was built in 2004. The H-chart showed similar results for all the other projects, with no work since their long-life construction.

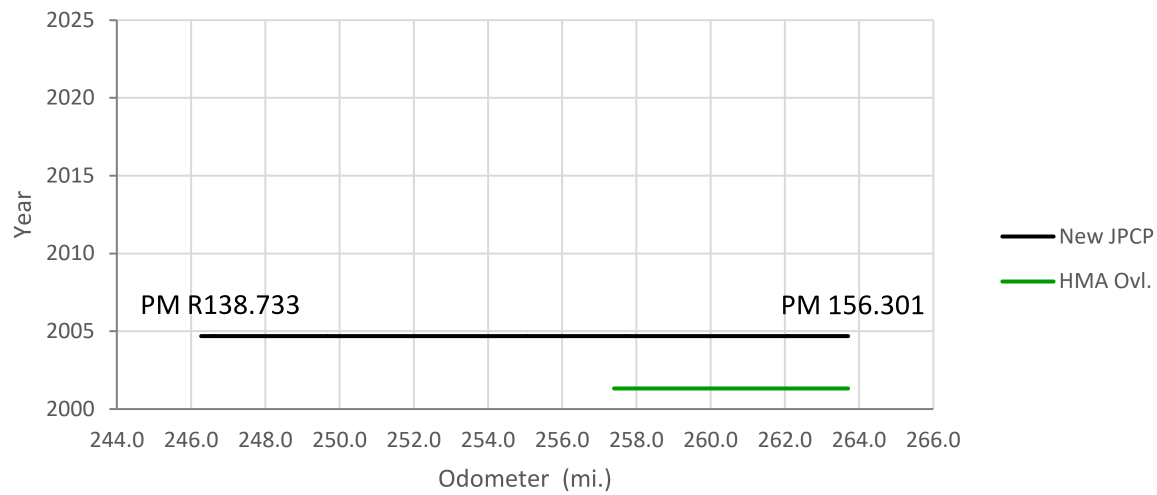



**Figure 2.2: H-chart for I-15-Baker, Lane N3.**

## 2.2 Cracking Performance

The cracking measured in the JPCP long-life projects is shown in Figure 2.3 (I-15-Baker), Figure 2.4 (I-15-Victorville), and Figure 2.5 (I-40-Ludlow). Overall, cracking performance is excellent as the third-stage cracking remains essentially zero in all lanes of the three projects, which total 263 lane-miles. Some lanes present some first-stage cracking: I-15-Victorville northbound Lane 3 (N3) and southbound Lane 3 (S3), with around 4% of slabs with first-stage cracking in 2021, and I-40-Ludlow eastbound Lane 2 (E2), with around 7% of slabs with first-stage cracking in 2021. This cracking is almost entirely longitudinal, shown in Figure 2.6. In this figure, the percentage of slabs with longitudinal cracking and the percentage of slabs with transverse cracking are shown for the three previously discussed lanes (I-15-Victorville N3 and S3 and I-40-Ludlow E2). Of the first-stage cracking, 91% to 94% was longitudinal.

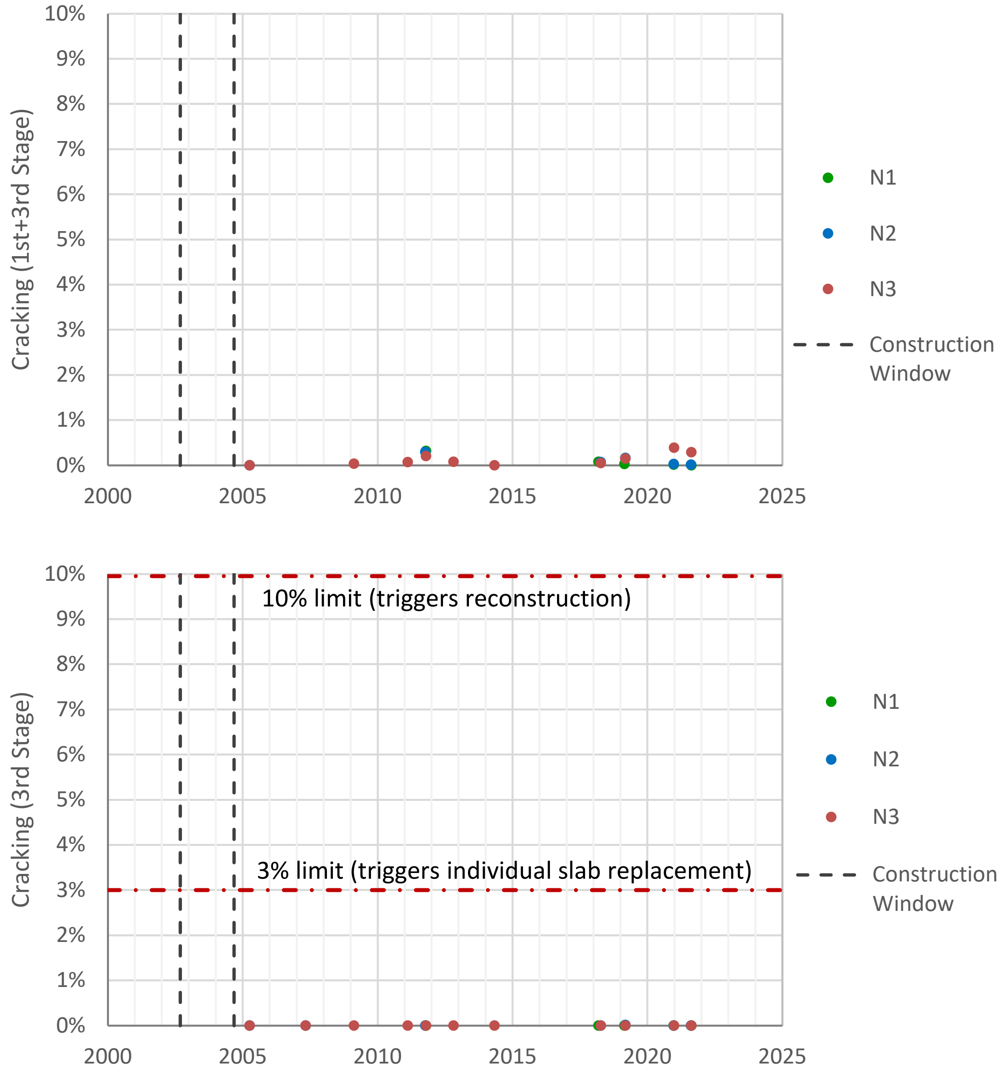



**Figure 2.3: Measured first-stage (top) and third-stage (bottom) cracking, I-15-Baker.**


**Figure 2.4: Measured first-stage (top) and third-stage (bottom) cracking, I-15-Victorville.**

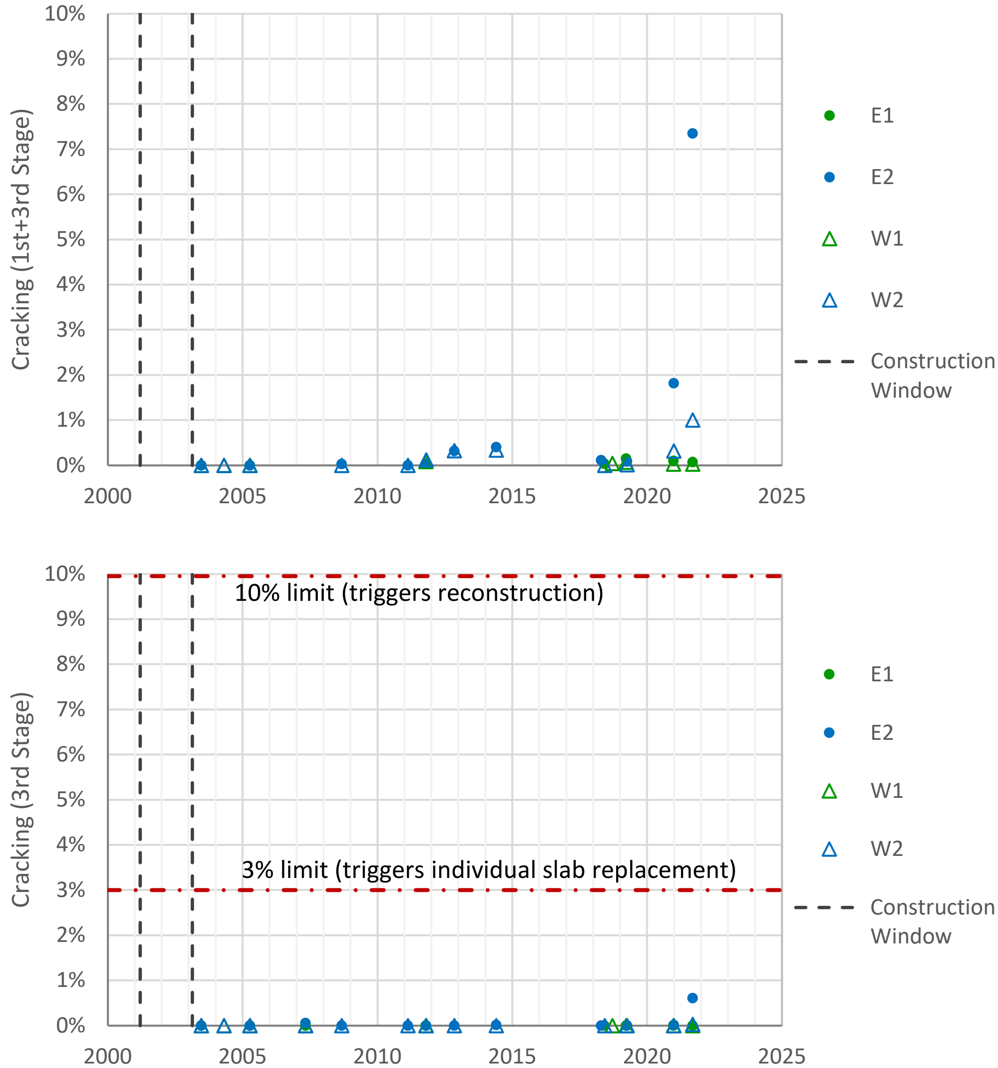



**Figure 2.5: Measured first-stage (top) and third-stage (bottom) cracking, I-40-Ludlow.**

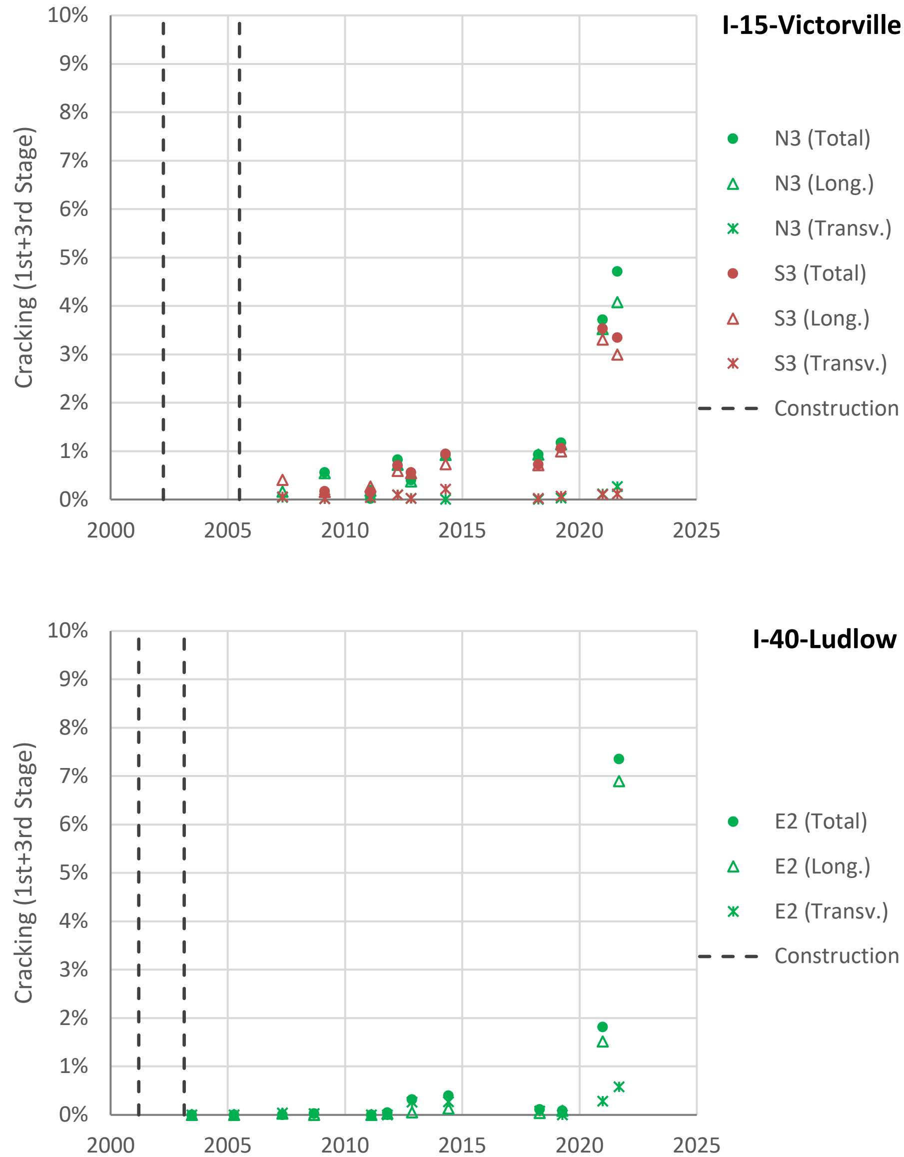



**Figure 2.6: Measured first-stage and third-stage cracking by cracking type, I-15 Victorville (top) and I-40-Ludlow (bottom).**

The amount of longitudinal cracking measured in the I-40-Ludlow truck lane, Lane E3, is relatively high, around 7%. The relatively high cracking level may be related to the use of a 2 ft. widened lane in the desert environment where there is high drying shrinkage, together with a slab that is not particularly thick (11 in.). No information was available about the slab-lean concrete base separation layer (bond-breaker) used in I-40-Ludlow project.

## 2.3 Faulting Performance

The percentage of faulted transverse joints, defined as joints with more than 0.15 in. faulting, is shown in Figure 2.6 (I-15-Baker), Figure 2.7 (I-15-Victorville), and Figure 2.9 (I-40-Ludlow). Overall, performance is excellent, as the measured faulting remains essentially zero, well below the level that would trigger a grinding operation, which is 25% of joints with faulting greater than 0.15 in. The excellent faulting performance agrees with the high LTE measured with the FWD (shown in Section 3.4). This outcome validates current Caltrans specifications that require the use of dowels at JPCP transverse joints.

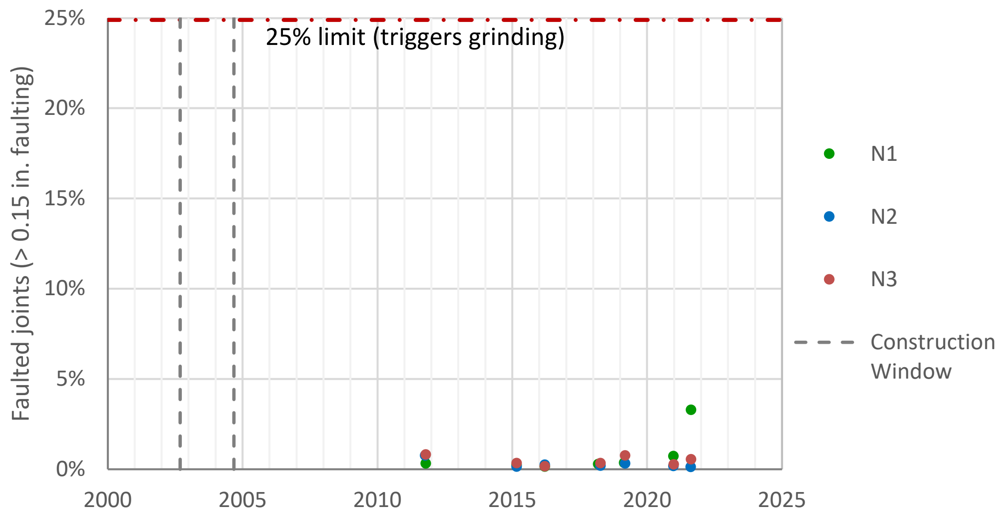



**Figure 2.7: Measured faulting, I-15-Baker.**

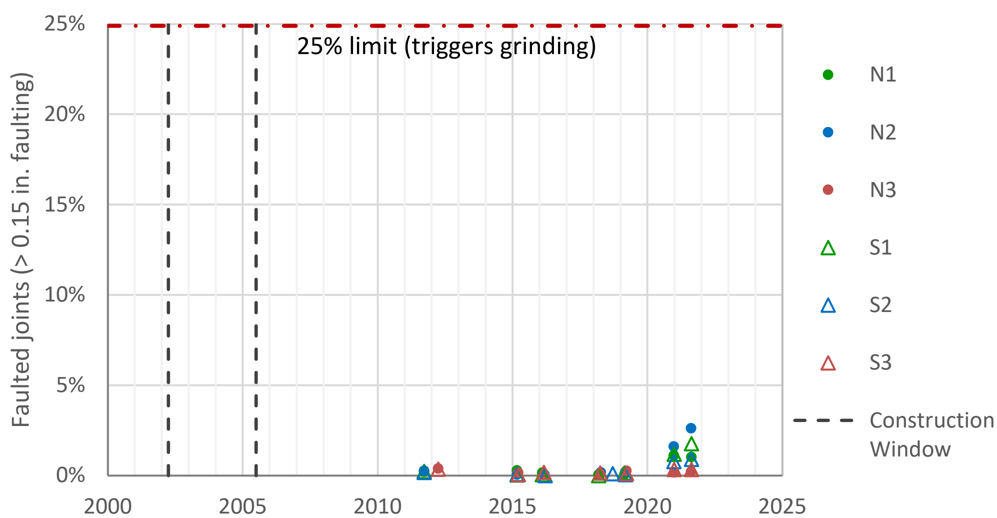



**Figure 2.8: Measured faulting, I-15-Victorville.**

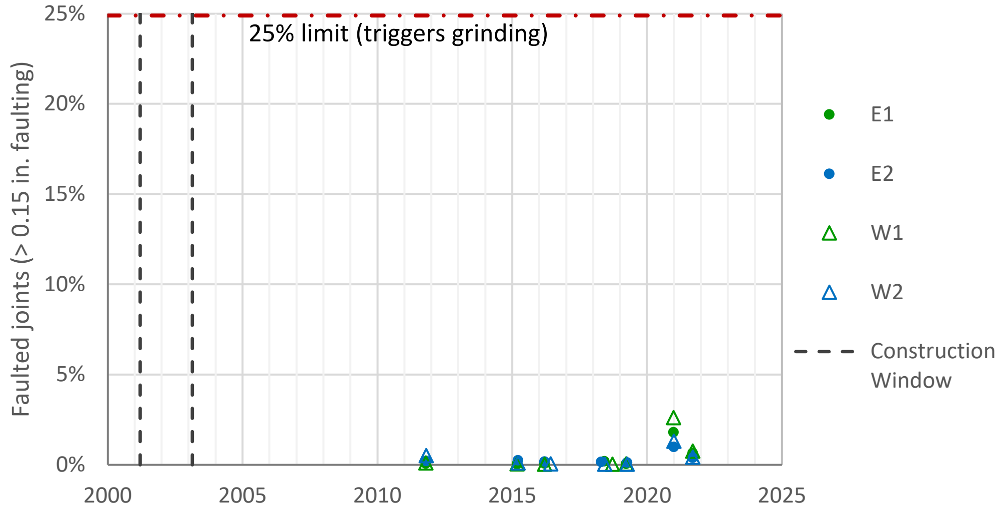



**Figure 2.9: Measured faulting, I-40-Ludlow.**

## 2.4 Smoothness Performance

The measured IRI is shown in Figure 2.9 (I-15-Baker), Figure 2.10 (I-15-Victorville), and Figure 2.11 (I-40-Ludlow). Overall, the IRI remained around 100 to 140 in./mi. for all projects. This is a little change from the initial constructed IRI values for these pavements, which were between 100 and 130 in./mi. While these values are relatively poor based on current Caltrans construction smoothness standards, they are far from the 170 in./mi. limit that would trigger a grinding operation. All these sections were built with construction smoothness standards from the early 2000s that were not based on the IRI and typically delivered relatively rough pavement compared with current standards. From the structural performance point of view, the main observation is that the IRI remains stable in all lanes in the three projects, an outcome that agrees with the low faulting measured in the projects and the lack of third-stage cracking. The stability of the IRI emphasizes the relevance of achieving a good initial IRI. This outcome supports recent Caltrans smoothness specifications that include pay factor adjustments tied to the post-construction IRI.

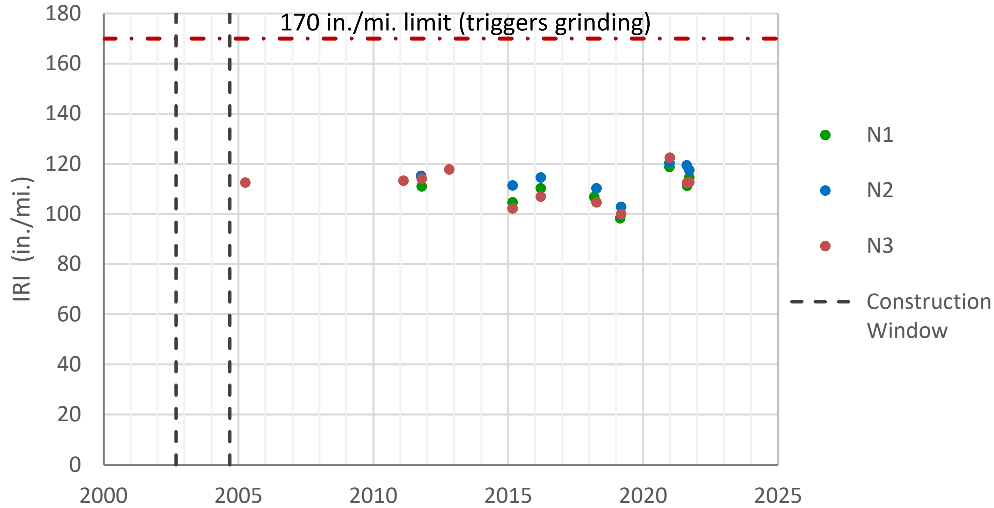



**Figure 2.10: Measured IRI, I-15-Baker.**

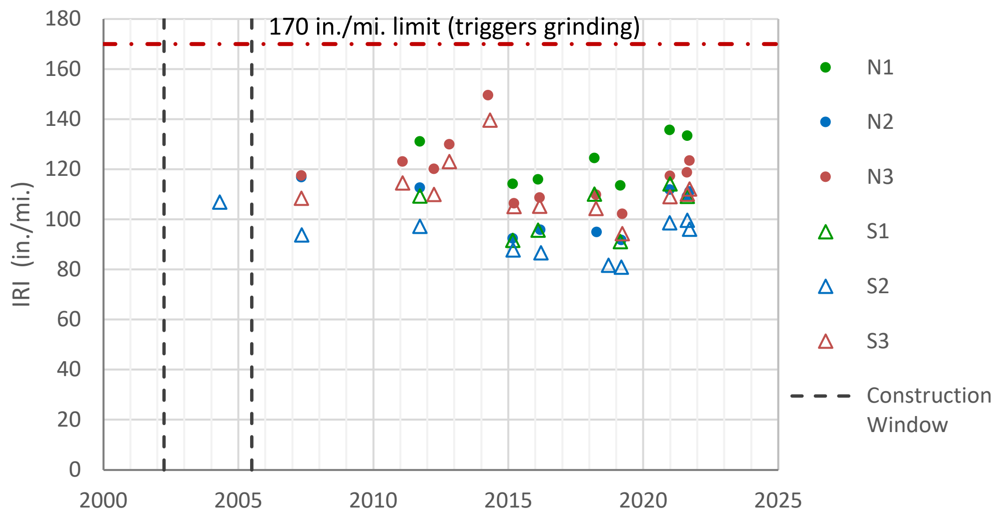



**Figure 2.11: Measured IRI, I-15-Victorville.**

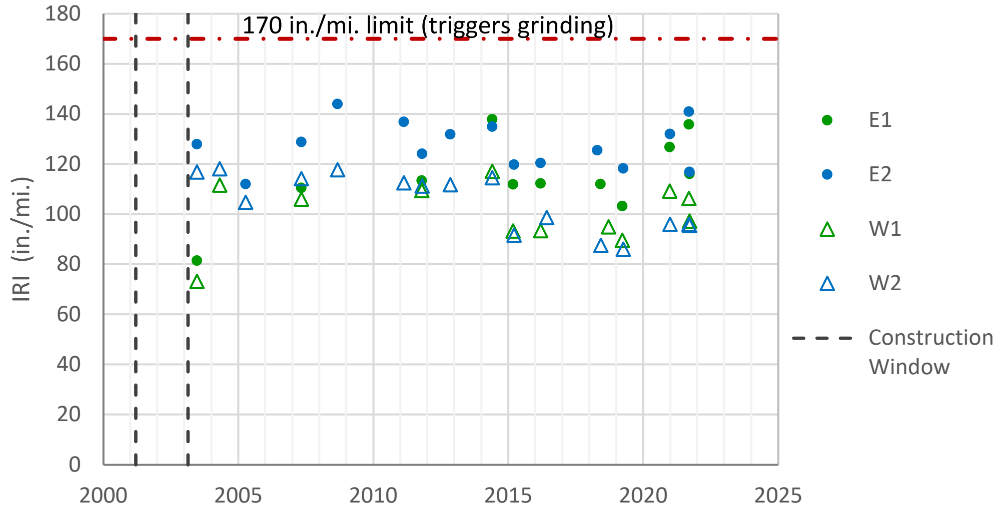



**Figure 2.12: Measured IRI, I-40-Ludlow.**

# 3 IN-SITU EVALUATION OF THE PROJECTS

As explained previously in Section 1.2, in addition to the PCS and APCS data, the present condition of the JPCP long-life projects was assessed by an in-situ evaluation conducted by the UCPRC. The in-situ evaluation included laser profiling of the projects in September 2021 and a road closure of one mile per project for visual inspection, coring, and FWD testing in February and March 2022. Evaluation methodology followed principles and practice included in Caltrans site investigation guide *(16)*. The location of the one-mile segment that was evaluated in each project and the corresponding evaluation date are shown in Table 3.1.

**Table 3.1: Location of One-Mile Road Closure for Visual Inspection, Coring, and Falling Weight Deflectometer Testing**

| Project | Date | Lane | Post Mile (PM) |
|---|---|---|---|
| I-15-Baker | 2022-Mar-15 | N3 (northbound, Lane 3) | 140.0 to 141.0 |
| I-15-Victorville | 2022-Feb-28 | S3 (southbound, Lane 3) | 63.0 to 64.0 |
| I 40-Ludlow | 2022-Mar-01 | W2 (westbound, Lane 2) | 66.0 to 67.0 |

## 3.1 Laser Profiler Evaluation

The smoothness of the projects was evaluated with an inertial laser profiler. The goal of the evaluation was verifying the IRI values extracted from the PMS database. In all cases, the measured IRI matched the values extracted from the database. An example of the agreement is shown in Figure 3.1, which corresponds to the I-15-Baker project. Consequently, the IRI values measured by the UCPRC were added to the collection of values extracted from the PMS database.

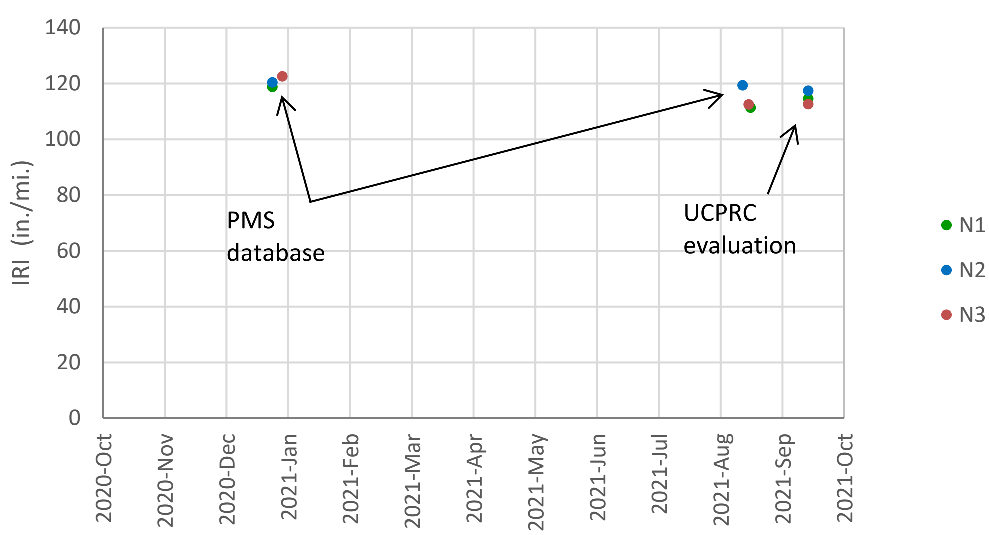



**Figure 3.1: Comparison of IRI measured by UCPRC versus IRI extracted from PMS database, I-15-Baker.**

## 3.2 Visual Inspection

The visual inspection was conducted by walking a one-mile section. The FHWA distress identification manual was used as the guide to identify and measure observed pavement distresses *(17)*. The inspections were conducted in the daytime under clear and sunny weather conditions.

### 3.2.1 I-15-Baker

The I-15-Baker section exhibited pavement in good condition. Only two transverse cracks and one corner crack (Figure 3.2) were observed over the mile surveyed. The transverse joints were in good to fair condition with some low severity spalling, as shown in Figure 3.3. Localized diamond grinding, which likely occurred during construction, was observed, shown in Figure 3.2 and Figure 3.3. Hairline map cracking was present in the wheelpaths.


**Figure 3.2: Corner crack, I-15-Baker.**

**Figure 3.3: Low severity spalling on a transverse crack, I-15-Baker.**

### 3.2.2 I-15-Victorville

The I-15-Victorville section was in very good condition. Some longitudinal cracking was observed in both wheelpaths as well as between the wheelpaths. Except for two locations with moderate severity longitudinal cracks, the longitudinal cracks were low in severity, shown in Figure 3.4. Localized diamond grinding was evident in some areas (left picture), which was likely done during construction. Hairline map cracking (left picture) was observed over the one mile surveyed. Some low severity transverse cracking was observed (right picture). The joints were in good condition with some low severity spalling.


**Figure 3.4: Low severity longitudinal cracks, I-15-Victorville.**

**Figure 3.5: Map cracking (left) and transverse cracking (right), I-15-Victorville.**

### 3.2.3 I-40-Ludlow

The Ludlow section exhibited a pavement in good condition. Moderate severity spalling was present at the transverse joints and corners, shown in Figure 3.6. Low severity longitudinal cracks were present at the wheelpaths (Figure 3.7). Hairline map cracking existed throughout the section. Most joints were in good condition. Localized diamond grinding was evident in some areas.

**Figure 3.6: Spalling in the transverse joint and corner, I-40-Ludlow.**

**Figure 3.7: Low severity longitudinal cracking at wheelpath, I-40-Ludlow.**

### 3.3 Coring and Lab Testing of the Cores

Seven to eight cores, each 6 in. in diameter, were extracted from each of the projects. The cores were extracted at the middle of the slabs. The quartile plots of the measured core thickness are shown in Figure 3.8. Overall, the measured thickness is at or above the design thickness, as expected. Based on the extracted cores, the type of base was asphalt concrete in the three projects and the base was debonded from the PCC in most cores.

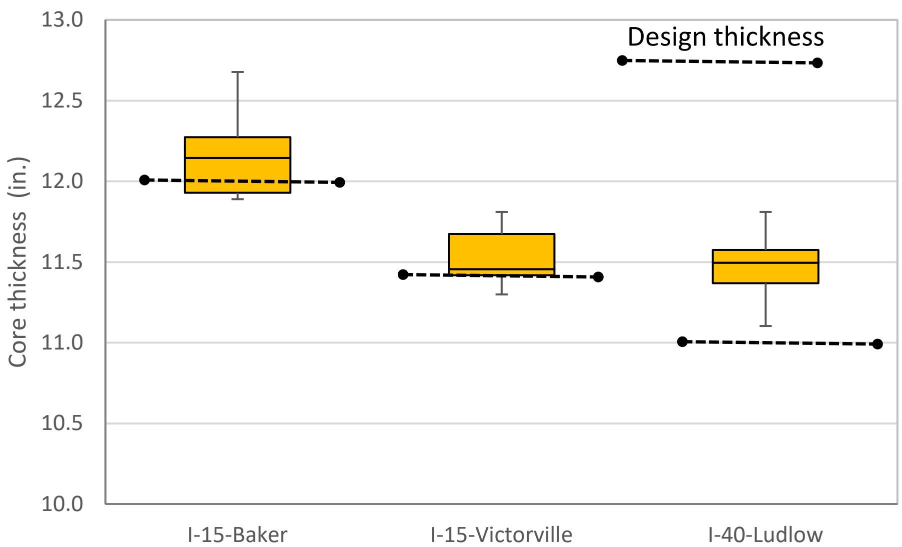



**Figure 3.8: Comparison of design thickness versus thickness measured from cores.**

The PCC cores were trimmed (top and bottom) and then used for determining strength (*fc*) and modulus of elasticity (*MoE*), following ASTM C39-21 and ASTM C469-22, respectively. One core was used for the initial estimation of *fc*, a parameter required for modulus of elasticity testing. Then three cores were tested for *MoE* followed by *fc* testing. The results of the testing are shown in Figure 3.9 (*fc*) and Figure 3.10 (*MoE*). The figures also include the PCC properties assumed for developing the new Caltrans rigid pavement design catalog , which are based on a 28-day compressive strength of 4500 psi, the ACI formula for converting *fc* to *MoE* ($MoE = 33*\rho^{1.5}*fc^{0.5}$, where $\rho$ is PCC density in pcf), and the default *Pavement ME* strength evolution function *(13)*. Overall, *fc* and *MoE* are below the values assumed for developing Caltrans rigid pavement design catalog. Lower *fc* generally hurts cracking performance while lower *MoE* generally improves cracking performance because it results in lower stresses for a given temperature and/or drying shrinkage difference between the top and bottom of the concrete slabs.

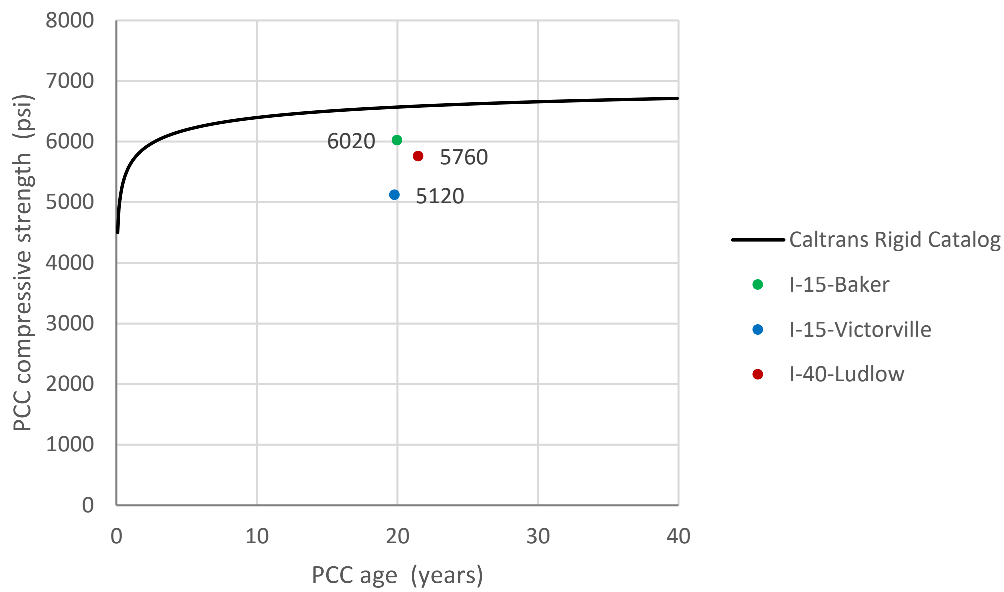



**Figure 3.9: Portland cement concrete (PCC) compressive strength.**

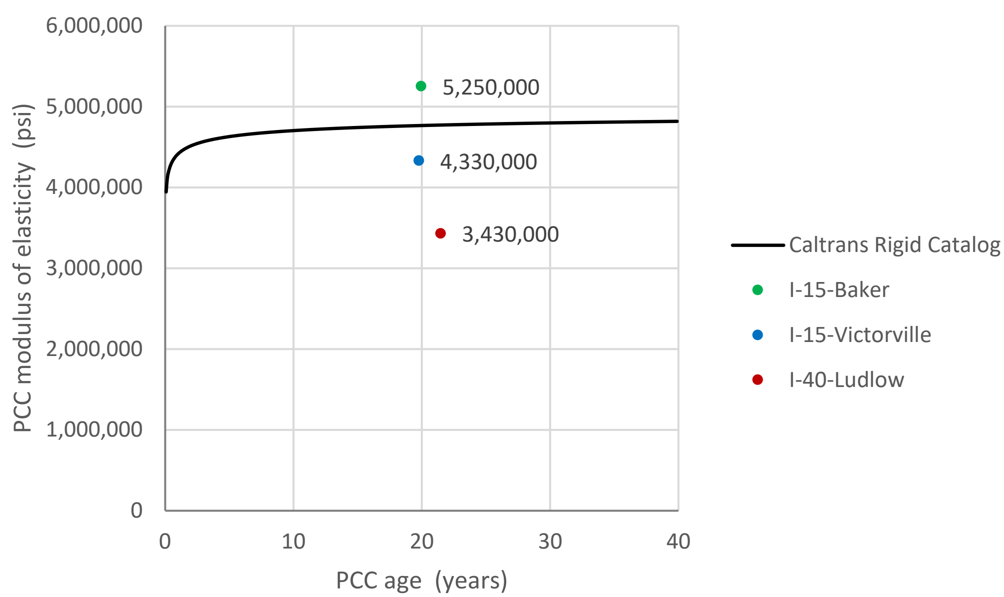



**Figure 3.10: Portland cement concrete (PCC) modulus of elasticity.**

## 3.4 FWD Evaluation

Each JPCP long-life project was tested with the FWD on five sets of slabs. Each set consisted of five consecutive slabs, shown in Figure 3.11. The five sets were uniformly distributed along the one-mile lane closure. As shown in Table 3.1, the tested lanes were N3 on I-15-Baker, S3 on I-15-Victorville, and W2 on I-40-Ludlow, all of which are truck lanes. Each slab was tested at two locations along the right wheelpath, mid-slab and the approaching edge of the transverse joint (Figure 3.11). Each location was tested twice, first in the morning and then in the afternoon, to capture possible thermal effects on the LTE of the transverse joints. In summary, 100 FWD tests were conducted per project: (5 sets of slabs) × (5 slabs per set) × (2 locations per slab) × (2 tests [morning and afternoon] per location).

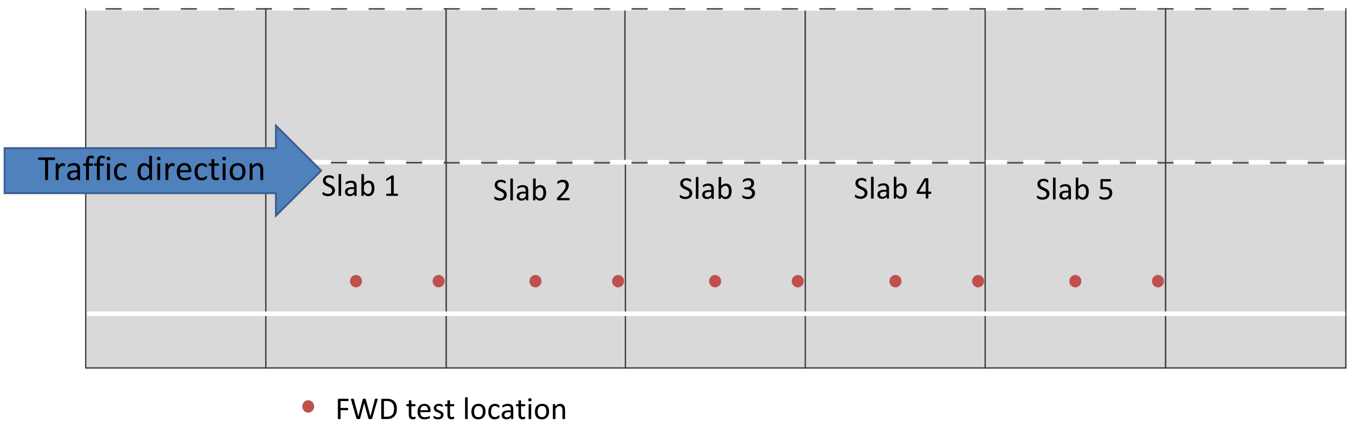



**Figure 3.11: Layout of one set of slabs (five consecutive slabs) for FWD testing.**

The LTE measured in all the projects was high, as expected from JPCP with good-performing dowels. The average LTEs were 83%, 84%, and 80% for I-15-Baker, I-15-Victorville, and I-40-Ludlow, respectively, with LTE defined as $D_{12}/D_0$, where $D_0$ is the deflection measured under the loading plate and $D_{12}$ is the deflection measured at a distance of 12 in. from the loading plate center, which is on the other side of the transverse joint. Further, the LTE was very uniform along the sections and presented minimal diurnal variation (morning versus afternoon), indicating that the dowels have not loosened. The LTE values are shown in Figure 3.12 (I-15-Baker), Figure 3.13 (I-15-Victorville), and Figure 3.14 (I-40-Ludlow).

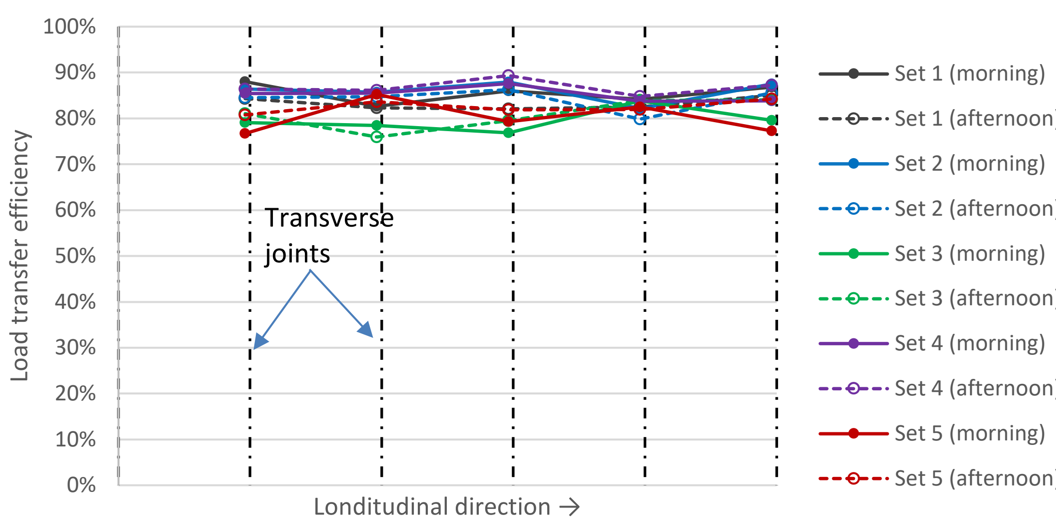



**Figure 3.12: LTE measured with the FWD in I-15-Baker project (Load = 15.7 kips).**

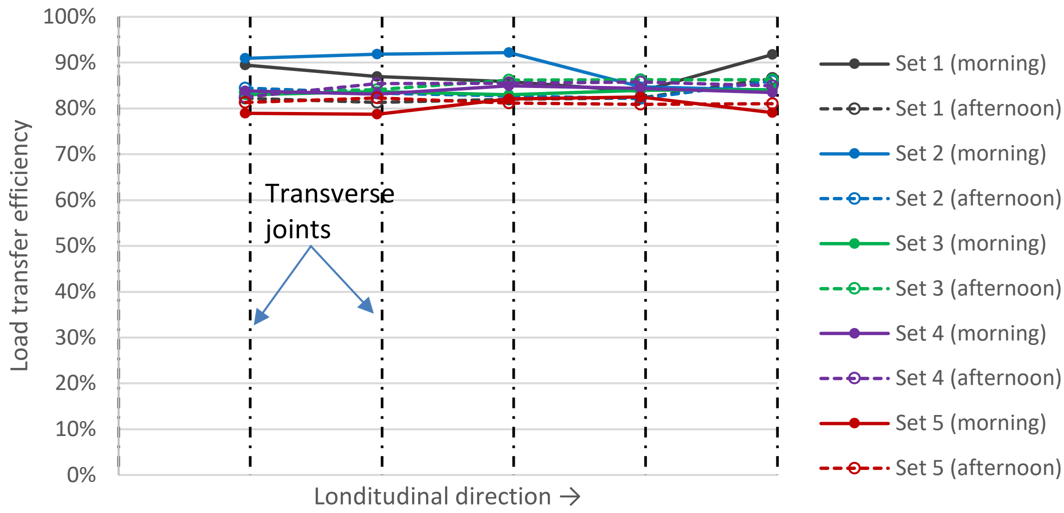



**Figure 3.13: LTE measured with the FWD in I-15-Victorville project (Load = 15.7 kips).**

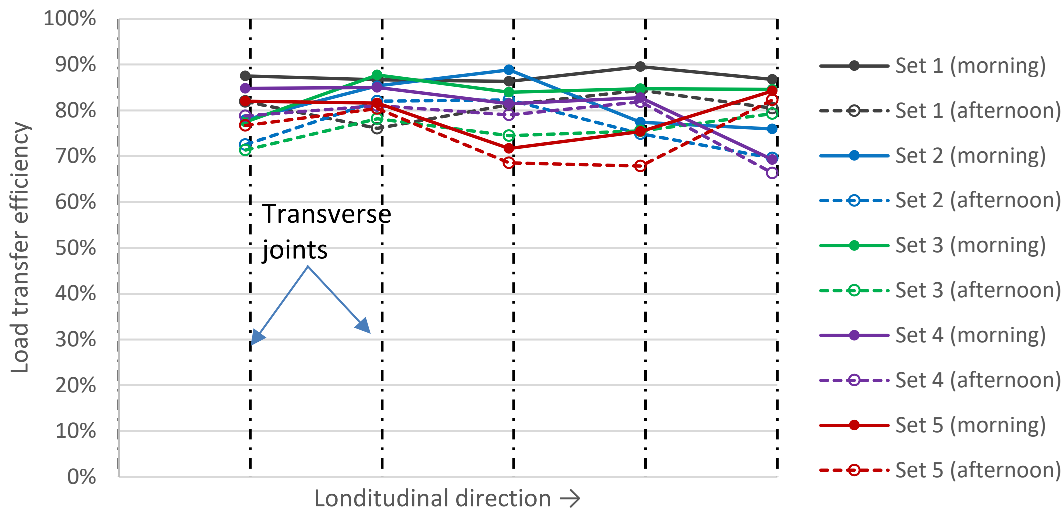



**Figure 3.14: LTE measured with the FWD in I-40-Ludlow project (Load = 15.7 kips).**

Three load levels were applied in each FWD test: 6.7, 11.2, and 15.7 kips (30, 50, and 70 kN). The LTE values presented in Figure 3.12 to Figure 3.14 correspond to the highest load level (15.7 kips). In any case, the LTE was roughly constant versus the load level, which indicates that it is unlikely that there are gaps between the concrete and the asphalt base below the transverse joints. The LTE versus load level results can be seen in Figure 3.15 (I-15-Baker), Figure 3.16 (I-15-Victorville), and Figure 3.17 (I-40-Ludlow).

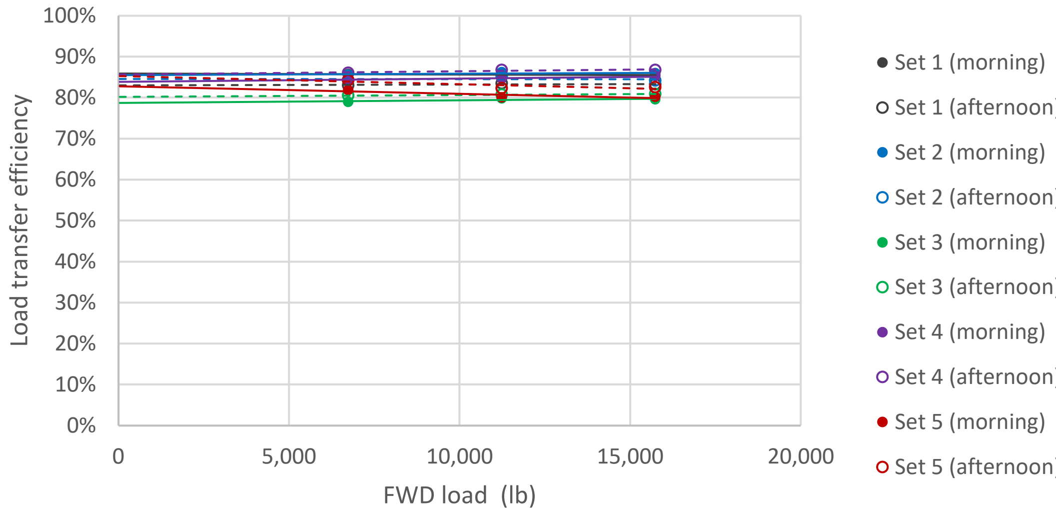



**Figure 3.15: LTE versus load level in I-15-Baker project.**

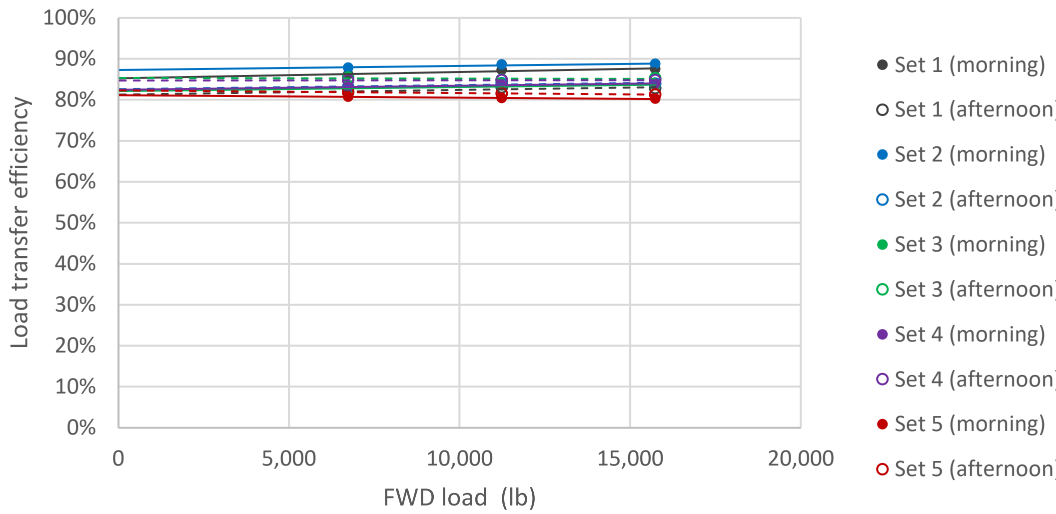



**Figure 3.16: LTE versus load level in I-15-Victorville project.**

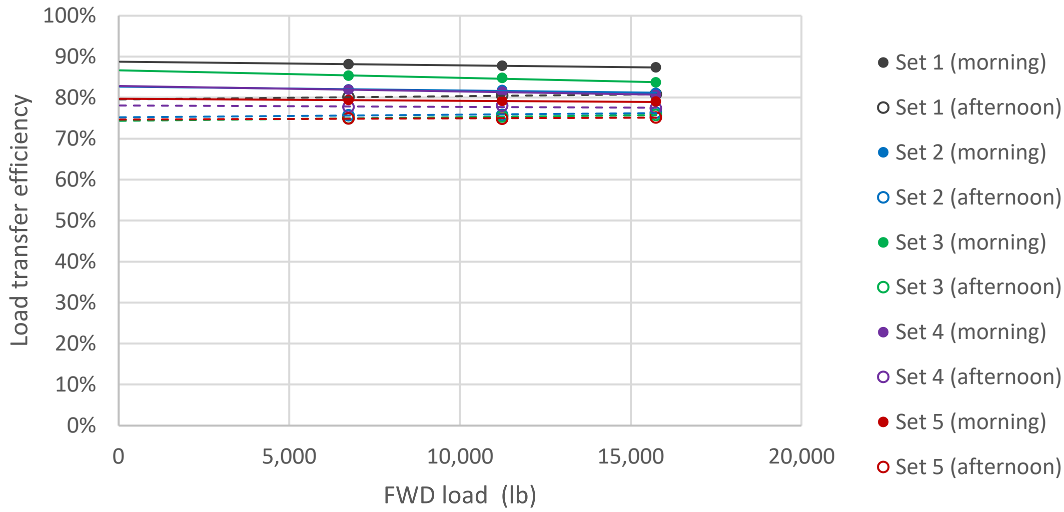



**Figure 3.17: LTE versus load level in I-40-Ludlow project.**

# 4 MECHANISTIC-EMPIRICAL MODELING OF THE PAVEMENTS

The JPCP cracking performance was modeled with *Pavement ME* (version 2.5.5). An HMA base, 3.0 in. thick, on top of a coarse-grained soil A-3 (AASHTO soil classification system), with no subbase, was assumed in all cases. The concrete properties were assumed to be the same as those used for developing the new Caltrans rigid pavement design catalog, including 637 psi 28-day flexural strength (equivalent to 4,500 psi compressive strength), modulus of elasticity computed internally by the software, 4.8 με/°F coefficient of thermal expansion, and 646 με ultimate drying shrinkage *(13)*. The concrete slabs and the base were assumed to be debonded (debonding age was set to zero months). The truck traffic volume and characteristics of the truck lanes were adopted in the modeling of the three projects. The truck lanes are Lane N3 for I-15-Baker, Lane N3 and Lane S3 for I-15-Victorville, and Lane E2 and Lane W2 for I-40-Ludlow (see WIM numbers and AADTT in Table 1.2). Only transverse cracking performance was modeled since *Pavement ME* cannot predict JPCP longitudinal cracking or third-stage cracking.

The transverse cracking predicted by *Pavement ME* at the 50% reliability level and in the truck lanes at year 20 is essentially zero in the three projects. The lack of transverse cracking predicted by *Pavement ME* agrees with the measured performance. Transverse cracking measured in the truck lanes of the three JPCP long-life projects is shown in Figure 4.1.

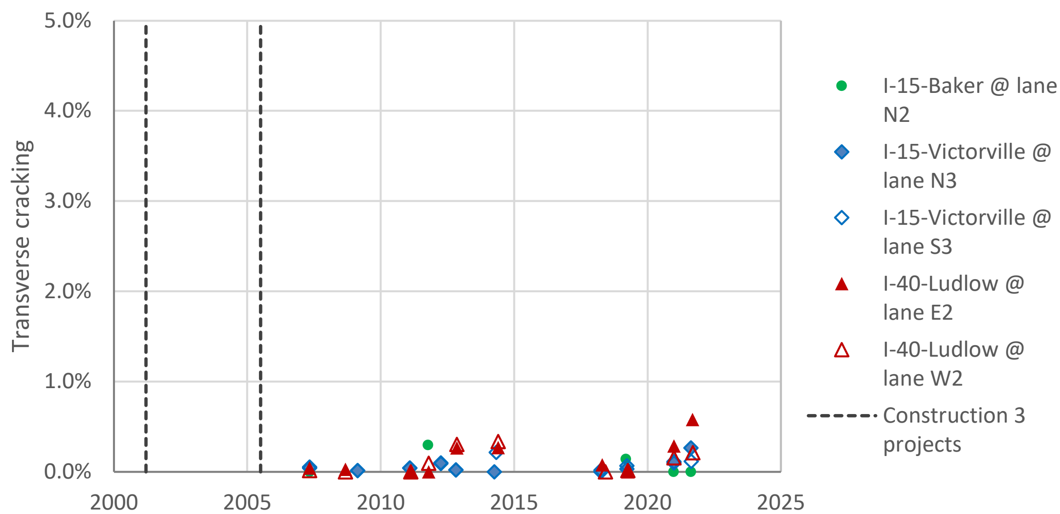



**Figure 4.1: Measured transverse cracking, truck lanes.**

Based on *Pavement ME* and the assumptions used for developing the new Caltrans rigid pavement design catalog, including 95% reliability, the slab thickness of the three JPCPs would be somewhat below the original design thickness, 0.6 to 2.5 in. thinner, shown in Table 4.1 *(13)*. The original designs were developed using the Caltrans concrete pavement design catalog from the late 1990s or early 2000s, which was primarily built on empirical evidence and judgment.

**Table 4.1: Original Design Thickness Versus Thickness Based on New JPCP Design Catalog**

| Project | Original PCC Design Thickness (in.)[a] | PCC Thickness from New JPCP Design Catalog (in.) | Difference (in.) |
|---|---|---|---|
| I-15-Baker | 12.0 | 9.5 | 2.5 |
| I-15-Victorville | 11.4 | 10.8 | 0.6 |
| I-40-Ludlow | 11.0 | 9.4 | 1.6 |

[a] Shown in Figure 1.2.

# 5 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

## 5.1 Summary

This technical memorandum evaluates the half-life performance of three long-life JPCPs that were built in Southern California in the early 2000s and designed for a 40-year life. The projects are located in or close to the Mojave Desert on heavily trafficked interstate highways, with AADTT levels from 2,800 to 5,100 for the design lane. The JPCPs include doweled transverse joints and either a tied rigid shoulder or 2 ft. widened lane. The 40-year life was twice the standard 20-year design life used for JPCP at that time. The three projects total 260 lane-miles.

The performance of the projects has been evaluated mainly based on Caltrans pavement management system databases, including pavement condition survey (PCS and APCS) databases with data about per-lane cracking, transverse joint faulting, and smoothness data, and the PMS as-built database that includes all maintenance, rehabilitation, and reconstruction activities conducted on the Caltrans road network. PCS and APCS data up to 2021 have been analyzed in this technical memorandum.

The PMS databases were complemented with an in-situ evaluation of the projects that included an inertial profiler evaluation and a road closure of one mile per project for visual inspection, coring, and FWD testing.

## 5.2 Conclusions

Overall, the performance of the projects has been excellent so far with the following conclusions:

- The truck lanes of the projects have supported between 19 and 33 million trucks since the construction.
- The third-stage cracking (slabs with two or more cracks) is essentially zero in all lanes.
- Three lanes presented some longitudinal cracking, from 4% to 7%. On the contrary, transverse cracking in these three lanes was negligible.
- The faulting (percentage of transverse joints with more than 0.15 in. faulting) is essentially zero in all lanes.
- The IRI has been stable since the construction of the projects, although the pavements were constructed rougher than is allowed under the current construction smoothness specifications.
- None of the projects has required any maintenance or rehabilitation activity (e.g., individual slab replacement or grinding) since the construction. Further, the three condition indices (third-stage cracking, faulting, and IRI) are, for all projects and lanes, far below the levels that would trigger any maintenance or rehabilitation activity based on Caltrans PMS decision trees.

The visual inspection confirmed the excellent condition of the projects and, in particular, the absence of third-stage cracking. However, it revealed the presence of low severity (hairline) map cracking, likely related to the dry climate area where the projects are located.

The smoothness values measured by the UCPRC in 2021 agree with the values extracted from the Caltrans PCS database. The FWD evaluation indicated that the load transverse efficiency of the transverse joints was high, from 80% to 85%. LTE was also very uniform along the sections and presented minimal diurnal variation (morning versus afternoon). This outcome indicates good-performing doweled transverse joints and agrees with the lack of faulting and the stable IRI. Mechanistic-empirical modeling with *AASHTOWare Pavement ME Design* (version 2.5.5) supports the excellent performance of the projects and the lack of transverse cracking, in particular.

## 5.3 Recommendations

As stated in the conclusions, three lanes presented 4% to 7% longitudinal cracking with negligible transverse cracking. This outcome agrees with other studies conducted by the UCPRC that indicate that JPCP longitudinal cracking may be as important or more important than the transverse cracking on the Caltrans road network in terms of the risk of occurrence. *Pavement ME* and the Caltrans rigid pavement design catalog (which is based on *Pavement ME*) only considers JPCP transverse cracking. It is recommended that a JPCP longitudinal cracking model be developed and implemented in *Pavement ME*.

The longitudinal cracking in the I-40-Ludlow project may be related to the use of a 2 ft. widened slab shoulder. It is recommended that the impact of 2 ft. widened slab shoulders with JPCP in dry climate regions like the Desert, High Desert, and Inland Valley should be investigated further and that considerations of safety, maintenance, and pavement longitudinal cracking be included in any updating of design standards.

While the IRI remained stable since the construction of the projects, it remained stable around 100 to 140 in./mi., which indicates a relatively poor smoothness based on current construction smoothness Caltrans standards. The stability of the IRI emphasizes the relevance of achieving a good initial IRI. This outcome supports recent Caltrans smoothness specifications that include pay factor adjustments tied to the post-construction IRI.

No other changes are proposed for the Caltrans JPCP design and construction practices after this half-life evaluation of the three JPCP long-life projects with respect to cracking, faulting, and smoothness standards.

The good performance of the three long-life projects evaluated in this study has resulted in considerable cost savings for Caltrans, due to the lack of costly maintenance and rehabilitation operations, and for the highway users, due to the negative impact that maintenance and rehabilitation operations have in the highway traffic. It is recommended that life cycle cost analysis and life cycle assessment are conducted to quantify the economic and environmental benefits associated to the selection of 40-year design versus other design alternatives with lower initial cost and shorter expected life.

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