# Optimization of Traffic Data Collection for Specific Pavement Design Applications

PUBLICATION NO. FHWA-HRT-05-079 MAY 2006


U.S. Department of Transportation
**Federal Highway Administration**

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

## FOREWORD

The objective of this study is to establish the minimum traffic data collection effort required for pavement design applications satisfying a maximum acceptable error under a prescribed confidence level. The approach consists of simulating the traffic data input to the 2002 National Cooperative Highway Research Program (NCHRP) 1-37A design guide for 17 distinct traffic data collection scenarios using extended-coverage, weigh-in-motion (WIM) data from the Long-Term Pavement Performance database. They include a combination of site-specific, regional, and national WIM, automated vehicle classification, and automated traffic recorder data of various lengths of coverage. Regional data were obtained using clustering techniques. Pavement life was estimated using mean traffic input and low-percentile input to the NCHRP 1-37A design guide for three levels of confidence: 75 percent, 85 percent, and 95 percent. For each confidence level, ranges in pavement life prediction errors were estimated. A three-dimensional plot was produced, indicating the maximum error by confidence level for each of the traffic data collection scenarios analyzed. This plot can be used to establish the minimum required traffic data collection effort, given the acceptable error and the desirable level of confidence.

Gary L. Henderson.
Director, Office of Infrastructure
Research and Development

## NOTICE



## QUALITY ASSURANCE STATEMENT

**Technical Report Documentation Page**

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| FHWA-HRT-05-079 | | |

**4. Title and Subtitle**
Optimization of Traffic Data Collection for Specific Pavement Design Applications

**5. Report Date**
May 2006

**6. Performing Organization Code**

**7. Author(s)**
A.T. Papagiannakis, M. Bracher, J. Li, and N. Jackson

**8. Performing Organization Report No.** 123210-8

**9. Performing Organization Name and Address**
Nichols Consulting Engineers
1885 South Arlington Avenue,
Suite 111
Reno, NV 89509-3370

Washington State University
Department of Civil and Environmental Engineering
101 Sloan Hall
Spokane Street
Pullman, WA 99164-2910

**10. Work Unit No. (TRAIS)**

**11. Contract or Grant No.**
DTFH61-02-D-00139

**12. Sponsoring Agency Name and Address**
Office of Infrastructure Research and Development
Federal Highway Administration
6300 Georgetown Pike
McLean, VA 22101-2296

**13. Type of Report and Period Covered**
Final Report
March 2003 to July 2005

**14. Sponsoring Agency Code**

**15. Supplementary Notes**
Contracting Officer's Technical Representative (COTR): Larry Wiser, Long-Term Pavement Performance Team

**16. Abstract**
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| 17. Key Words | 18. Distribution Statement |
|---|---|
| Traffic input, NCHRP 1-37A design guide, LTPP, clustering, tolerable errors, confidence level. | No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. |

| 19. Security Classification (of this report) | 20. Security Classification (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 126 | |

**Form DOT F 1700.7** **Reproduction of completed page authorized**

# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oF$ | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AADT | Average Annual Daily Traffic |
| AADTT | Average Annual Daily Truck Traffic |
| AADW | Annual Average Day of Week |
| AASHTO | American Association of State Highway and Transportation Officials |
| AC | Asphalt Concrete |
| AEPV | Average ESALs per Vehicle |
| ATR | Automated Traffic Recorder |
| AVC | Automated Vehicle Classification |
| CMAWD | Combined Month and Average Weekday |
| CMDW | Combined Month and Day of Week |
| COTR | Contracting Officer's Technical Representative |
| CRC | Continuously Reinforced Concrete |
| CRCP | Continuously Reinforced Concrete Pavement |
| CTDB | Central Traffic Database |
| CWAWD | Combined Week and Average Weekday |
| DAR | Daily Adjustment Ratio |
| DOT | Department of Transportation |
| DOW | Day of Week |
| DTR | Daily Traffic Ratio |
| ESAL | Equivalent Single-Axle Load |
| FHWA | Federal Highway Administration |
| GPS | General Pavement Study |
| GVW | Gross Vehicle Weight |
| ICM | Integrated Climatic Model |
| IRI | International Roughness Index |
| JPCP | Jointed Plain Concrete Pavement |
| LTPP | Long-Term Pavement Performance |
| M | Monthly Adjustment Factor |
| MADT | Monthly Average Daily Traffic |
| MADW | Monthly Average Day of Week |
| MAF | Monthly Adjustment Factor |
| MAR | Monthly Adjustment Ratio |
| MDW | Month and Day of Week |
| MDWTR | Monthly Day of Week Traffic Ratio |
| MTR | Monthly Traffic Ratio |
| N | National |
| NCHRP | National Cooperative Highway Research Program |
| PCC | Portland Cement Concrete |
| PDG | Pavement Design Guide |
| PSI | Present Serviceability Index |
| QC | Quality Control |
| R | Regional |
| RFP | Request for Proposal |
| RH | Relative Humidity |

| | |
|---|---|
| SAS | Statistical Analysis System® |
| SD | Specific Day |
| SD | Standard Deviation |
| SDNN | Specific Day With Noon-to-Noon Factors |
| SN | Structural Number |
| SS | Site Specific |
| SWDW | Separate Week and Day of Week |
| TMG | Traffic Monitoring Guide |
| TTC | Truck Traffic Class |
| TWRG | Truck Weight Road Group |
| VC | Vehicle Class |
| VMT | Vehicle-Miles Traveled |
| VOL | Daily Vehicle Volume Count |
| WIM | Weigh-in-Motion |

# EXECUTIVE SUMMARY

This study presents a comprehensive approach for establishing the minimum traffic data collection effort required for pavement design applications satisfying a maximum acceptable error under a prescribed confidence level. This approach consists of simulating the traffic data input to the new National Cooperative Highway Research Program (NCHRP) 1-37A design guide for 17 distinct traffic data collection scenarios using extended-coverage, weigh-in-motion (WIM) data from the Long-Term Pavement Performance (LTPP) database. This simulation involves data typically collected by other technologies, such as automated vehicle classification (AVC) and automated traffic recorders (ATR). These scenarios are described in table 8 in the report.

Extended coverage was defined as 299 or more days per year of level E WIM data, (i.e., data that has passed the quality control (QC) checks conducted by State departments of transportation (DOTs) and the LTPP regional support contractor offices). Analysis of LTPP Standard Data Release 16.0 revealed a total of 178 general pavement studies (GPS) satisfying this requirement. For all of these sites, central traffic database (CTDB) data were extracted in the form of daily summaries (level 3). From these sites, a total of 30 sections (15 flexible and 15 rigid) were selected for NCHRP 1-37A design guide pavement performance estimation. The selection was based on the widest possible distribution of average annual daily truck traffic (AADTT) volumes and structural thicknesses.

A number of the traffic data collection scenarios simulated involved continuous site-specific data coverage for axle loads, classification, or counts, while others involved discontinuous site-specific data coverage (1 month per season, 1 week per season, and so on). Data elements, which were assumed to be unavailable at a site for simulation purposes, were estimated from regional data. Regional vehicle classification and axle-load data were obtained from the remaining LTPP sites identified using clustering techniques. Scenarios involving national data used the default traffic input in the NCHRP 1-37A design guide. For each of the traffic data collection scenarios involving discontinuous coverage of site-specific data, statistics for each traffic data element were computed by considering all possible time-coverage combinations. This allowed the establishment of low percentiles for each input to simulate underestimation of the actual traffic volumes/loads at a site. This was considered to be critical since it would result in thinner pavement designs that failed prematurely. Four confidence levels were selected: 75 percent, 85 percent, 95 percent, and 99.9 percent. Traffic input for the continuous-coverage traffic data collection scenarios involved no variation because of the sampling scheme used. All scenarios were simulated using a 4 percent annual growth in AADTT. Additional analysis was conducted to compute the annual growth rate in AADTT and its effect on pavement life predictions.

The NCHRP 1-37A design guide pavement life predictions for each scenario were analyzed to compute percentage errors in pavement life predictions with respect to the life predictions obtained under continuous site-specific WIM data (scenario 1-0). Reasonable life predictions were obtained for 17 of the 30 sections analyzed; the remainder experienced either premature failures or no failure at all. Two pavement life prediction error components were identified:

- “A” is the estimated error from the traffic input of a continuous scenario or from the mean traffic input of a discontinuous time-coverage scenario.

- “B” is the additional error possible in discontinuous-coverage scenarios by inputting the lowest percentile input for all traffic input estimates simultaneously.

Computing statistics for error component “A” for all 17 sections revealed that its mean is negligible for all of the scenarios analyzed. Its standard deviation allowed establishment of a range of errors by confidence level (table 1 below and figure 22 in the report).

**Table 1. Range in life prediction percentage errors from mean traffic input.**

| Error Range by Probability of Exceeding Them | | | |
|---|---|---|---|
| **Scenario** | **25 percent** | **15 percent** | **5 percent** |
| 1-1 | 5.32 | 8.26 | 13.42 |
| 1-2 | 6.87 | 10.66 | 17.33 |
| 2-0 | 10.74 | 16.65 | 27.08 |
| 2-1 | 10.28 | 15.94 | 25.91 |
| 2-2 | 10.72 | 16.62 | 27.03 |
| 2-3 | 10.94 | 16.97 | 27.59 |
| 3-0 | 25.29 | 39.22 | 63.78 |
| 3-1 | 25.00 | 38.77 | 63.05 |
| 4-0 | 27.08 | 41.99 | 68.29 |
| 4-1 | 26.38 | 40.90 | 66.51 |
| 4-2 | 25.11 | 38.94 | 63.32 |
| 4-3 | 28.48 | 44.17 | 71.83 |
| 4-4 | 30.17 | 46.78 | 76.08 |
| 4-5 | 30.38 | 47.10 | 76.60 |
| 4-6 | 30.12 | 46.71 | 75.96 |
| 4-7 | 32.49 | 50.39 | 81.94 |

Statistics for error component “B” were processed to yield the mean error and the standard deviation in the mean error by traffic data collection scenario. This allowed computation of the range in mean error resulting from specifying the lowest percentile for all traffic inputs simultaneously. While this is quite conservative, it addresses the question of reliability, so that the designer is guaranteed that given a level of confidence, a particular error level will not be exceeded. Overall error was computed by adding the range in error from component “A” to the range in mean error from component “B.” The results were plotted in a three-dimensional plot, indicating the maximum error by confidence level for each of the traffic data collection scenarios analyzed (table 2 below and figure 23 in the report). Figure 23 can be used to establish the minimum required traffic data collection effort, given the acceptable error and the desirable level of confidence.

**Table 2. Range in combined life prediction errors from low-percentile traffic input.**

| Overall Range in Errors by Probability of Exceeding Them | | | |
|---|---|---|---|
| **Scenario** | **25 percent** | **15 percent** | **5 percent** |
| 1-1 | 20.89 | 27.45 | 41.57 |
| 1-2 | 28.59 | 35.91 | 55.81 |
| 2-0 | 10.74 | 16.65 | 27.08 |
| 2-1 | 34.70 | 42.65 | 58.96 |
| 2-2 | 23.79 | 36.55 | 44.31 |
| 2-3 | 37.24 | 51.79 | 89.88 |
| 3-0 | 25.29 | 39.22 | 63.78 |
| 3-1 | 30.07 | 45.78 | 74.02 |
| 4-0 | 27.08 | 41.99 | 68.29 |
| 4-1 | 32.14 | 47.47 | 76.75 |
| 4-2 | 47.22 | 72.55 | 105.66 |
| 4-3 | 63.66 | 92.44 | 151.79 |
| 4-4 | 30.17 | 46.78 | 76.08 |
| 4-5 | 35.36 | 54.36 | 86.77 |
| 4-6 | 70.17 | 112.32 | 174.65 |
| 4-7 | 83.84 | 139.25 | 206.75 |

# CHAPTER 1. INTRODUCTION

## OBJECTIVE

Traffic loads are an essential input to the pavement analysis and design process. In the past, the effect of traffic was aggregated into equivalent single-axle loads (ESALs) and input into regression-based pavement performance equations. The NCHRP 1-37A design guide[(1)] characterizes traffic in terms of axle numbers by type and their load frequency distribution (i.e., axle-load spectra). This is a significant improvement over past methods because it allows a mechanistic pavement design approach. It involves computing the pavement structural responses to load (i.e., stresses and strains), translating them into damage, and accumulating the damage into distress and reduced pavement performance over time.

Traffic data collection is carried out by a combination of data acquisition technologies, including WIM systems, AVC, and ATR. Typically, traffic data unavailable at a pavement design location are borrowed from other data collection sites that exhibit similar traffic loading and classification properties.

The data coverage of traffic data acquisition systems can vary widely from continuously operating to simple 48-hour (h) (or less) data coverage. Even for continuously operating data acquisition systems; however, data coverage may be limited by system malfunctions. These are detected by performing a number of data QC checks. This technology has evolved significantly in response to the needs of the LTPP program.[(2)] It is typically based on the repeatability of certain traffic patterns (e.g., the distribution of the gross vehicle weight of five-axle semitrailer trucks is used for WIM load data QC). Data that fail to pass these QC tests are considered suspect and should be excluded from the data coverage of these systems.

Hence, there is wide variation in traffic data availability and time coverage between pavement design sites. The challenge at hand is to determine the combination of traffic data acquisition technology and the time coverage required for particular pavement design situations. This issue needs to be addressed in light of the sensitivity of the pavement design and performance analysis to the level of traffic data input.

The objective of this study is to resolve this problem. A comprehensive approach is used for establishing the relationship between traffic data collection efforts (e.g., combination of traffic data acquisition technologies and length of time coverage) and the variability in the predicted pavement life using the NCHRP 1-37A design guide. Extended-coverage WIM data are used from the LTPP database to simulate these traffic data collection scenarios.

## REPORT ORGANIZATION

The report is organized in sections that address each of the tasks identified in the request for proposals (RFPs):

- Task 1. Literature review.
- Task 2. Identification of traffic data collection scenarios and knowledge gaps.
- Task 5. Definition of traffic data collection requirements.
- Task 6. LTPP data analyzed.

- Task 4. Sensitivity analysis of the NCHRP 1-37A design guide to traffic input.
- Task 7. Recommendations on the minimum traffic data collection effort required, given a desired reliability level.

Note that task 3 as described in the RFP involved submission of an interim report. Those findings were incorporated throughout this final report.

## LITERATURE REVIEW

The literature review focuses on two main areas:

- Methodologies used for obtaining traffic data input to pavement design and its variability as a function of the type of data available and its time coverage.
- Sensitivity of the pavement design process to the variability in traffic-load input.

In carrying out this review, emphasis was placed on the methodologies used for estimating traffic-load data as described in the 2001 *Traffic Monitoring Guide* (TMG)[3] and the recently completed NCHRP 1-39 study,[4] as well as the handling of traffic data input to the NCHRP 1-37A design guide.[5-7] The following paragraphs offer a summary of the literature reviewed.

Early work by Ritchie and Hallenbeck[8] described the relationship between sampling effort in terms of the number of weekdays of continuous ATR data available and the accuracy in estimating the average annual daily traffic (AADT). Using the central limit theorem produced the expression in equation 1 for the difference interval *d* between the true and the estimated AADT:

$$d = Z_{a/2} \frac{S_p}{\sqrt{n}} \qquad (1)$$

Where:

| | | |
|---|---|---|
| $d$ | = | Difference interval between the true and the estimated AADT. |
| $Z_{a/2}$ | = | Standard normal deviate at a confidence level (1-$a$). |
| $S_p$ | = | Standard deviation in the population of daily traffic volumes. |
| $n$ | = | Number of weekdays averaged to estimate the AADT. |

Accordingly, the accuracy in predicting AADT increases with the number of days used in establishing the mean. Seasonal factors for each month, denoted by $\beta$, were derived using two alterative methods. First, a zero-intercept, regression-based method shown in equation 2 was used:

$$AADT = \beta\, VOL + \varepsilon \qquad (2)$$

Where:

| | | |
|---|---|---|
| $AADT$ | = | Average annual daily traffic. |
| $VOL$ | = | Daily vehicle volume count obtained by averaging the counts for 3 weekdays (e.g., Tuesday through Thursday). |
| $\beta$ | = | Seasonal factors for each month. |
| $\varepsilon$ | = | Error term. |

Second, a simple ratio-based method shown in equation 3 was used:

$$\frac{AADT}{VOL} = \beta + u \tag{3}$$

Where:

- $AADT$ = Average annual daily traffic.
- $VOL$ = Daily vehicle volume count obtained by averaging the counts for 3 weekdays (e.g., Tuesday through Thursday).
- $\beta$ = Seasonal factors for each month.
- $u$ = Error term.

It was rationalized that the second method avoided the problem of heteroscedasticity (a condition where the variance in the regression error $\varepsilon$ depends on the magnitude of the independent variable *VOL*); therefore, it was deemed preferable for the first method, and later it was adopted by the American Association of State Highway and Transportation Officials (AASHTO).[9] Statistics for these monthly ratios were calculated for groups of roads in Washington State organized by geographic region and highway functional class.

The AASHTO Joint Task Force on Traffic Monitoring Standards proposed the following method for estimating AADT from short-term daily traffic volume (i.e., ATR) counts:

- Compute the average day of week (DOW) for each month (for example, an average Monday or Tuesday).
- Compute an annual average value for that DOW.
- Compute an average of the seven DOWs to arrive at the AADT.

This method is expressed mathematically as in equation 4.

$$AADT = \frac{1}{7}\sum_{i=1}^{7}\left[\frac{1}{12}\sum_{j=1}^{12}\left(\frac{1}{n}\sum_{k=1}^{n} VOL_{ijk}\right)\right] \tag{4}$$

Where:

- $AADT$ = Average annual daily traffic.
- $VOL_{ijk}$ = Daily traffic volume for day $k$ of DOW $i$ and month $j$.
- $i$ = DOW ranging from 1 to 7 (i.e., Monday through Sunday).
- $j$ = Month of the year ranging from 1 to 12 (i.e., January through December).
- $n$ = Number of data days from a particular DOW used in computing the average of that DOW in a particular month (maximum of five).
- $k$ = Data day used in computation.

This approach limits the bias that would result from simply averaging traffic volumes for the days of the year available. In implementing this approach, holidays and the days that precede and follow them should be excluded. The AASHTO procedure is the one recommended by the 2001 TMG. Accordingly, monthly adjustment factors (*MAF* or *M*) are calculated as in equation 5.

$$MAF = M = \frac{AADT}{VOL} \tag{5}$$

Where:

| | | |
|---|---|---|
| *MAF* | = | Monthly adjustment factor. |
| *M* | = | Monthly adjustment factor. |
| *AADT* | = | Average annual daily traffic. |
| *VOL* | = | Average daily volume count, computed by one of the two alternative methods using either the simple averaging approach or the AASHTO approach. |

Finally, AASHTO recommended an averaging procedure for estimating missing traffic volume data. For example, if the traffic volume for a Wednesday is missing, it can be estimated as equal to the average of the available traffic volumes for the other Wednesdays in a particular month. Similarly, estimating missing vehicle classification data would involve averaging the volume counts by class or groups of similar classes for the same days in the month. Furthermore, missing WIM data can be estimated from the vehicle classification data obtained this way and the frequency distribution of axle loads by axle configuration available for the same days of the month.

A Federal Highway Administration (FHWA)-funded study used continuous ATR, AVC, and WIM data from traffic monitoring sites to compute:

- AADT.
- Vehicle miles traveled (VMT).
- AADT by vehicle class.
- VMT by vehicle class.
- ESALs.

The study examines the sensitivity of the computed statistics to various simulated sampling schemes and factoring procedures.[10] Seven factoring procedures were described for computing AADT from ATR (vehicle count) data, which are listed in table 3 in order of increasing accuracy and complexity.[10]

**Table 3. Accuracy of AADT predictions as a function of factoring procedure.[10]**

| No. | Factoring Procedure | Involves | Mean Absolute Error (percentage) | Average Percentage Error | $P(e > 0.2)$ (percentage) |
|---|---|---|---|---|---|
| 0 | Unfactored | – | 12.4 | −0.6 | 18.2 |
| 1 | Separate month and DOW (MDW) | Set of 12 monthly factors and another set of 7 DOW factors (total of 19) | 7.5 | −0.5 | 6.2 |
| 2 | Combined month and average weekday (CMAWD) | Set of average weekday and average weekend factors for each month (total of 24) | 7.6 | +0.4 | 5.9 |

**Table 3. Accuracy of AADT predictions as a function of factoring procedure (continued).**

| No. | Factoring Procedure | Involves | Mean Absolute Error (percentage) | Average Percentage Error | $P(e > 0.2)$ (percentage) |
|---|---|---|---|---|---|
| 3 | Separate week and DOW (SWDW) | Set of 52 weekly factors and another set of 7 DOW factors (total of 59) | 7.5 | −0.9 | 6.0 |
| 4 | Combined month and DOW (CMDW) | Set of 7 DOW factors for each month (total of 84) | 7.4 | −0.2 | 5.8 |
| 5 | Combined week and average weekday (CWAWD) | Set of average weekday and weekend factors for each week of year (total of 104) | 7.3 | +0.5 | 5.1 |
| 6 | Specific day (SD) | Set of day factors for each day, (midnight-to-midnight) of the year (total of 365) | 7.1 | +0.2 | 5.1 |
| 7 | Specific day with noon-to-noon factors (SDNN) | Similar to the one above, except counts are noon-to-noon | 7.0 | +0.3 | 4.8 |

This study recommended that procedure 4 (the CMDW method highlighted in table 3) is a good compromise between accuracy and complexity. This is the same method recommended by the 2001 TMG.[3] Accordingly, equation 6 shows the combined monthly and DOW factor for month *i* and DOW *j* at ATR station *l*, denoted by $CMDWF_{ijl}$.

$$CMDWF_{ijl} = \frac{AADT_l}{MADW_{ijl}} \tag{6}$$

Where:

$CMDWF_{ijl}$ = Combined month and day of week factor for month *i* and *DOW j* at station *l*.
$AADT_l$ = Average annual daily traffic at station *l*.
$MADW_{ijl}$ = Average traffic volume for month *i* and *DOW j* at station *l*.

In applying this procedure, it is recommended to exclude weekdays close to holidays (e.g., the Friday after Thanksgiving), although these days should be included in computing the AADT. If instead of vehicle counts, conventional axle counts are available, additional axle factoring would be necessary to convert axle counts to vehicle counts.

The traffic patterns established from continuously operating ATR sites can be used to compute AADT from short-term volume counts at other comparable sites.[10] Comparable sites are established on the basis of roadway functional class. Short-term counts should be taken over at least a 24-h period and preferably over multiple 24-h periods, although the improvement in predicting AADT from 24 to 48 weekday-h samples was marginal, producing a reduction in absolute error of 1 percent. The procedures described for factoring ATR data to obtain AADT[10] also applies for factoring AVC data to obtain the AADTT by truck class. The essential difference is that the counts are per vehicle class rather than for all classes collectively. A subsequent study examined the effect of the traffic data collection effort and methodology used in obtaining the traffic input necessary for forecasting cumulative ESALs and the resulting difference in pavement life predictions and life-cycle pavement costs.[11]

The 2001 TMG recommends collecting traffic volume data through a combination of a limited number of continuously operating reference ATRs and a larger number of shorter duration coverage ATRs.[3] Coverage ATRs should record data over at least 24 h and preferably more than 48 h using systems that summarize the data hourly. These short-duration counts require adjustments to reduce the effects of temporal bias. Adjustment factors are developed for particular months and DOWs by analyzing data from continuously operating reference ATR stations. Data from these stations are combined into groups of similar characteristics, either subjectively (e.g., in terms of geographic location or roadway functional class) or preferably through statistical clustering techniques. Appendix 2-b of the 2001 TMG gives an example of clustering in identifying ATR sites with similar MAFs using the Statistical Analysis System (SAS®) statistical package.[3,12]

AVC counts are collected following principles similar to those used for collecting ATR counts. The main difference is that seasonal traffic volume adjustment factors (monthly and daily) are developed for three or four broad vehicle classes (passenger cars, single-unit trucks, single-trailer trucks, and multitrailer trucks) rather than for all vehicles collectively. This is one of the major differences of the 2001 TMG compared to earlier TMG versions (1992 and 1995), and it was introduced to account for the seasonal variation in traffic volume patterns of various classes. These seasonal factors are developed by analyzing data from continuously operating reference AVC stations representing the traffic conditions of the selected roadway groups. These groups can be established subjectively (e.g., based on roadway functional class) or through clustering techniques, although no particular example for doing so is given in the TMG. Shorter duration AVC counts are to cover, at a minimum, 48 consecutive hours, with a recommended monitoring cycle of 6 years. It is suggested that an improvement of between 3 and 5 percent in the accuracy of predicting annual average traffic volumes can be achieved by increasing the duration of classification counts from 24 to 48 h.[13] Low-volume roads exhibited an even higher increase in accuracy because of the higher variation in daily traffic counts.[10] The only exception to the 48-h data collection recommendation is made for urban areas, where traffic congestion imposes variable vehicle speeds. In such situations, it is allowable to collect vehicle classification data over shorter periods of time (e.g., 15 minutes (min)) during which traffic is detected to be moving at a constant speed. The AADTT for vehicle class $c$ ($AADTT_c$) is computed using equation 7, an expression similar to the one for AADT in equation 4.

$$AADTT_c = \frac{1}{7}\sum_{i=1}^{7}\left[\frac{1}{12}\sum_{j=1}^{12}\left(\frac{1}{n}\sum_{k=1}^{n} AADTT_{ijkc}\right)\right] \qquad (7)$$

Where:

| | | |
|---|---|---|
| $AADTT_c$ | = | Average annual daily truck traffic for truck class $c$. |
| $i$ | = | DOW ranging from 1 to 7 (i.e., Monday through Sunday). |

$j$ = Month of the year ranging from 1 to 12 (January through December).
$n$ = Number of times data from a particular DOW is available for computing the average in a given month (i.e., 1, 2, 3, 4, or 5).
$AADTT_{ijkc}$ = Average annual daily truck traffic volume for vehicle class $c$, day $k$ of DOW $i$, and month $j$.
$k$ = Data day used in computation.

Consequently, adjustment factors are developed from continuously operating AVC sites for a particular vehicle class $c$, DOW $i$, and month $j$ to AADTT for that vehicle class at location $l$. They are extensions of equation 6, which by dropping the subscript $l$ for the sake of simplicity, is expressed as equation 8.

$$CMDWTF_{ijc} = \frac{AADTT_c}{MADWT_{ijc}} \tag{8}$$

Where:

$CMDWTF_{ijc}$ = Combined month-DOW factor for truck class $c$, DOW $i$, and month $j$.
$AADTT_c$ = Average annual daily truck traffic for truck class $c$.
$MADWT_{ijc}$ = Daily average traffic count by month by DOW for truck class $c$, DOW $i$, and month $j$.

The 2001 TMG[(3)] gives a slightly different expression, shown in equation 9**,** for the difference interval $d$ between the true and the estimated AADT and the one used by Ritchie and Hallenbeck.[(8)]

$$d = t_{1-a/2,\, n-1} \frac{S}{\sqrt{n}} \tag{9}$$

Where:

$d$ = Difference interval between the true and the estimated AADT.
$t_{1-a/2,\, n-1}$ = Standard deviate of the Student's t-distribution at a confidence level (1-a) for n - 1 degrees of freedom.
$S$ = Coefficient of variation in the daily traffic volumes.
$n$ = Number of days averaged to estimate the AADT.

The reason for using the Student's t-distribution instead of the normal distribution is that the coefficient of variation in the daily traffic volume population is not really known from the relatively small number of days sampled.

The 2001 TMG defines truck load data collection as the means of obtaining the distribution of axle loads by axle configuration and vehicle class for selected roadway groups.[(3)] This information can be obtained only with WIM systems. Establishing roadway groups with comparable axle-load distribution patterns is essential in maximizing the benefit of the limited number of WIM sites typically available in a jurisdiction. These roadway groups need not be identical to the roadway groups identified with reference to the vehicle classification data obtained from AVC sites. They can be established subjectively (e.g., based on roadway functional class and predominant commodity being carried) or through clustering techniques, although no particular example for doing so is given in the TMG. In establishing the number of WIM sites *n* required per roadway group, the expression in equation 10 is used.

$$n = t_{a/2}{}^{2}\ \frac{S^2}{D^2} \tag{10}$$

Where:

*n* = Number of times data from a particular DOW is available for computing the average in a given month.

*t* = Value of the Student's t-distribution for the selected level of confidence $\alpha$.

*S* = Standard deviation established from a sample of a traffic quantity (e.g., gross vehicle weight (GVW) or ESAL for FHWA class 9 vehicles).

*D* = Desired accuracy range in this traffic quantity.

Based on this approach and by specifying values of *D* for GVW and ESAL for class 9 vehicles of 0.19 and 0.13, respectively, a minimum required number of six WIM sites per roadway group is estimated (at 95 percent confidence). It is emphasized that it is more important to have accurate rather than continuous WIM data, although it is preferable to have at least one of the six WIM sites in each roadway group operating continuously. This allows establishment of daily, weekly, and seasonal patterns in the traffic-load data for the particular roadway group. Where continuous operation is not possible, WIM systems should operate for at least a period of 7 continuous days to capture daily variations.

NCHRP 1-37A is the main study for the development of a new pavement design guide. (See references 1, 5, 6, and 7.) The mechanistic pavement damage computations in the NCHRP 1-37A design guide require traffic-load spectra, defined as the number of axle passes by load level and axle configuration. In practice, this axle-load spectra information is synthesized by combining data from WIM, AVC, and ATR systems, including either the specific pavement site or other regional/representative traffic data collection sites. Table 4 (of this report) outlines the actual combination of the technology/data used in establishing the load spectra defines four levels of traffic input, as described in appendix AA in the final report.[1]

**Table 4. Traffic input levels in the NCHRP 1-37A design guide.**

| **Data Element/Input Variables** | **Traffic Input Levels** | | | |
|---|---|---|---|---|
| | **1** | **2** | **3** | **4** |
| WIM data: Site/segment specific | X | – | – | – |
| WIM data: Regional representative | – | X | X | – |
| WIM data: National representative weight (LTPP) | – | – | – | X |
| AVC data: Site/segment specific | X | X | – | – |
| AVC data: Regional representative | – | – | X | – |
| AVC data: National representative classification (LTPP) | – | – | – | X |
| ATR data: Site specific | – | – | X | X |

It should be noted that the NCHRP 1-37A design guide makes no explicit recommendations on the length of data coverage for these data sets that would produce "reliable" estimates of the required input elements. It should also be noted that these traffic input levels are not rationally related to the input levels identified by the NCHRP 1-37A design guide for other groups of input (e.g., layer properties and environmental data). A more detailed description of the traffic input levels and the technology required for obtaining them is given in table 5.

**Table 5. Detailed description of the NCHRP 1-37A design guide traffic data input levels.**

| NCHRP 1-37A Design Guide Traffic Input Levels | Description |
|---|---|
| 1 | Requires site-specific vehicle classification and axle-load data. The traffic data measured at the site includes counts, classification, and weighing by lane and direction over a sufficiently long period of time to reliably establish patterns in these traffic inputs. It is possible only with an onsite WIM installation, and it is recommended for use in designing most high-volume highways. |
| 2 | Requires site-specific vehicle classification data, but it relies on representative (e.g., regional) axle weight data by vehicle class and axle configuration. The regional axle-load data are to be obtained from WIM installations on roadways that exhibit similar traffic-load patterns as the site in question. It is possible with an onsite AVC installation and sufficient WIM data from installations that have similar traffic-load patterns. Recommended for roadways of lesser importance. |
| 3 | Requires site-specific traffic volume counts and percentage truck data. It relies on representative (e.g., regional) vehicle classification and axle weight data. These regional data are to be obtained from AVC and/or WIM installations from sites that exhibit similar traffic distributions and load patterns as the site in question. It is possible with an onsite ATR installation and onsite truck percentage counts. The latter can be either automated (e.g., vehicle length based algorithm) or manual. Recommended for roadways of even lesser importance. |
| 4 | Similar to level 3 input, with the only difference being the lack of regional classification and load data. This approach resorts to default (i.e., national average) vehicle classification and axle-load distributions. Suggested as the minimum possible traffic input level for roadways of very low importance. |

The axle-load spectra information in the NCHRP 1-37A design guide is synthesized from input arranged in four main modules:

1. Traffic Volume:

- Average annual two-directional, multilane daily truck traffic (i.e., FHWA classes 4 through 13).
- Number of lanes in the design direction.
- Percentage of trucks in the design direction.

- Percentage of trucks in the design lane.
- Operational speed.

Note that the first of these input components can be updated annually through a specified linear or compound growth rate (see next input module), while the remaining four are treated as constant throughout the pavement design life.

2. Traffic Volume Adjustment Factors:

- Monthly adjustments factors (MAFs as defined by equation 5) for each month per truck class (FHWA classes 4 through 13) with a default of 1.00.
- Truck class distribution, defined in terms of the percentage of the traffic volume by vehicle class (4 through 13).
- Hourly frequency distribution.
- Traffic growth factors, either the same for all classes or per individual vehicle class.

Note that all of these factors are treated as constant throughout the pavement design life.

3. Axle-Load Distribution Factors:

- Load frequency distribution (i.e., percent axles by load level) by axle configuration, by month, and by truck class.

Note again that these factors are treated as constant throughout the pavement design life.

4. General Traffic Input:

- Number of axles by axle configuration and truck class.
- Axle/tire configuration, spacing, and tire inflation pressure.
- Wheelbase data.

Note that this input is also treated as constant throughout the pavement design life. A summary of the traffic input components, the size of the associated data tables, and the flow of calculations in the NCHRP 1-37A design guide software is given in table 6. The resulting number of axles by load level, axle configuration, and month is further disaggregated by the distribution of truck traffic volume through the typical day. It should be noted that no differentiation is made in traffic volumes by the DOW within each month. For flexible pavements, the NCHRP 1-37A design guide software considers the following distresses:

- Fatigue cracking (bottom-up alligator and top-down longitudinal).
- Plastic deformation as a result of nonrecoverable strain in all pavement and subgrade layers.
- Roughness (international roughness index (IRI)).

**Table 6. NCHRP 1-37A design guide flow of calculations in assembling axle-load spectra.**

| Traffic Input Component | Main Data Element | Input Array Size | Calculation and Result |
|---|---|---|---|
| 1 | AADTT in the design lane | 1 | – |
| 2 | Distribution of trucks by class (FHWA 4 through 13) | 1 by 10 | 1 by 2 = annual average daily number of trucks by class |
| 3 | MAFs by truck class | 12 by 10 | 1 by 2 by 3 = adjusted average daily number of trucks by class, by month |
| 4 | Number of axles by axle configuration (single, tandem, triple, quad), by truck class | 4 by 10 | 1 by 2 by 3 by 4 = average number of axles by axle configuration, by month |
| 5 | Load-frequency distribution (percentage) by axle configuration, by month, by truck class | 4 by 12 by 10 by 41 | 1 by 2 by 3 by 4 by 5 = number of axles by load range, by axle configuration, by month |

The NCHRP 1-37A design guide considers two types of portland cement concrete (PCC) pavement structures: jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP). JPCP can be either doweled or nondoweled. The following distress mechanisms are considered:

- Fatigue transverse cracking, both bottom-up and top-down (JPCP).
- Joint faulting (JPCP).
- Punchouts (CRCP).
- Roughness (JPCP and CRCP).

Cracking-related damage is accumulated for both flexible and rigid pavements using Miner's hypothesis. This consists of summing the damage ratios calculated by dividing the actual number of strain cycles by the number of cycles that would cause fatigue failure at this strain level.

$$Damage = \sum_i \sum_j \sum_k .. \frac{n_{ijk}}{N_{ijk}} 100 \qquad (11)$$

Where:

$Damage$ = Damage (percentage) associated with particular distress mechanism.

$n_{ijk}$ = Actual number of pavement response cycles from axle configuration *i*, load level *j* over month *k*.

$N_{ijk}$ = Number of pavement response cycles that cause failure from axle configuration *i*, load level *j* over month *k*.

$i$ = Axle configuration.

| | | |
|---|---|---|
| $j$ | = | Load level. |
| $k$ | = | Month. |

Plastic deformation of flexible pavements and faulting damage of rigid pavements are simply additive. More information on the actual damage functions used for each distress mechanism is given in the final report for the NCHRP 1-37A design guide.[1]

NCHRP study 1-39[4] developed a methodology for processing the output of a combination of AVC and WIM systems in a jurisdiction to synthesize the axle-load spectra input to the NCHRP 1-37A design guide for a particular pavement design site.[4] This methodology relies on factoring the available traffic data at that site using the temporal axle-load and vehicle classification distribution patterns from similar sites in the jurisdiction (e.g., State) as prescribed by the 2001 TMG.[3] The type of technology (AVC and WIM) and the length of coverage involved at these traffic data collection sites define the level of traffic input. This methodology is implemented in a software package called TrafLoad. The input of TrafLoad is in terms of the standardized output of AVC and WIM systems, as the hourly summary C-records or 4-cards and the individual vehicle W-records or 7-cards, respectively. The format of the standard cards is given in appendix A. These data are assumed to have passed independent QC tests before inputting into TrafLoad. In addition, the user needs to input the following information:

- Vehicle classification scheme in the jurisdiction (the 13 FHWA classes or others).
- Any aggregation of these vehicle classes.
- Grouping of traffic data sites in the jurisdiction with respect to vehicle classification distributions (e.g., the 17 truck traffic classes (TTC) distinguished in the NCHRP 1-37A design guide).
- Grouping of traffic data sites with respect to axle-load distributions (truck weight road groups (TWRGs) based on indicators of pavement loading or functional class.
- Seasonal load spectra by either month or month and DOW.

The seasonal load spectra is used in factoring incomplete sets of load spectra, as explained later. It should be noted that some of this input, especially the site grouping and the seasonal load spectra computations, may require considerable preprocessing of the available WIM and AVC data before running TrafLoad.

TrafLoad distinguishes several levels of traffic input, depending on the load and classification data available at a particular pavement design site/lane. In terms of WIM data availability, there are three pavement design levels:

- Level 1. Site-specific, high-quality WIM data over periods of time sufficient to estimate monthly or monthly DOW load spectra at the site/design lane (12 sets or 12 × 7 = 84 sets). In this case, “sufficient” implies a minimum length of continuous coverage of high-quality WIM data for at least each of the seven DOW in each month, which is, in effect, continuous WIM data coverage over a year. These data are calculated externally by the user and supplied as input to TrafLoad. Where partial sets of WIM data are available (e.g., missing DOW or months), TrafLoad estimates them through factoring, as explained later.

- Level 2. No site-specific WIM data are available; however, the site can be clearly assigned to a TWRG for which level 1 WIM data are available.

- Level 3. No site-specific WIM data are available, and the site cannot be clearly assigned to a TWRG. In such cases, jurisdiction-wide averages of load spectra need to be used.

It should be noted that since levels 2 and 3 lack site-specific WIM data, their assignment to one of the TWRGs is, by necessity, subjective.

For complete year-long level 1 WIM data, TrafLoad produces all of the necessary input to the NCHRP 1-37A design guide. For incomplete level 1 WIM data, TrafLoad uses DOW and monthly factor ratios based on complete level 1 WIM sites belonging to the same TWRG. This is done in terms of the pavement damage affected by month and DOW as indexed by the average ESALs per vehicle (AEPV). As shown in equation 12, the daily adjustment ratio (*DAR*) for a particular DOW *d* is computed as the average over the number of months available *m* of the ratio of the *AEPV* for that missing DOW divided by the monthly *AEPV*:

$$DAR_{ipd} = \left[ Average_m \left( \frac{AEPV_{impd}}{AEPV_{imp}} \right) \right]^{1/4} \qquad (12)$$

Where:

| | | |
|---|---|---|
| $DAR_{ipd}$ | = | Daily adjustment ratio for WIM TWRC group *i*, pavement type *p*, and DOW *d*. |
| $Average_m$ | = | Average for month *m*. |
| $AEPV_{impd}$ | = | Average ESAL per vehicle for WIM TWRG group *i*, month *m*, pavement type *p*, and day *d*. |
| *i* | = | WIM TWRG group. |
| *p* | = | Pavement type (i.e., flexible versus rigid). |
| *d* | = | DOW. |
| *m* | = | Month. |

These ratios allow estimation of the number of vehicles by class for missing DOWs, accounting for the relative pavement damage affected in these DOWs. The monthly adjustment ratios (MARs) for a missing month $m'$ is computed from the available months *m* using equation 13.

$$MAR_{ipm} = \left[ Average_m \left( \frac{AEPV_{ipm}}{AEPV_{ip}} \right) \right]^{1/4} \qquad (13)$$

Where:

| | | |
|---|---|---|
| $MAR_{ipm}$ | = | Monthly adjustment ratios, WIM TWRG, pavement type, and month. |
| $Average_m$ | = | Average month. |
| $AEPV_{impd}$ | = | Average ESAL per vehicle for WIM TWRG group *i*, month *m*, pavement type *p*, and DOW *d*. |
| $AEPV_{ip}$ | = | Average ESAL per vehicle for WIM TWRG group *i*, pavement type *p*. |

This allows estimation of the number of vehicles for missing months, accounting for the relative pavement damage affected in these months. Finally, load spectra adjustment ratios are computed by load range using equation 14.

$$A_{ijmk} = \sum_{d} \frac{MADW_{imd}}{\sum_{d} MADW_{imd}} A_{ijmkd} \tag{14}$$

Where:

| | | |
|---|---|---|
| $A_{ijmkd}$ | = | Load spectrum value corresponding to load range *k*, vehicle class *i*, axle type *j*, month *m*, and day *d*. |
| $MADW_{imd}$ | = | Monthly average DOW traffic volumes for WIM TWRG group *i*, month *m*, and day *d*. |
| $A_{ijmk}$ | = | Load spectrum value corresponding to load range *k*, vehicle class *i*, axle type *j*, and month *m*. |
| $d$ | = | Data day used in computation. |

In terms of AVC data availability, TrafLoad distinguishes the following levels:

- *Level 1*. Continuous AVC data are available for at least 1 week for each of 12 months per year. This level is further subdivided into 1A and 1B for site-specific AVC data and adjacent site/same route AVC data, respectively.

- *Level 2A*. Sites for which continuous AVC counts are available over a period of at least 48 weekday hours.

- *Level 2B*. Sites where continuous manual vehicle classification counts are available over a period of at least 6 weekday hours.

- *Level 3A*. Sites where only site-specific vehicle count data are available (no vehicle classification data are available).

- *Level 3B*. Other.

TrafLoad processes the AVC data from level 1A sites to establish monthly, daily, and hourly trends in vehicle classification counts. This is done in the following sequence:

1. For each vehicle class i and lane l, the average hourly vehicle count AADTil is computed by month and DOW (total of 12×7×24 = 2016 average hourly counts per vehicle class).

2. Average DOW volumes are computed by vehicle class by month MADWil, by summing the hourly volumes within each DOW.

3. Annual average DOW AADWil is computed by averaging the MADWil values for 12 consecutive months.

4. Annual average daily traffic for vehicle class i and lane l AADTil is computed by averaging the seven AADWil values computed above.

This information serves two functions: (1) It contributes input to the NCHRP 1-37A design guide for analyzing the particular pavement site, and (2) it provides traffic distribution trends for factoring data from similar sites with lesser AVC information (e.g., AVC sites 1B, 2, and 3). Factoring in TrafLoad is carried out by dividing the short-term count by a traffic ratio. This is a departure from the standard practice that involves multiplying the short-term count by a traffic factor as suggested by AASHTO and the 2001 TMG (i.e., table 3 and equations 6 and 10). The difference between these two apparently equivalent factoring approaches arises when averaging factors versus averaging ratios from a group of sites. The rationale for selecting ratios is that the target value (e.g., AADTT) is in the denominator, and therefore, averaging ratios from a group of AVC sites with the same AADTT would yield the intuitive value of 1.00.[(4)]

As explained next, this study follows the NCHRP 1-37A design guide approach in identifying four traffic data collection input levels by a *combination* of the traffic data collection technologies involved for a particular site (WIM, AVC, or ATR). It identifies a number of traffic data collection scenarios by extending these four levels identified in table 4 by specifying the length of the site-specific data coverage. Furthermore, this study uses clustering techniques for identifying regional vehicle classification groups and regional axle-load distribution groups. These yield the second and fifth traffic input components to the NCHRP 1-37A design guide, which are in frequency distribution format, as described in table 6; therefore, it is not necessary to establish regional traffic data sets in the conventional TRWG sense, nor is it necessary to use the rather outmoded ESAL concept for doing so.

# CHAPTER 2. IDENTIFY SCENARIOS AND KNOWLEDGE GAPS

## METHODOLOGY FOR IDENTIFYING KEY PAVEMENT DESIGN SCENARIOS

Pavement design requirements are a function of the importance of a roadway facility. It is traditionally defined in terms of functional classification (Interstate, U.S. highway, State highway, or secondary road), which to a large extent reflects the traffic volumes and axle loads that need to be accommodated. Importance, in turn, defines the acceptable reliability in the pavement design of a facility and, hence, dictates the required quality of input data for both materials and traffic. Reliability is defined as the probability that a pavement section will not fail before the end of the analysis period is reached. Table 7 gives the pavement design reliability levels established by the 1993 edition of the AASHTO design guide, which provides a guideline for establishing reliability levels in the current study. [14] If the variation in the NCHRP 1-37A design guide output is known, appropriate levels of reliability of input can be selected. For traffic data input, this reliability will define the type of monitoring equipment and the length of data coverage required. This is the methodology that will be followed in establishing the traffic data collection scenarios required for specific pavement design applications.

**Table 7. Suggested levels of reliability for roads of various classes.**

| Functional Class | Urban (percentage) | Rural (percentage) |
|---|---|---|
| Interstate and other freeways | 85–99.9 | 80–99.9 |
| Principal arterials | 80–99 | 75–95 |
| Collectors | 80–95 | 75–95 |
| Local | 50–80 | 50–80 |

Results based on a survey of the AASHTO Pavement Design Task Force.

As described later, the traffic data collection scenarios will be identified by expanding the four levels of traffic input defined by the NCHRP 1-37A design guide (table 4) to account for varying time lengths of coverage in the site-specific traffic data.

## KNOWLEDGE GAPS IN THE SENSITIVITY OF THE PAVEMENT DESIGN PROCESS TO TRAFFIC INPUT

The majority of literature in this area treats traffic input in terms of cumulative ESALs and concerns the performance-based design process of the 1993 AASHTO design guide.[14] This process treated uncertainty in predicting performance as the present serviceability index (PSI) by artificially increasing the estimated number of ESALs. This was done by adding to the logarithm of the estimated ESALs, the product of the standard normal deviate corresponding to the desired reliability multiplied by the standard error in predicting PSI. This increased significantly the number of ESALs input to the empirical performance equations (e.g., for 85 percent confidence and a standard error in predicting PSI of 0.5, the logarithm of ESALs was increased by $1.037 \times 0.5 = 0.5185$, which arithmetically is a factor of 3.3). Although this is not directly applicable to the design philosophy of the new NCHRP 1-37A design guide, it does reflect the significant uncertainties in quantifying traffic loading.

There are few exceptions in the literature where axle-load spectra are used directly in damage calculations, such as the rigid pavement design procedure developed by the Portland Cement Association.[15] This procedure uses axle-load spectra and computes the resulting slab fatigue damage and joint erosion through a Miner's hypothesis-type accumulation algorithm. Experience with this method shows that:

- A large number of light axle-load passes causes negligible damage.
- A significant percentage of the damage is caused by the few passes of heavy (especially over the legal limit) axle loads.
- Layer thickness indisputably affects damage accumulation.

The third fact reemphasizes the need for performing any pavement design sensitivity analysis of traffic loads by considering the thickness of the layers involved.

In summary, the knowledge gap in this area is considerable. Little is known about the sensitivity of the new NCHRP 1-37A design guide design process to traffic input. For a particular pavement type and combination of layer thicknesses, there is a need to study the extent of variation in pavement life predictions by distress type, in response to variations in traffic input.

## KNOWLEDGE GAPS IN DATA VARIATION FROM DIFFERENT TRAFFIC COLLECTION SCENARIOS

As summarized in the literature review, considerable work has been done to analyze the effects of various traffic data collection scenarios on the accuracy of traffic volume estimates, such as AADT and AADTT, as well as cumulative pavement damage, such as ESALs.[2,11-12] The common method used in these studies is simulating traffic data collection scenarios from continuous traffic records and comparing the traffic estimates to the ground truth, thereby establishing accuracy levels. There has been little work, however, on the accuracy in axle-load distribution estimates from short-term WIM data and particularly on the ability to capture the few high axle loads that cause disproportionately high pavement damage. Hence, there is some literature related primarily to the first four traffic input components to the NCHRP 1-37A design guide (table 6), but little is available on the fifth traffic input component, the distribution of axle loads. As described later in "LTPP Data Analysis" (chapter 4), extended-coverage WIM data from LTPP sites will be used to simulate the effects of various sampling scenarios on the traffic data input components.

## SUMMARY

Two main knowledge gaps were identified in selecting a traffic data collection effort for particular NCHRP 1-37A design guide applications:

- Extent of variation in traffic data input with respect to the type of traffic data monitoring equipment and length of coverage available.
- Sensitivity of the NCHRP 1-37A design guide output to variations in traffic data input.

These knowledge gaps will be filled by analyzing data from the LTPP database and conducting a sensitivity analysis of the new NCHRP 1-37A design guide software output with respect to traffic input.

# CHAPTER 3. DEFINE TRAFFIC DATA COLLECTION REQUIREMENTS FOR EACH SELECTED APPLICATION

Traffic data collection requirements were based on the four levels of traffic monitoring technology defined in table 4 of this report based on Appendix AA of the final NCHRP 1-37A report.(1) Distinct scenarios were developed by defining the length of data coverage of the site-specific data. Seventeen traffic-sampling scenarios were selected, as shown in table 8, where *SS* denotes site-specific, *R* denotes regional, and *N* denotes national data. The third column of this table, highlighted by bold letters, specifies the time coverage of the site-specific data. The fourth column provides identification codes for these scenarios, consisting of two numbers separated by a dash; the first number indicates the NCHRP 1-37A design guide traffic input level, and the second number identifies the length of data coverage (e.g., scenario 2-1 signifies site-specific AVC data with a coverage of 1 month in each of 4 seasons plus regional WIM data). In selecting these scenarios, the following two main criteria were adhered to:

- WIM and AVC systems are typically fixed, and therefore, are likely to operate over longer periods of time than ATRs.
- Jurisdictions with neither AVC nor WIM data are unlikely to have extended time coverage of site-specific ATR counts.

**Table 8. Selected traffic data collection scenarios.**

| NCHRP 1-37A Design Guide Traffic Input Level | Traffic Data Source | Time Coverage of Site-Specific Data Over 1-Year Period | Scenario ID |
|---|---|---|---|
| 1 | **WIM Data = SS** | Continuous | 1-0 |
| | AVC Data = R | 1 month/4 seasons | 1-1 |
| | | 1 week/4 seasons | 1-2 |
| 2 | WIM Data = R | Continuous | 2-0 |
| | **AVC Data = SS** | 1 month/4 seasons | 2-1 |
| | | 1 week/4 seasons | 2-2 |
| | | 1 week | 2-3 |
| 3 | WIM Data = R | Continuous | 3-0 |
| | AVC Data = R | 1 month/4 seasons | 3-1 |
| | **ATR Data = SS** | | – |
| 4 | WIM Data = N | Continuous | 4-0 |
| | AVC Data = R | 1 week/4 seasons | 4-1 |
| | **ATR Data = SS** | 1 week | 4-2 |
| | | 1 weekday plus 1 weekend day | 4-3 |
| | WIM Data = N | Continuous | 4-4 |
| | AVC Data = N | 1 week/4 seasons | 4-5 |
| | **ATR Data = SS** | 1 week | 4-6 |
| | | 1 weekday plus 1 weekend day | 4-7 |

SS = Site-specific, R = Regional, N = National (NCHRP 1-37A design guide defaults)

As described later, representative regional (R) traffic input can be obtained by averaging data from sites with similar traffic characteristics. There are a variety of methods for establishing similarities in traffic characteristics, ranging from the purely subjective (e.g., same roadway functional class) to the fairly mathematical (e.g., clustering techniques).[3,17] The clustering approach was selected for identifying similarities between the LTPP sites selected for the detailed NCHRP 1-37A design guide analysis and the remaining extended-coverage LTPP sites. Similarities were established on the basis of vehicle classification distributions and tandem-axle load distributions. The average traffic element for each cluster defined the regional data input for each site. In simulating these scenarios, the default values provided in the NCHRP 1-37A design guide software were assumed to represent the national (*N*) traffic input. For each of these traffic data collection scenarios, the range in the traffic input elements to the NCHRP 1-37A design guide (table 3) are computed and the resulting range in pavement performance predictions by distress are estimated. This process is shown schematically in figure 1, where *S* symbolizes the standard deviation in a particular traffic data input element, in this case, load frequency, and $Z_a$ is the standard normal deviate (i.e., values for $Z_a$ will be selected in accordance to the desired reliability level as per table 9). For each sampling scenario and reliability level selected, the range in pavement life predictions by distress mechanism is obtained using the software for the NCHRP 1-37A design guide.

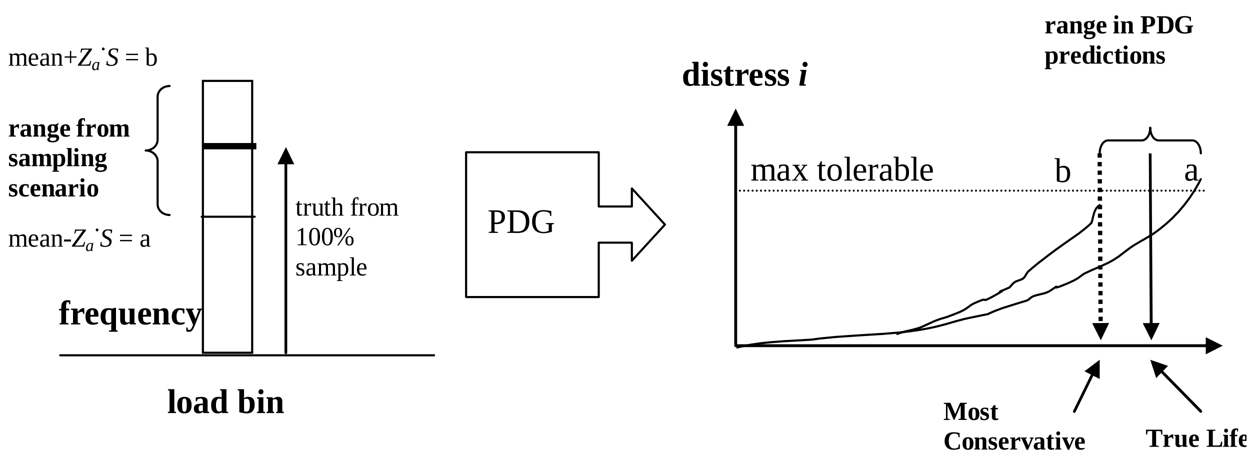



**Figure 1. Schematic of the sensitivity of distress predictions to load spectra input.**

This type of sensitivity analysis will be conducted for both flexible and rigid pavements under realistic structural conditions. This involves site-specific layer thicknesses as described in the LTPP database and environmental conditions as simulated by the NCHRP 1-37A design guide software. Layer moduli were specified in the same fashion for all sites simulated in order to keep the variation in nontraffic-related properties to a minimum. Incidentally, another study is needed to establish the sensitivity of the NCHRP 1-37A design guide design process to variations in layer properties, considering the traffic input as a constant. This would ensure that groups of input with comparable accuracy would be used in pavement design.

**Table 9. Relationship between two-sided probability of survival/failure and standard normal deviate in pavement life predictions.**

| **Percentage of Probability of Survival/Failure** | **Standard Normal Deviate $Z_a$** |
|---|---|
| 50/50 | 0.00 |
| 75/25 | 1.15 |
| 85/15 | 1.44 |
| 95/5 | 1.96 |
| 99.9/0.1 | 3.18 |

# CHAPTER 4. LTPP DATA ANALYSIS

The data necessary for filling the two knowledge gaps identified earlier were extracted from the LTPP database:

- Extended-coverage WIM data to allow simulation of the selected traffic data collection scenarios identified in table 8.
- Detailed structural data for the pavement sites selected to ensure realistic simulation of their performance under the selected traffic input scenarios.

The following subsections present:

- Data extraction from extended-coverage WIM sites in the LTPP database.
- Rationale for selecting several of these sites for the sensitivity analysis, while using the remainder to obtain the regional data sets necessary for factoring short-term, site-specific data in simulating the selected scenarios.
- Analysis conducted for establishing the regional traffic data sets.
- Methodology used for simulating each of the traffic data collection scenarios.

## LTPP WIM DATA EXTRACTED

The main criterion for selecting data from the LTPP database was the extent of WIM data coverage in terms of the total number of data days per year. A search of the LTPP database[16] was performed based on this criterion. Initially, a filter of 359 days per year or greater was selected (i.e., 2 percent of days per year missing). This resulted in a total of 58 sites, some involving multiple data years. To increase the number of sites available for analysis, a lower threshold filter was used involving WIM coverage of 299 days per year or greater (i.e., 20 percent of days per year missing). This resulted in a total of 178 sites, some involving multiple data years. The number of LTPP sites meeting these two criteria versus the number of data years available are plotted in figures 2 and 3, respectively. Figure 2, for example, suggests that 46 sites have more than 359 days per year of WIM data for 1 year; 6 sites do so for 2 years, and so on. Multiple years of data for the same site are advantageous because they allow for the establishment of traffic growth patterns. The data quality for these sites was deemed to be level E (i.e., the data had passed the quality control conducted by the State DOTs and the LTPP regional support contractor offices). To further ensure data quality, the LTPP quality assurance reports pertaining to these 178 sites were examined. They revealed no particular problems with any of them. These quality assurance reports were not appended here, but they are available on request.

The highest resolution of traffic data necessary for simulating the scenarios in table 8 is daily summaries, which are not contained in Data Release; therefore, data had to be retrieved from the CTDB. It contains traffic data at five levels of resolution:

- *Level 1*. Annual load/count summary records by axle (uploaded to the information management system database to become part of the periodic Data Release).
- *Level 2*. Annual loads by vehicle class and annual load spectra by truck type.
- *Level 3*. Daily summary traffic records.

- *Level 4*. Submitted traffic loading records (i.e., raw individual card-4 and card-7 data).
- *Level 5*. Additional traffic loading information.

Given the highest resolution of daily data desired for simulating the 17 traffic scenarios, level 3 WIM data were extracted from the CTDB for the 178 WIM sites for the data years identified. The data fields extracted are described in table 10. The data was in Microsoft® Access format. It contained the daily number of axle passes by truck class, axle type, and load bin as it combined axle weight and vehicle classification information.

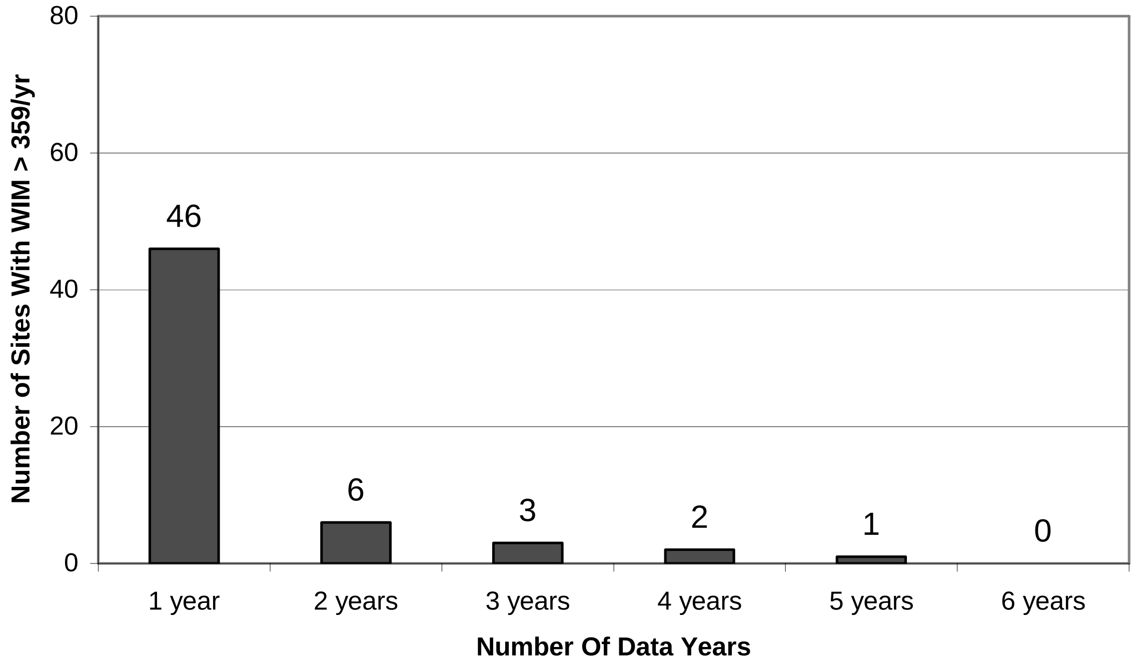



**Figure 2. LTPP sites with WIM data available for periods longer than 359 days per year.**[16]

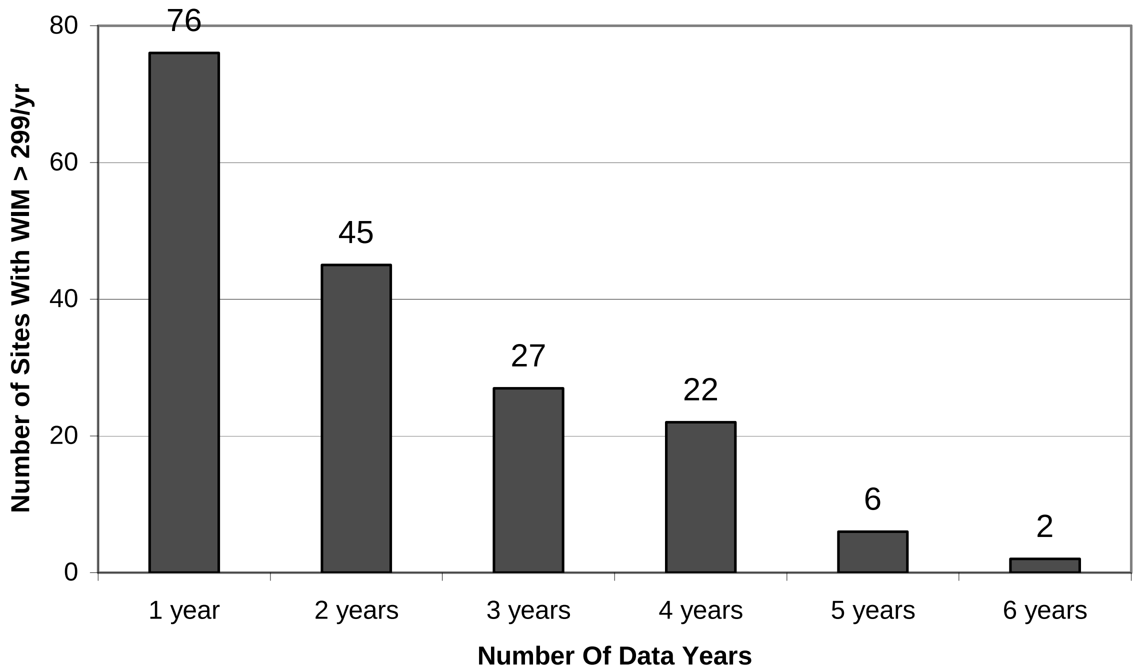



**Figure 3. LTPP sites with WIM data available for periods longer than 299 days per year.**[(16)]

**Table 10. Definition of variables extracted from the CTDB.**

| Variable Name | Definition |
|---|---|
| STATE_CODE | State/province ID |
| SHRP_ID | Test section LTPP identifier |
| LANE_TRF | Lane identifier, where 1 is the lane nearest the right-hand shoulder |
| DIR_TRF | Traffic direction (1, 2, 3, 4 indicate east, west, north, south, respectively) |
| VEH_CLASS | FHWA vehicle classes 1 through 13; 14 indicates “other,” 15 indicates “unknown” |
| AXLE_GROUP | Axle configuration (1, 2, 3, 4 indicate single, tandem, tridem, quad axles, respectively) |
| YEAR | Year the data were collected |
| MONTH | Month the data were collected |
| DAY | Day of week |
| RECORD_STATUS | QC code from A through E |
| AX_CT_01 to AX_CT_40 | Number of axle passes by load bin. Depending on axle type, these bins are: • Singles: AX_CT_01 is 0 to 4.44 kilonewtons (kN) (0 to 9,892 pounds force (lbf) • Tandems: AX_CT_01 is 0 to 8.89 kN (0 to 1999 lbf); subsequent bins are in increments of 907 kilograms (kg) (2,000 pounds (lb)). • Triples/Quads: AX_CT_01 is 0 to 13.34 kN (0 to 2999 lbf); subsequent bins are in increments of 13.35 kN (3001 lbf). |

## RATIONALE FOR SELECTING SITES FOR THE DETAILED SENSITIVITY ANALYSIS

A number of these extended WIM data coverage LTPP sites were selected for the detailed sensitivity analysis of the NCHRP 1-37A design guide with respect to the traffic input obtained from the simulated traffic data collection scenarios (table 8). The remaining sites were used for obtaining the regional traffic data sets (i.e., vehicle classification and axle-load distribution estimates for the detailed sensitivity analysis sites).

The following criteria were used for selecting sites for the detailed sensitivity analysis:

- WIM data coverage of preferably 299 days per year or greater.
- Availability of WIM data over several years to allow the study of the effect of traffic growth.
- Distribution of sites over a wide range of truck traffic volumes (i.e., AADTT) and structural thicknesses.

The latter was indexed by the structural number (SN) and the concrete slab thickness for flexible and rigid pavement sites, respectively. Figures 4 and 5 show the distribution of AADTT versus structural thickness for all of the extended-coverage WIM sites identified from the LTPP database for flexible and rigid pavements, respectively. For each pavement type, two AADTT intervals were identified.

For flexible pavements, two truck traffic volumes were defined:

- Fewer than or equal to 800 trucks/day/lane.
- More than 800 trucks/day/lane.

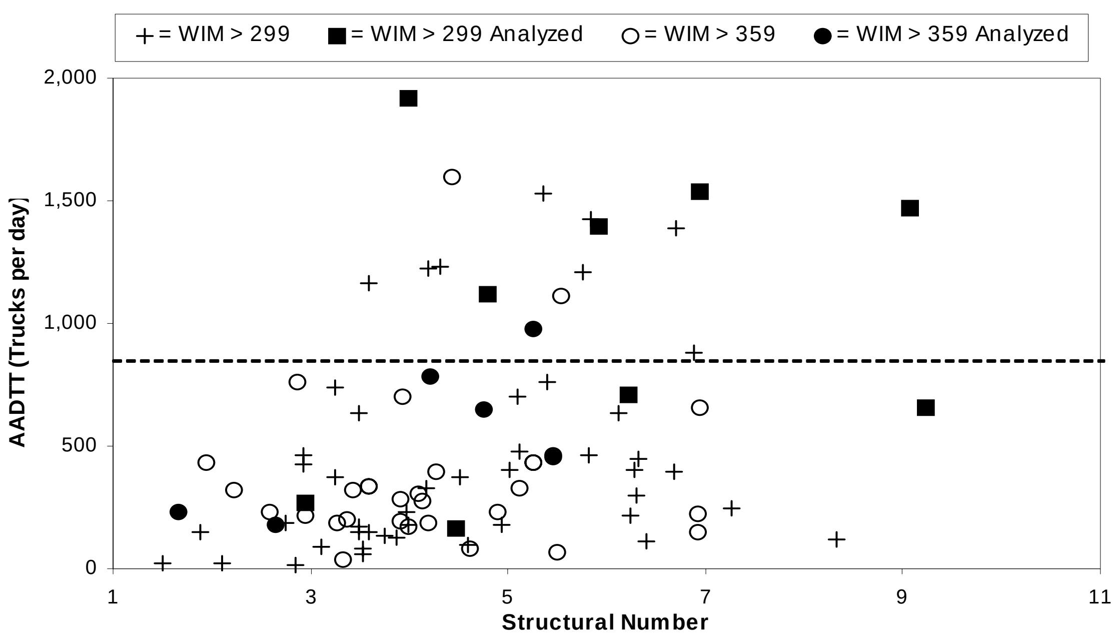



**Figure 4. Flexible pavement site selection by AADTT and structural number.**

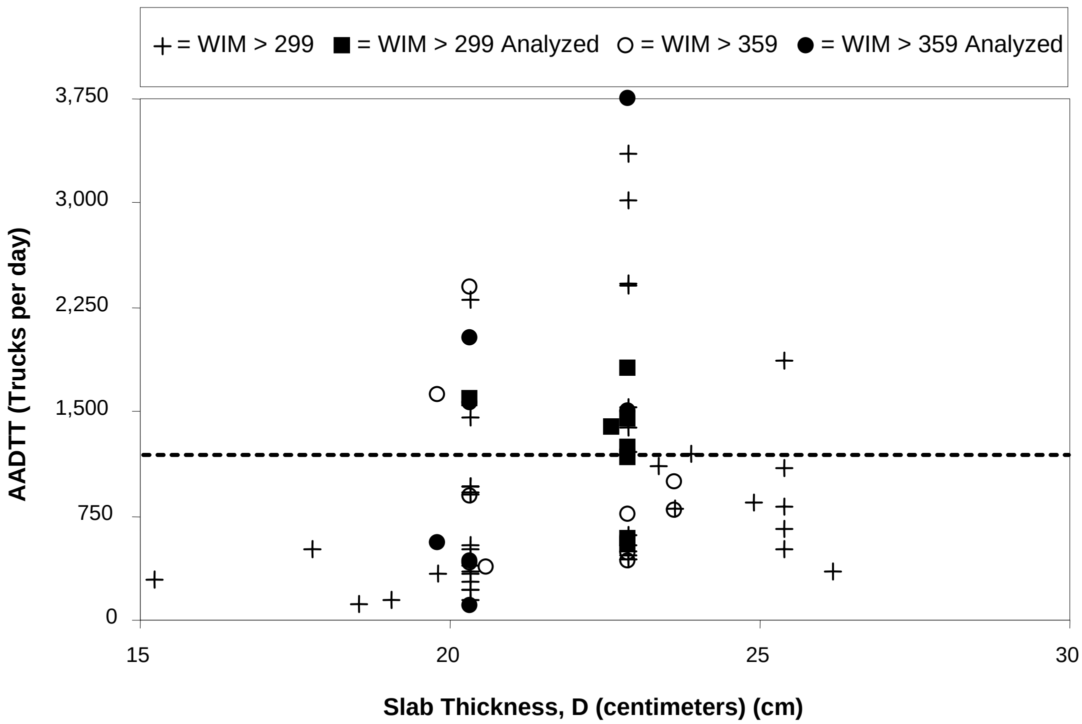



**Figure 5. Rigid pavement site selection by AADTT and slab thickness.**

For rigid pavements, two truck traffic volumes were defined:

- Fewer than or equal to 1,200 trucks/day/lane.
- More than 1,200 trucks/day/lane.

The final selection of sites for the detailed sensitivity analysis was carried out by identifying 5 to 10 sites in each AADTT interval. For each interval, the sites selected covered a range in AADTT, while satisfying the other two criteria listed earlier (i.e., highest possible WIM data coverage over multiple years). For rigid pavement selection, additional consideration was given to structural configuration (roughly half of the pavement sections selected was jointed and the other half was continuously reinforced). Background information on the sections selected for the detailed sensitivity analysis of the NCHRP 1-37A design guide is given in tables 11 and 12. These tables identify the years of extended WIM data coverage (i.e., 299 days per year or greater), the AADTT for the year selected for the detailed sensitivity analysis, and the structural thickness/configuration of the sites. The data for the remaining years were used to establish the truck traffic growth rate for these sites.

## IDENTIFYING GROUPS OF SITES FOR OBTAINING REGIONAL DATA

As shown in table 8, the numerous traffic data collection scenarios needed for simulation involve representative regional traffic data; therefore, it was necessary to establish a formal process for developing representative regional traffic data for the detailed sensitivity analysis sites identified above (tables 11 and 12). This grouping needs to be carried out separately for establishing vehicle classification information and axle-load information (the second and fifth input components of the NCHRP 1-37A design guide, respectively, as described in table 6). It could be done subjectively using roadway functional class criteria, such as the ones shown in table 13. It is clearly better to do so using objective criteria, such as clustering techniques. As described in the literature review, clustering was introduced in the 2001 TMG (appendix 2-b as the preferred technique for identifying sites with similar seasonal traffic volume distribution patterns.)[(3)] Clustering is used in this study to identify sites with similar vehicle classification distributions and axle-load distributions. As mentioned earlier, the vehicle classification and axle-load distributions in the NCHRP 1-37A design guide are input in the form of frequency distributions (percentage). As a result, there is no need to establish regional sites in terms of similar pavement loading, as is done for conventional TWRGs, nor it is necessary to use the rather outmoded ESAL concept for doing so (this is likely to influence future editions of the TMG).

In terms of load distribution, regional clusters were identified with respect to tandem axles only because they are the most common in the traffic stream. It should be noted that a number of alternatives were considered, including the use of raw load distribution for all four-axle types and the load distribution of all four axle types weighed by their relative frequency in the traffic stream. Using the distribution of the tandem axles was only favored for its simplicity. Furthermore, in developing regional traffic data, clustering was done by State. Although there is no fundamental reason for partitioning the nationwide data, it better simulates the practice of individual DOTs that work primarily with their own data. A detailed description of the clustering technique can be found in statistical texts.[(16)] A brief overview of the method is given below and explained through an example involving the LTPP WIM sites in Washington State.

**Table 11. Background information on the flexible LTPP sites selected.**

| Site | State | Structural Number in millimeters (mm) (inches) | Data years[1] | Data Days[2] | AADTT[2] | AADTT Level |
|---|---|---|---|---|---|---|
| 091803 | CT | 114 (4.5) | **1994**,95 | 359 | 165 | **AADTT ≤ 800** |
| 261004 | MI | 43 (1.7) | 1992,94,95,96,97,**98** | 348 | 229 | |
| 271019 | MN | 76 (3.0) | 1992,94,95,**96** | 313 | 268 | |
| 282807 | MS | 140 (5.5) | 1995,**96** | 321 | 457 | |
| 531007 | WA | 66 (2.6) | 1993,94,**95** | 365 | 177 | |
| 182008 | IN | 158 (6.2) | 1992,93,97,**98** | 349 | 709 | |
| 182009 | IN | 234 (9.2) | **1998** | 356 | 655 | |
| 261010 | MI | 122 (4.8) | 1994,95,**98** | 362 | 647 | |
| 536048 | WA | 107 (4.2) | **1994** | 365 | 783 | |
| 261012 | MI | 135 (5.3) | 1994,95,**98** | 355 | 977 | **AADTT > 800** |
| 181028 | IN | 178 (7.0) | 1997,**98** | 319 | 1535 | |
| 186012 | IN | 231 (9.1) | 1992,97,**98** | 324 | 1473 | |
| 261013 | MI | 150 (5.9) | 1994,**98** | 334 | 1395 | |
| 283081 | MS | 122 (4.8) | **1993** | 356 | 1120 | |
| 283093 | MS | 102 (4.0) | **1995** | 341 | 1920 | |

[1]Data year used in traffic data collection scenario simulation is bolded.
[2]AADTT volumes and data days are for the year bolded.

**Table 12. Background information on the rigid LTPP sites selected.**

| Site | State | Slab in mm (inches)) | Configuration | Data Years[1] | Data Days[2] | AADTT[2] | AADTT Level |
|---|---|---|---|---|---|---|---|
| 094020 | CT | 230 (9.0) | JRCP | **1994** | 308 | 546 | AADTT ≤ 1200 |
| 263069 | MI | 230 (9.0) | JRCP | 1994,95,**97** | 319 | 577 | |
| 284024 | MS | 200 (8.0) | JRCP | **1995** | 360 | 99 | |
| 501682 | VT | 200 (8.0) | JRCP | 1992,94,95,**97** | 363 | 419 | |
| 533813 | WA | 198 (7.8) | JRCP | 1992,93,**94** | 365 | 548 | |
| 185022 | IN | 230 (9.0) | CRCP | **1997** | 313 | 1164 | |
| 094008 | CT | 230 (9.0) | JRCP | **1994** | 364 | 1496 | AADTT > 1200 |
| 265363 | MI | 230 (9.0) | CRCP | 1993,94,95,**97** | 355 | 1247 | |
| 274055 | MN | 225 (8.9) | JRCP | **1994**,97 | 300 | 1381 | |
| 275076 | MN | 230 (9.0) | CRCP | **1997** | 344 | 1438 | |
| 095001 | CT | 200 (8.0) | CRCP | **1995** | 323 | 1590 | |
| 185518 | IN | 230 (9.0) | CRCP | 1994,**97**,98 | 365 | 3746 | |
| 264015 | MI | 230 (9.0) | JRCP | 1994,96,97,**98** | 341 | 1807 | |
| 285006 | MS | 200 (8.0) | CRCP | 1993,94,**95**,97 | 361 | 1559 | |
| 285805 | MS | 200 (8.0) | CRCP | 1993,94,**95** | 361 | 2024 | |

[1]Data year used in traffic data collection scenario simulation is bolded.
[2]Volumes and data days are for the year bolded.

**Table 13. Identification codes for roadway functional classes as defined by LTPP database field FUNCTIONAL_CLASS in table INV_ID.**

| ID | Roadway Functional Class |
|---|---|
| 1 | Rural Principal Arterial: Interstate |
| 2 | Rural Principal Arterial: Other |
| 6 | Rural Minor Arterial |
| 7 | Rural Major Collector |
| 8 | Rural Minor Collector |
| 9 | Rural Local Collector |
| 11 | Urban Principal Arterial: Interstate |
| 12 | Urban Principal Arterial: Other Freeways or Expressways |
| 14 | Urban Other Principal Arterial |
| 16 | Urban Minor Arterial |
| 17 | Urban Collector |
| 19 | Urban Local |

Clustering is a mathematical approach for establishing similarities between different objects. Objects are described by their attributes. For this particular example, the objects are the LTPP WIM sites identified in Washington State (the 17 that met the study criteria) and the attributes are the distribution of the load of tandem axles (40 load bins from 8.90 to 355.9 kN (2 to 80 thousand pounds force (kips)). In this particular example, the attributes need not be normalized because they are all frequencies adding up to 100 percent. The next step is to compute a dissimilarity coefficient matrix. For this purpose, the so-called Euclidean distance $e$ is used, which is defined as the distance between attributes for each pair of objects. If there were only two attributes, $i$ and $j$, and they were plotted in a Cartesian coordinate system, the Euclidean distance $e_{ij}$ would be the linear distance between the two objects defined on this plot by their coordinates. For more than two attributes, a similar definition would apply, the difference being that this would be a multidimensional plot (40 dimensional in this example). The Euclidean matrix for the annual distribution of tandem-axle loads in Washington State LTPP sites is shown in table 14. A value of the coefficient $e_{ij}$ close to 0.0 suggests a similarity between the pair of objects, while higher $e_{ij}$ values suggest a significant difference between the pair of objects. The next step is to construct what is referred to as a *clustering tree*, where pairs of similar objects are successively grouped together and compared with the remaining objects in order of increasing $e_{ij}$. The clustering tree for this example is presented in table 15 and plotted graphically in figure 6. This clustering method is referred to as Ward's Minimum Variance Method. All of these calculations were carried out using an add-on function to Microsoft Excel found in the statistiXL® library.[(17)] Figure 6 allows identification of groups of WIM sites in Washington State with similar distributions of tandem-axle loads, given a selected value of the Euclidean distance, and therefore, a level of acceptable dissimilarity. Three clusters were identified, assuming an $e_{ij}$ value of 0.07.

For the two WIM sites to be analyzed (6048 and 1007 as indicated by arrows), the selected groups for obtaining regional WIM data are identified by the two uppermost squares in figure 6. Figures 7 and 8 show the frequency distributions of tandem-axle loads for these two groups and illustrate the distinct difference in the patterns between the two groups of WIM sites identified. For the LTPP sites selected for traffic scenario simulation, tables representing clustering trees by State are presented in appendix B. This includes clusters with respect to the annual average tandem-axle load distributions and clusters with respect to the annual average truck classification and distributions (i.e., FHWA classes 4 through 13). The actual LTPP sites finally selected for obtaining regional AVC and WIM data are summarized in tables 16 and 17, respectively. The highlighted sites in these two tables are the ones used in the detailed sensitivity analysis of the NCHRP 1-37A design guide, while data from the other sites are used to estimate regional vehicle classification and axle-load distributions. As an example, the regional vehicle classification data for site 182008 were estimated as the average of the vehicle classification distributions for sites 181037, 183031, and 184042. For sites that exhibit no similarities with others (e.g., site 091803), the statewide average was assumed to be representative of the regional data.

**Table 14. Euclidean distance matrix: Annual distributions of tandem-axle loads, Washington State LTPP sites,**

| | Washington State LTPP Sites Analyzed | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1002** | **1005** | **1006** | **1007** | **1008** | **1801** | **3011** | **3013** | **3014** | **3019** | **3812** | **3813** | **6020** | **6048** | **6056** | **7322** |
| 1002 | | | | | | | | | | | | | | | | |
| 1005 | 0.016 | | | | | | | | | | | | | | | |
| 1006 | 0.003 | 0.018 | | | | | | | | | | | | | | |
| 1007 | 0.005 | 0.011 | 0.013 | | | | | | | | | | | | | |
| 1008 | 0.009 | 0.007 | 0.016 | 0.002 | | | | | | | | | | | | |
| 1801 | 0.021 | 0.025 | 0.018 | 0.030 | 0.034 | | | | | | | | | | | |
| 3011 | 0.010 | 0.012 | 0.014 | 0.009 | 0.011 | 0.012 | | | | | | | | | | |
| 3013 | 0.016 | 0.031 | 0.012 | 0.033 | 0.039 | 0.006 | 0.017 | | | | | | | | | |
| 3014 | 0.017 | 0.029 | 0.026 | 0.012 | 0.016 | 0.028 | 0.008 | 0.033 | | | | | | | | |
| 3019 | 0.024 | 0.008 | 0.033 | 0.015 | 0.011 | 0.034 | 0.015 | 0.044 | 0.030 | | | | | | | |
| 3812 | 0.011 | 0.006 | 0.010 | 0.017 | 0.016 | 0.016 | 0.013 | 0.015 | 0.034 | 0.016 | | | | | | |
| 3813 | 0.004 | 0.011 | 0.005 | 0.010 | 0.013 | 0.009 | 0.004 | 0.007 | 0.016 | 0.020 | 0.006 | | | | | |
| 6020 | 0.011 | 0.019 | 0.006 | 0.020 | 0.023 | 0.006 | 0.010 | 0.005 | 0.024 | 0.034 | 0.011 | 0.004 | | | | |
| 6048 | 0.003 | 0.010 | 0.004 | 0.006 | 0.008 | 0.011 | 0.004 | 0.012 | 0.013 | 0.019 | 0.008 | 0.002 | 0.005 | | | |
| 6056 | 0.018 | 0.036 | 0.013 | 0.037 | 0.044 | 0.010 | 0.022 | 0.001 | 0.040 | 0.052 | 0.017 | 0.010 | 0.007 | 0.016 | | |
| 7322 | 0.025 | 0.039 | 0.017 | 0.044 | 0.050 | 0.006 | 0.024 | 0.002 | 0.043 | 0.055 | 0.020 | 0.013 | 0.008 | 0.019 | 0.002 | |
| 7409 | 0.012 | 0.009 | 0.014 | 0.015 | 0.016 | 0.007 | 0.005 | 0.012 | 0.022 | 0.012 | 0.005 | 0.004 | 0.010 | 0.006 | 0.016 | 0.017 |

**Table 15. Summary of clustering strategies and associated Euclidean distance: Annual distributions of tandem-axle loads, Washington State LTPP sites.**

| Cluster | First Item | Second Item | Euclidean Distance |
|---|---|---|---|
| 1 | 6056 | 3013 | 0.001 |
| 2 | 1008 | 1007 | 0.002 |
| 3 | 6048 | 3813 | 0.002 |
| 4 | Cluster 1 | 7322 | 0.003 |
| 5 | 1006 | 1002 | 0.005 |
| 6 | Cluster 3 | 3011 | 0.007 |
| 7 | 7409 | 3812 | 0.005 |
| 8 | 6020 | 1801 | 0.006 |
| 9 | 3019 | 1005 | 0.008 |
| 10 | Cluster 7 | Cluster 6 | 0.022 |
| 11 | Cluster 8 | Cluster 4 | 0.028 |
| 12 | Cluster 10 | Cluster 5 | 0.036 |
| 13 | Cluster 9 | Cluster 2 | 0.045 |
| 14 | Cluster 12 | 3014 | 0.059 |
| 15 | Cluster 14 | Cluster 13 | 0.078 |
| 16 | Cluster 15 | Cluster 11 | 0.132 |

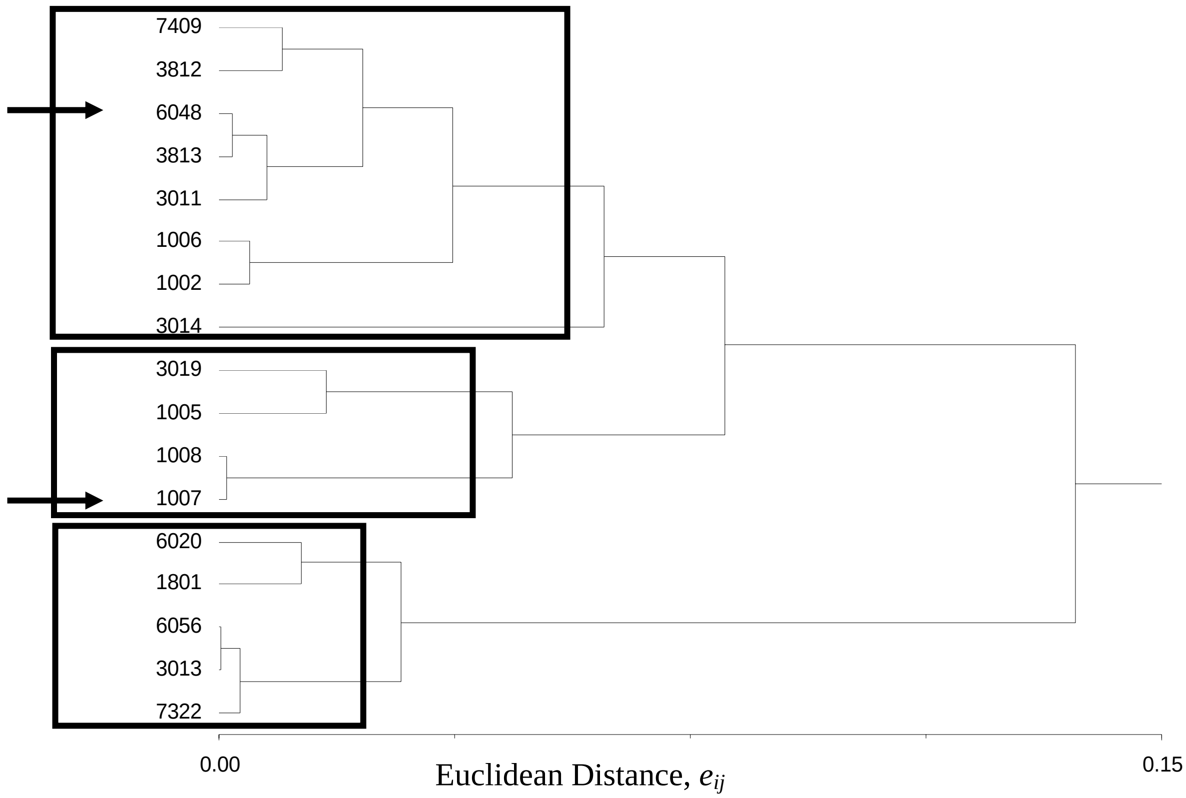
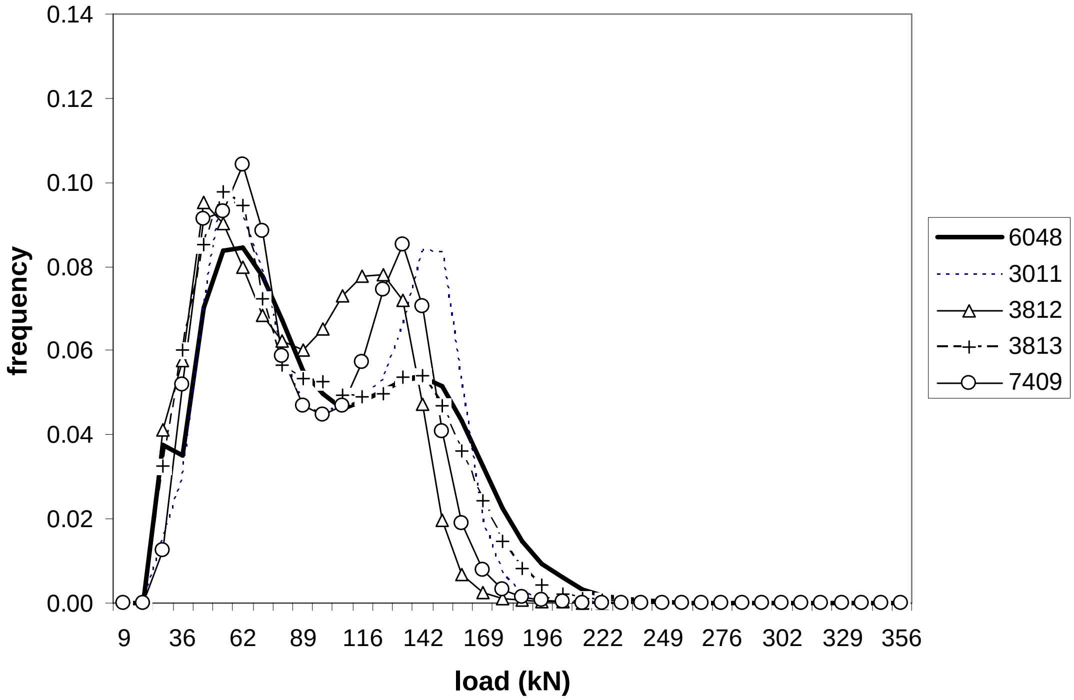
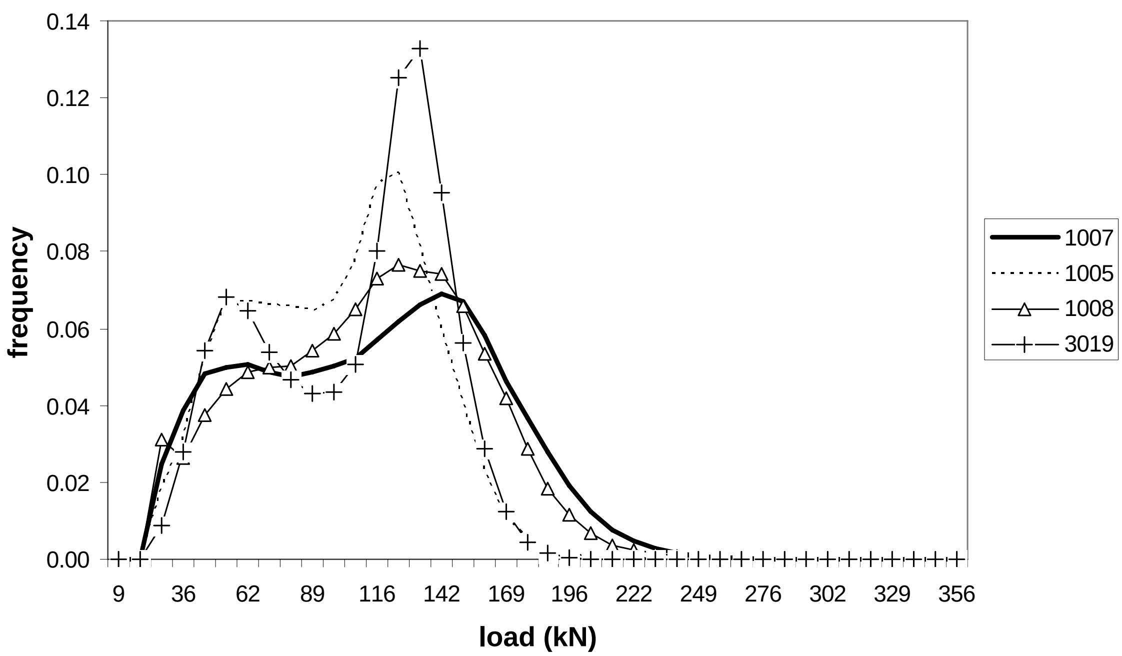



**Figure 6. Annual distributions of tandem-axle loads, Washington State LTPP sites.**




1 kN=225 lbf

**Figure 7. Tandem-axle load distributions for the cluster of Washington State LTPP site 6048.**




1 kN=225 lbf

**Figure 8. Tandem-axle load distributions for the cluster of Washington State LTPP site 1007.**

**Table 16. LTPP sites used for obtaining regional vehicle classification data.**

| State Code | Vehicle Classification Cluster Sites | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 4008 | 4020 | 5001 | – | – | – | – | – | – | – | – | – |
| 9 | 1803 | – | – | – | – | – | – | – | – | – | – | – |
| 18 | 1028 | 5518 | 6012 | 9020 | – | – | – | – | – | – | – | – |
| 18 | 4042 | 3031 | 2008 | 1037 | – | – | – | – | – | – | – | – |
| 18 | 5538 | 5528 | 2009 | 5022 | 5043 | 3030 | – | – | – | – | – | – |
| 26 | 1010 | 1001 | 1004 | – | – | – | – | – | – | – | – | – |
| 26 | 9030 | 9029 | 5363 | – | – | – | – | – | – | – | – | – |
| 26 | 7072 | 4015 | 3069 | 1012 | 1013 | – | – | – | – | – | – | – |
| 27 | 4055 | 1023 | 1028 | 1085 | 3003 | 4033 | 4040 | 4054 | 5076 | 6251 | 7090 | 9075 |
| 27 | 1016 | 1019 | 1087 | 3013 | 4037 | 4050 | – | – | – | – | – | – |
| 28 | 2807 | 1001 | 1016 | 3087 | 3089 | 4024 | 5025 | – | – | – | – | – |
| 28 | 5006 | 3081 | 9030 | 7012 | 3094 | 3093 | 3019 | 3018 | 3099 | 5805 | 3091 | 1802 |
| 28 | 3085 | 3083 | 3090 | – | – | – | – | – | – | – | – | – |
| 50 | 1682 | 1002 | 1681 | 1683 | – | – | – | – | – | – | – | – |
| 50 | 1004 | – | – | – | – | – | – | – | – | – | – | – |
| 53 | 1007 | 1005 | 1801 | 3014 | 3019 | 7409 | – | – | – | – | – | – |
| 53 | 7322 | 6056 | 3013 | 3813 | 3011 | 1002 | – | – | – | – | – | – |
| 53 | 6048 | 1006 | 1008 | 3812 | 6020 | – | – | – | – | – | – | – |

Note: The 30 sites used for the detailed sensitivity analysis are shaded.

**Table 17. LTPP sites used for obtaining regional axle-load data.**

| State Code | Tandem-Axle Load Cluster Sites | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 4008 | 1803 | 4020 | 5001 | – | – | – | – | – | – | – | – | – | – |
| 18 | 1028 | 2009 | 3030 | 3031 | 4042 | 5022 | 5043 | 5518 | 9020 | – | – | – | – | – |
| 18 | 6012 | 1037 | 2008 | – | – | – | – | – | – | – | – | – | – | – |
| 18 | 5538 | 5528 | – | – | – | – | – | – | – | – | – | – | – | – |
| 26 | 1010 | 1001 | 1004 | 1004 | 1012 | 1013 | 3069 | 4015 | 5363 | 7072 | 9029 | 9030 | – | – |
| 27 | 4055 | 1023 | 1028 | 4054 | 5076 | – | – | – | – | – | – | – | – | – |
| 27 | 6251 | 4050 | 4040 | 4037 | 4033 | 1019 | 1016 | 9075 | 1085 | 7090 | 1087 | 3003 | – | – |
| 27 | 3013 | – | – | – | – | – | – | – | – | – | – | – | – | – |
| 28 | 2807 | 1001 | 1016 | 1802 | 3018 | 3019 | 3083 | 3085 | 3087 | 3089 | 3090 | 3091 | 4024 | 5025 |
| 28 | 9030 | 3099 | 3094 | 3093 | 5805 | 5006 | 3081 | 7012 | – | – | – | – | – | – |
| 50 | 1682 | 1002 | 1004 | 1681 | 1683 | – | – | – | – | – | – | – | – | – |
| 53 | 1007 | 1005 | 1008 | 3019 | – | – | – | – | – | – | – | – | – | – |
| 53 | 6020 | 1801 | 6056 | 3013 | 7322 | – | – | – | – | – | – | – | – | – |
| 53 | 6048 | 1002 | 1006 | 3011 | 3014 | 3812 | 3813 | 7409 | – | – | – | – | – | – |

Note: The 30 sites used for the detailed sensitivity analysis are shaded.

## SIMULATING TRAFFIC DATA COLLECTION SCENARIOS

As described in the literature review, obtaining traffic input to the NCHRP 1-37A design guide from short-term traffic samples involves considerable calculations in factoring the site-specific data available using representative regional or national vehicle distribution and axle-load distributions. TrafLoad[13] could be used to carry out these calculations; however, it accepts as input raw data (e.g., card-4 and card-7) and therefore, was not directly applicable to the daily summary data format used in this study. More important, TrafLoad could not be used to analyze all of the possible combinations of data used in simulating short-term scenarios from extended-coverage WIM data (1 month/season of data involves $3^4 = 81$ combinations of months, as described later). Therefore, it was decided to develop customized software for computing the traffic data input to the NCHRP 1-37A design guide. The software developed is written in Microsoft Visual Basic®. It reads daily traffic data summaries from the Microsoft Access database extracted from the CTDB and computes the traffic input elements to the NCHRP 1-37A design guide following the procedures described in the 2001 TMG.[3] Furthermore, it adopts the traffic ratio approach in factoring short-term counts, as described by NCHRP 1-39.[13] Accordingly, equations 15, 16, and 17 for factor ratios are used. (The subscripts *i* for vehicle class and *l* for direction were dropped for brevity.)

$$MDWTR = \frac{MADW}{AADT} \tag{15}$$

$$MTR = \frac{MADT}{AADT} \tag{16}$$

$$DTR = \frac{AADW}{AADT} \tag{17}$$

Where:

| | | |
|---|---|---|
| *MDWTR* | = | Monthly DOW traffic ratios. |
| *MADW* | = | Monthly average day of week. |
| *MTR* | = | Monthly traffic ratios. |
| *MADT* | = | Monthly average daily traffic. |
| *DTR* | = | Daily traffic ratios. |
| *AADW* | = | Annual average day of week. |

For each of the traffic data collection scenarios, the software computes the mean and the standard deviation (SD) for each of the NCHRP 1-37A design guide traffic data input elements outlined in table 6. The methodology used for doing so follows.

### Scenario 1-0: Site-Specific Continuous WIM Data

This scenario represents the most complete traffic data set for generating input to the NCHRP 1-37A design guide, and for this reason, it is defined as the truth in traffic data. For the 30 sites analyzed, WIM data coverage ranged from more than 299 days per year to more than 359 days per year. Following is an explanation of how the five traffic data input components to the NCHRP 1-37A design guide (refer to table 6) were computed:

- Component 5 of the NCHRP 1-37A Design Guide Input (Axle-Load Distributions):
  - Browse the daily summary data table to obtain the number of days per DOW (from Sunday through Saturday) for each month that has traffic records.
  - For each month and DOW, sum the axle passes per truck class for each axle type and each load bin.
  - Divide each sum by the number of days of data computed above to obtain the average number of daily axle passes per bin, per axle type, per truck class for each DOW and month.
  - Average the number of daily axle passes per bin for the seven DOWs to obtain the monthly average number of axle passes by axle type, load bin, and truck class for each month.
  - Translate the number of passes per bin into load distributions (percent) by axle type, truck class, and month.

- Component 4 of the NCHRP 1-37A Design Guide Input (Number of Axles per Truck):
  - Compute the average daily number of axles by axle type and truck class, regardless of load bin, over the 12-month period.
  - Compute the average daily number of trucks by class.
  - Divide the two values computed above to obtain the average number of axles by truck class and axle type.

- Components 1, 2, and 3 of the NCHRP 1-37A Design Guide Input (AADTT, Truck Class Distribution, and MAFs):
  - For each month and DOW, sum the number of trucks by class.
  - Divide each sum by the number of days of data computed above to obtain the average number of daily vehicle passes by truck class per DOW and month.
  - Average the number of trucks by class for the seven DOWs to obtain the monthly average number of trucks by class per month.
  - Average the number of trucks for the 12 months to obtain AADTT by truck class.
  - Translate these average values into frequencies (percentage).
  - Add the number of trucks for all classes to obtain AADTT.
  - Compute MAFs by truck class using the data above and equation 5.

The procedure described above accommodates WIM traffic data sets with missing data days. For some of the WIM sites that have the largest number of missing days (i.e., 299 days of WIM data per year or more), additional assumptions had to be made:

- Where entire months of data are missing, data are assumed to have values equal to the average of the data for the months available.
- Where entire DOWs are missing for a particular month, data are assumed to have values equal to the average of the data for the available DOWs for the same month.

**Scenario 1-1: Site-Specific WIM Data for 1 Month/4 Seasons**

This scenario involves WIM data that cover 1 month in each of 4 seasons. It is simulated from the continuous WIM data set of the 30 sites selected and is carried out by computing all of the necessary traffic input to the NCHRP 1-37A design guide from random combinations of sets of 4 months, each from a different season (a maximum of 81 combinations is possible). Only months with more than 25 days of data were considered for this analysis. The challenge in simulating this scenario is that the traffic volume by truck class is not known for all months of the year. All that is known for the site is the volume for 4 months of the year. The following paragraphs describe the methodology used in obtaining each of the five traffic data components input to the NCHRP 1-37A design guide (table 6).

**Component 3 of the NCHRP 1-37A Design Guide Input (MAFs):**
There are a number of alternative algorithms for computing traffic volumes and, as a result, MAFs by vehicle classification for the months considered missing. The one selected for this study uses the average regional MAF values for all truck classes to estimate truck volumes by class for the missing months. This algorithm is explained in the following example, and it is demonstrated in table 18.

**Table 18. Example of computing MAFs from regional data.**

| Month | R MAF(all truck classes) | Measured VOL by Class | Estimating VOL by Class | VOL by Class | Estimated SS MAF by Class |
|---|---|---|---|---|---|
| January | 0.8 | 900 | – | 900 | 0.85 |
| February | 0.9 | – | 8,489x0.9/8.06 = | 948 | 0.90 |
| March | 1.09 | – | 8,489x1.09/8.06 = | 1,148 | 1.09 |
| April | 1.05 | 1,100 | – | 1,100 | 1.04 |
| May | 1.12 | – | 8,489x1.12/8.06 = | 1,180 | 1.12 |
| June | 1.15 | – | 8,489x1.15/8.06 = | 1,211 | 1.15 |
| July | 1.1 | 1,200 | – | 1,200 | 1.14 |
| August | 1 | – | 8,489x1/8.06 = | 1,053 | 1.00 |
| September | 1 | – | 8,489x1/8.06 = | 1,053 | 1.00 |
| October | 0.99 | 950 | – | 950 | 0.90 |
| November | 0.95 | – | 8,489x0.95/8.06 = | 1,001 | 0.95 |
| December | 0.85 | – | 8,489x0.85/8.06 = | 895 | 0.85 |
| Sum of four MAFs | 3.94 | Sum = 4,150 | – | AADTT= 1,053 | Sum =12.00 |
| 12 (sum of 4 MAFs) | 8.06 | 8,489 | | | |

Consider that for a given truck class, daily traffic volumes (VOL) are available only for January, April, July, and October (they add up to a volume of 4,150 vehicles). Given the average regional MAF values above, compute the sum of them for the available months (i.e., 3.94). This suggests that the sum of the regional MAF values for the 8 missing months is 8.06 (=12−3.94), which gives a total volume of 8,489 (= 4,150×8.06/3.94) for these months. This, in turn, allows estimation of the traffic volume of the missing months (e.g., February volume is computed as 8,489×0.9/8.06 and so on). Note that this approach preserves the traffic volume for the available months.

The group of sites used for obtaining the regional MAF data was identified as the agency-specific cluster that exhibited a similar truck classification pattern as the site under consideration (truck classification clusters are presented in appendix B and summarized in table 16). This was deemed to be reasonable compromise between using agencywide average MAF data for all truck classes and MAF cluster data for individual truck classes. Furthermore, it was practical to implement since the monthly vehicle classification distributions are relatively stable (table 19), and thus identifying a cluster from 4 months of traffic data is realistic.

**Table 19. Monthly versus annual vehicle class distribution, AVC cluster, Washington State site 6048.**

| | Vehicle Class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Month** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** |
| Jan. | 2.3 | 34.0 | 5.6 | 0.1 | 7.8 | 36.4 | 3.9 | 1.2 | 1.7 | 7.1 |
| Feb. | 2.3 | 34.2 | 6.1 | 0.2 | 7.9 | 35.5 | 3.8 | 1.2 | 1.8 | 7.2 |
| Mar. | 1.2 | 37.3 | 5.8 | 0.2 | 5.4 | 36.1 | 3.8 | 1.4 | 1.7 | 7.2 |
| Apr. | 1.4 | 41.7 | 5.9 | 0.3 | 5.8 | 31.6 | 3.6 | 1.1 | 1.6 | 7.0 |
| May | 1.5 | 43.4 | 6.3 | 0.3 | 6.4 | 29.8 | 3.4 | 1.1 | 1.5 | 6.4 |
| June | 1.5 | 42.6 | 6.2 | 0.2 | 6.9 | 29.2 | 3.8 | 1.1 | 1.4 | 7.0 |
| July | 1.6 | 49.4 | 5.8 | 0.3 | 7.4 | 24.4 | 3.2 | 0.6 | 1.2 | 6.2 |
| Aug. | 1.4 | 49.5 | 5.7 | 0.5 | 8.6 | 22.0 | 3.2 | 0.5 | 1.3 | 7.2 |
| Sept. | 1.9 | 45.2 | 5.8 | 0.2 | 9.5 | 25.0 | 2.9 | 0.6 | 1.3 | 7.8 |
| Oct. | 1.5 | 45.9 | 6.2 | 0.3 | 7.0 | 27.4 | 3.0 | 0.6 | 1.2 | 6.9 |
| Nov. | 1.6 | 46.3 | 6.3 | 0.4 | 4.9 | 29.0 | 3.5 | 0.6 | 1.3 | 6.3 |
| Dec. | 1.6 | 46.0 | 5.4 | 0.4 | 4.3 | 30.3 | 3.6 | 0.6 | 1.3 | 6.5 |
| Mean | 1.7 | 43.0 | 5.9 | 0.3 | 6.8 | 29.7 | 3.5 | 0.9 | 1.4 | 6.9 |

**Components 1, 2, and 5 of the NCHRP 1-37A Design Guide Input (AADTT, Truck Class, and Axle-Load Distribution):**

Having established the volumes by truck class for the missing months, the algorithm used for obtaining traffic data input components 1, 2, and 5 was identical to that for scenario 1-0.

**Component 4 of the NCHRP 1-37A Design Guide Input (Number of Axles per Truck):**

The number of axles by axle configuration and truck class was assumed to be constant and equal to each statewide average for the sites analyzed. This assumption is justified considering that the number of axles for the most common truck classes (classes 5 and 9) is relatively constant. Tables 20 and 21 show the number of single and tandem axles per vehicle for the Washington State sites analyzed. It can be seen that the number of single and tandem axles for vehicle classes 5 and 9 varies only slightly between sites. This is not the case for vehicle classes 7 and 11; however, they account for less than 4 percent of the total truck volumes. Another reason for this assumption was that the number of axles per vehicle type (i.e., 4 by 10 matrix) had to be input manually to the NCHRP 1-37A design guide software, and therefore, assuming it to be constant for each agency, significantly reduced the data input effort.

**Table 20. Number of single axles per vehicle, annual Washington State data.**

| | Vehicle Class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** |
| 1002 | 1.59 | 1.99 | 1.00 | 0.67 | 2.40 | 1.21 | 1.21 | 4.52 | 3.78 | 2.39 |
| 1005 | 1.21 | 2.00 | 1.00 | 0.64 | 2.26 | 1.15 | 1.07 | 4.53 | 3.83 | 2.14 |
| 1006 | 1.36 | 1.97 | 1.00 | 1.08 | 2.26 | 1.14 | 1.10 | 4.61 | 3.02 | 2.37 |
| 1007 | 1.49 | 1.99 | 1.07 | 1.15 | 2.26 | 1.20 | 1.06 | 4.73 | 3.75 | 2.22 |
| 1008 | 1.21 | 2.00 | 1.00 | 0.98 | 2.24 | 1.28 | 1.22 | 4.86 | 3.45 | 1.90 |
| 1801 | 1.59 | 1.98 | 1.00 | 0.98 | 2.34 | 1.22 | 1.03 | 3.61 | 3.62 | 2.53 |
| 3011 | 1.25 | 2.00 | 1.00 | 0.73 | 2.38 | 1.03 | 1.03 | 4.33 | 3.21 | 1.76 |
| 3013 | 1.29 | 2.00 | 1.00 | 1.03 | 2.31 | 1.22 | 1.15 | 4.49 | 3.47 | 2.27 |
| 3014 | 1.65 | 1.99 | 1.23 | 0.94 | 2.56 | 1.14 | 1.07 | 4.35 | 3.62 | 2.29 |
| 3019 | 1.52 | 1.99 | 1.00 | 0.67 | 2.38 | 1.09 | 1.15 | 4.34 | 3.57 | 2.13 |
| 3812 | 1.81 | 2.00 | 1.00 | 0.44 | 2.59 | 1.10 | 1.07 | 4.34 | 3.65 | 1.82 |
| 3813 | 1.82 | 2.00 | 1.00 | 1.00 | 2.53 | 1.15 | 1.01 | 3.75 | 3.70 | 1.91 |
| 6020 | 1.26 | 2.00 | 1.00 | 1.25 | 2.24 | 1.13 | 1.35 | 4.66 | 3.34 | 2.25 |
| 6048 | 1.43 | 2.00 | 1.00 | 0.98 | 2.34 | 1.14 | 1.04 | 4.07 | 2.80 | 1.46 |
| 6056 | 1.41 | 1.99 | 1.05 | 1.24 | 2.31 | 1.25 | 1.12 | 4.21 | 3.48 | 2.06 |
| 7322 | 1.50 | 2.00 | 1.12 | 0.78 | 2.32 | 1.28 | 1.12 | 4.70 | 3.73 | 2.04 |
| 7409 | 1.71 | 2.00 | 1.00 | 0.97 | 2.16 | 1.09 | 1.12 | 3.97 | 3.58 | 2.38 |
| Mean | 1.48 | 1.99 | 1.03 | 0.91 | 2.35 | 1.17 | 1.11 | 4.36 | 3.51 | 2.11 |

**Table 21. Number of tandem axles per vehicle, annual Washington State data.**

| | Vehicle Class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** |
| 1002 | 0.73 | 0.06 | 1.00 | 1.00 | 0.66 | 1.88 | 1.06 | 0.67 | 1.10 | 2.21 |
| 1005 | 0.79 | 0.02 | 1.00 | 1.26 | 0.77 | 1.92 | 1.02 | 0.27 | 1.05 | 2.48 |
| 1006 | 0.72 | 0.03 | 1.00 | 0.84 | 0.75 | 1.92 | 0.99 | 0.96 | 1.21 | 2.06 |
| 1007 | 0.92 | 0.05 | 0.97 | 0.84 | 0.81 | 1.90 | 0.92 | 0.25 | 1.06 | 2.13 |
| 1008 | 0.79 | 0.01 | 1.00 | 1.06 | 0.76 | 1.85 | 1.06 | 0.27 | 1.11 | 2.04 |
| 1801 | 0.72 | 0.07 | 1.00 | 0.65 | 0.72 | 1.89 | 0.93 | 0.86 | 1.09 | 2.17 |
| 3011 | 0.76 | 0.01 | 1.00 | 1.28 | 0.58 | 1.98 | 1.06 | 0.47 | 1.32 | 2.45 |
| 3013 | 0.73 | 0.00 | 1.00 | 1.67 | 0.69 | 1.88 | 1.14 | 0.47 | 1.20 | 2.33 |
| 3014 | 0.36 | 0.01 | 0.89 | 0.13 | 0.61 | 1.93 | 0.93 | 0.26 | 1.11 | 2.34 |
| 3019 | 0.54 | 0.03 | 1.00 | 0.83 | 0.64 | 1.95 | 0.96 | 0.34 | 1.17 | 2.01 |
| 3812 | 0.21 | 0.00 | 1.00 | 1.54 | 0.42 | 1.94 | 0.96 | 0.39 | 1.11 | 2.52 |
| 3813 | 0.38 | 0.01 | 1.00 | 0.77 | 0.48 | 1.92 | 0.98 | 0.80 | 1.06 | 2.57 |
| 6020 | 0.75 | 0.01 | 1.00 | 0.90 | 0.76 | 1.93 | 1.34 | 0.41 | 1.19 | 2.36 |
| 6048 | 0.59 | 0.00 | 1.00 | 0.29 | 0.66 | 1.91 | 1.00 | 0.42 | 1.07 | 1.18 |
| 6056 | 0.77 | 0.01 | 0.98 | 1.35 | 0.71 | 1.87 | 1.14 | 0.56 | 1.23 | 2.25 |
| 7322 | 0.72 | 0.00 | 0.94 | 1.68 | 0.73 | 1.85 | 1.17 | 0.34 | 1.07 | 2.26 |
| 7409 | 0.54 | 0.01 | 1.00 | 0.51 | 0.84 | 1.95 | 1.04 | 0.63 | 1.19 | 2.34 |
| Mean | 0.65 | 0.02 | 0.99 | 0.98 | 0.68 | 1.91 | 1.04 | 0.49 | 1.14 | 2.22 |

**Scenario 1-2: Site-Specific WIM Data for 1 Week/Season**

This scenario was simulated in a manner similar to the one described under scenario 1-1. The difference was that only 1 week per season of WIM data was considered available. For each season, a week was selected at random, after excluding the dates involving national holidays and those having incomplete data. This simply yielded a higher number of combinations to be simulated (i.e., depending on data coverage, up to 20,736 combinations). Each week was assumed to be representative of the entire month. The handling of the remaining elements of the NCHRP 1-37A design guide input was identical to that described under scenario 1-1.

**Scenario 2-0: Continuous Site-Specific AVC Data and Regional WIM Data**

This scenario used only the vehicle classification information that is available from the 30 WIM sites being analyzed. NCHRP 1-37A design guide inputs 1, 2, and 3 were obtained in an identical manner as done for scenario 1-0. For input 4, the number of axles by configuration and vehicle class, the agencywide average was used for reasons explained earlier. Input 5, which uses the load frequency distribution by axle configuration, had to be estimated from regional WIM data. In doing so, it was assumed that although there are no site-specific WIM data, there is sufficient qualitative information for truck weights for the site to allow classification of it into one of the axle-load clusters determined within a particular agency. As a result, input 5 was obtained from the average WIM data of the appropriate cluster, rather than from agencywide WIM data.

**Scenario 2-1: Site-Specific AVC Data for 1 Month/Season and Regional WIM Data**

This scenario was simulated in a manner similar to that for scenario 1-1. The difference was that traffic data input 5, the load distribution by axle configuration, was obtained from regional WIM data as described under scenario 2-0.

**Scenario 2-2: Site-Specific AVC Data for 1 Week/Season and Regional WIM Data**

This scenario was simulated in a manner similar to that for scenario 1-2. The difference was that traffic data input 5, the load distribution by axle configuration, was obtained from regional WIM data as described under scenario 2-0.

**Scenario 2-3: Site-Specific AVC Data for 1 Week/Year and Regional WIM Data**

This scenario was simulated by assuming that the week of data considered available is representative of the month to which it belongs. After excluding those involving national holidays and those having incomplete data, weeks were selected at random, and subsequently, in traffic data input 3, the MAFs were estimated from the regional vehicle classification cluster corresponding to the site in question. Traffic data inputs 1, 2, and 4 were also estimated as per scenario 1-1. Finally, traffic data element 5, the load distributions by axle type, were obtained from regional WIM data as described under scenario 2-0.

**Scenario 3-0: Continuous Site-Specific ATR Data, Regional AVC Data, and Regional WIM Data**

This scenario consists of continuous site-specific vehicle counts for an entire year combined with regional AVC and regional WIM data. These vehicle counts include vehicle classes 1 through 3: motorcycles, passenger cars, and light four-tire trucks. Although no site-specific vehicle classification or load information is available, it was assumed that there exists qualitative information to assign the site correctly to one of the AVC clusters and one of the WIM clusters developed for the agencies analyzed; therefore, the percentage of trucks at the site (classes 4 through 13) was assumed to be equal to the average of the percentage of trucks at the sites that belong to the actual AVC cluster for this site. This allowed calculation of AADTT according to the method described under scenario 1-0. Traffic data input 2 was obtained as the average of the vehicle classification distribution for the sites that belong to the actual AVC cluster for the site. Similarly, traffic data input 3 was obtained as the average of the MAFs for the sites that belong to the actual AVC cluster for the site. Traffic data input 4, the number of axles by type and vehicle class, was assumed to be equal to the statewide average for the reasons described under scenario 1-1. Traffic data input 5, the load distribution by axle configuration, was obtained as the average of the data for the actual WIM cluster to which the site belongs. It should be noted that this scenario results in a far lower variation in traffic data input than most of the scenarios described earlier because it relies on continuous regional data for the majority of the input.

**Scenario 3-1: Site-Specific ATR Data for 1 Week/Season, Regional AVC Data, and Regional WIM Data**

This scenario was simulated in a manner similar to scenario 3-0. The only difference is that vehicle volume data are considered known only for 1 month for each of 4 seasons. Traffic data input 2, 3, 4, and 5 were obtained in a similar manner to scenario 3-0. Traffic data input 1, the AADTT, was computed as described under scenario 1-1.

**Scenario 4-0: Continuous Site-Specific ATR Data, Regional AVC Data, and National WIM Data**

This scenario is similar to scenario 3-0. The only difference was that the axle-load information from the WIM cluster was replaced with information from national average WIM data. The latter was assumed to be equal to the default axle-load distributions embedded into the NCHRP 1-37A design guide software. This assumption affected only traffic data input 5, the load distribution by axle configuration.

**Scenario 4-1: Site-Specific ATR Data for 1 Week/Season, Regional AVC Data, and National WIM Data**

This scenario was simulated in a manner similar to scenario 3-1. The difference was that the axle-load information from the WIM cluster was replaced with information from national average WIM data. The latter was assumed to be equal to the default axle-load distributions embedded into the NCHRP 1-37A design guide software.

**Scenario 4-2: Site-Specific ATR Data for 1 Week/Year, Regional AVC Data, and National WIM Data**

This scenario is a variation of scenario 4-1, where only a single week of data is available per year. As in scenario 2-3, 1 week was selected at random after excluding those weeks that involved national holidays or incomplete traffic data. This week was assumed to be representative of the entire year. As in scenario 3-0, regional AVC cluster data were used to compute percentage of trucks and average MAF values were used to obtain the traffic volumes by month and truck class. National WIM data (the default values in the NCHRP 1-37A design guide software) were used for traffic data input 5.

### Scenario 4-3: Site-Specific ATR Data for 1 Weekday Plus 1 Weekend/Year, Regional AVC Data, and National WIM Data

This scenario involves ATR counts from 1 weekday and 1 weekend day. Traffic volumes on these days were weighted by 5 and 2, respectively, to compute weekly traffic volumes. All weeks that did not involve holidays or missing data were considered at random under this scenario. Subsequently, all traffic data input elements were computed as described under scenario 4-2.

### Scenarios 4-4 through 4-7: Various-Coverage, Site-Specific ATR Data, National AVC Data, and National WIM Data

These scenarios are essentially identical to scenarios 4-0, 4-1, 4-2, and 4-3, respectively. The only difference is that traffic data inputs 2 and 3 were not computed from the regional AVC data, but rather from national data. For the latter, the default vehicle classification values embedded into the NCHRP 1-37A design guide were used. In doing so, the default classification distribution for truck traffic class (TTC) type 1 was arbitrarily selected and described as a major single-trailer truck route (i.e., predominantly class 9 trucks). The default MAF values embedded into the NCHRP 1-37A design guide were 1.00 for all months and vehicle classes. For each time coverage in site-specific ATR data, the method used for computing each of the traffic data input elements to the NCHRP 1-37A design guide was described earlier.

## ESTIMATING TRAFFIC INPUT

The preceding discussion documents in detail the methodology and assumptions used in obtaining each of the five traffic data input elements to the NCHRP 1-37A design guide (table 6) for each of the 17 traffic data collection scenarios considered (table 8). A summary of the source of data used in computing each traffic data input element to the NCHRP 1-37A design guide is given in table 22.

**Table 22. Summary of the source of traffic data input to the NCHRP 1-37A design guide for the selected scenarios.**

| NCHRP 1-37A Design Guide Input | | | | | | |
|---|---|---|---|---|---|---|
| **Scenario** | **AADTT** | **Percent Trucks by Class** | **Vehicle Classification Distribution** | **MAFs** | **No. of Axles per Truck** | **Load Frequency Distribution** |
| 1-0 | SS | SS | SS | SS | SS | SS |
| 1-1 | SS | SS | SS | From VC cluster | State average | SS |
| 1-2 | SS | SS | SS | From VC cluster | State average | SS |
| 2-0 | SS | SS | SS | SS | State average | From WIM cluster |
| 2-1 | SS | SS | SS | From VC cluster | State average | From WIM cluster |
| 2-2 | SS | SS | SS | From VC cluster | State average | From WIM cluster |
| 2-3 | SS | SS | SS | From VC cluster | State average | From WIM cluster |
| 3-0 | SS | From VC cluster | From VC cluster | From VC cluster | State average | From WIM cluster |
| 3-1 | SS | From VC cluster | From VC cluster | From VC cluster | State average | From WIM cluster |
| 4-0 | SS | From VC cluster | From VC cluster | From VC cluster | State average | National average |
| 4-1 | SS | From VC cluster | From VC cluster | From VC cluster | State average | National average |
| 4-2 | SS | From VC cluster | From VC cluster | From VC cluster | State average | National average |
| 4-3 | SS | From VC cluster | From VC cluster | From VC cluster | State average | National average |
| 4-4 | SS | National average | National average | National average | National average | National average |
| 4-5 | SS | National average | National average | National average | National average | National average |
| 4-6 | SS | National average | National average | National average | National average | National average |
| 4-7 | SS | National average | National average | National average | National average | National average |

Table 23 shows the number of possible time-coverage combinations analyzed for each scenario. Obviously, the continuous data coverage scenarios (i.e., scenarios 1-0, 2-0, 3-0, 4-0, and 4-4) involve only a single time-coverage combination and, as a result, yield singular estimates of the traffic data input elements of the NCHRP 1-37A design guide (table 6). On the other hand, the discontinuous scenarios yield one set of traffic data input elements per data coverage combination. Statistics for this traffic data input were computed and their range was established as a function of the desired level of confidence.

**Table 23. Number of possible traffic sampling combinations by scenario.**

| Scenario | Time-Coverage Combinations |
|---|---|
| 1-0 | 1 |
| 1-1 | 81 |
| 1-2 | 20,736 |
| 2-0 | 1 |
| 2-1 | 81 |
| 2-2 | 20,736 |
| 2-3 | 48 |
| 3-0 | 1 |
| 3-1 | 81 |
| 4-0 | 1 |
| 4-1 | 20,736 |
| 4-2 | 48 |
| 4-3 | 480 |
| 4-4 | 1 |
| 4-5 | 20,736 |
| 4-6 | 48 |
| 4-7 | 480 |

For each confidence level, NCHRP 1-37A design guide simulations for the discontinuous time-coverage scenarios were conducted by considering the lowest percentile for all traffic input elements simultaneously (i.e., 1, 2, 3, and 5 as identified in table 6). The reason for considering traffic underprediction as critical is because it results in pavement designs that are thinner than required, which, in turn, would fail prematurely. The reason for specifying the lowest percentile of all traffic input simultaneously is because it allows computation of the statistical maximum error in pavement life predictions given a confidence level. As a result, it reflects the confidence that this level of error will not be exceeded, which, in turn, is the reliability in the pavement design process. In performing these NCHRP 1-37A design guide simulations, it was decided to keep the traffic growth rate constant for all vehicle classes (4 percent annually) to ensure comparable results between sites. The effect of the actual traffic growth rate on pavement-performance predictions for each site was studied separately and is detailed in chapter 5 of this report.

# CHAPTER 5. SENSITIVITY ANALYSIS

## EFFECT OF TRAFFIC DATA COLLECTION SCENARIO

The 30 LTPP sections described in tables 11 and 12 were used in conducting the detailed sensitivity analysis of the NCHRP 1-37A design guide related to traffic input. The traffic data were simulated according to the scenarios described above. The NCHRP 1-37A design guide analysis was conducted using site-specific layer thicknesses and climatic data as summarized in appendix C; however, no site-specific pavement layer moduli were used because the available data were in the process of being reevaluated at the time of this study. A total of 1,950 NCHRP 1-37A design guide runs were planned (i.e., 30 pavement sites × (5 continuous-coverage scenarios + 12 variable-coverage scenarios × 5 reliability levels)). For the variable-coverage scenarios, five runs accommodate only one-sided reliability (i.e., traffic underprediction, which is critical), as explained earlier. However, early in the sensitivity analysis, it was concluded that only scenario 1-0 is capable of providing 99.9 percent reliability. As a result, NCHRP 1-37A design guide simulations for this level of confidence were not conducted for all of the sections, nor were they considered in developing the final traffic data collection recommendations. Instead, a number of NCHRP 1-37A design guide runs were conducted to simulate the performance of some of the selected sections on the other end of the confidence interval (traffic overprediction) to establish the complete range of pavement life prediction estimates. NCHRP 1-37A design guide pavement-performance predictions are in terms of particular distress parameters versus time. In defining pavement life, the limiting values of these parameters had to be assumed, as described in table 24.

**Table 24. Failure criteria for each pavement type.**

| Pavement Type | Failure Mode | Limit |
|---|---|---|
| Asphalt concrete (AC) | Rutting | 10 mm (0.40 inches) |
| | Longitudinal cracking | 20 percent or 200 meters per kilometer (m/km) (1,056 feet per mile (ft/mi)) |
| Jointed plain reinforced concrete (JPRC) | Slabs cracked | 50 percent of total slabs |
| Continuously reinforced concrete (CRC) | Punchouts | 19/km (30/mi) |

Pavement life was defined as the length of time it takes to reach the limiting value for one of these distresses, called the “critical distress parameter.” An example of these pavement life predictions is shown in figure 9 for section 181028, which was estimated to fail in rutting. Note that for clarity, only the results from the continuous-coverage scenarios are shown. For the particular site, it can be seen that the traffic data collection scenarios do have a significant effect on estimated pavement life. For this example, pavement life ranges from 26 years for scenario

3-0 to 43 years for scenario 4-4, but where the true estimate (i.e., obtained under scenario 1-0) is 28 years.

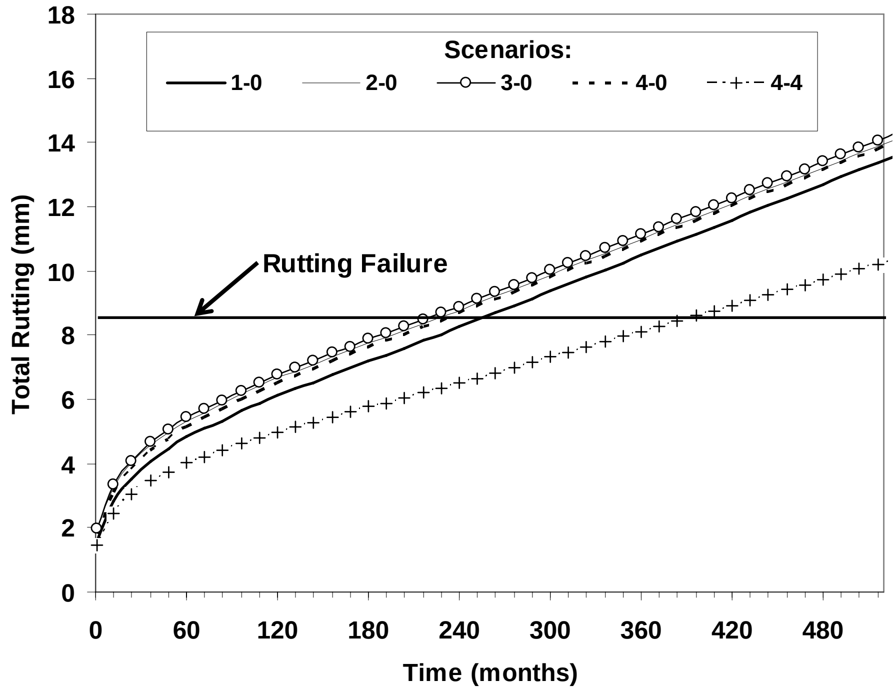



**Figure 9. Example of NCHRP 1-37A design guide output, site 181028 in Indiana.**

Obtaining pavement life from the output of the multitude of NCHRP 1-37A design guide simulations performed was automated using a macro that identified the critical pavement distress parameter and the number of years that it took to reach it. A summary of the estimated lives in years under scenario 1-0 and the critical distress parameters are given in tables 25 and 26 for the flexible and rigid sections, respectively. To facilitate interpretation of the pavement life prediction results across scenarios and confidence levels, it was decided to focus on a particular distress parameter, selected for each site, to be the one critical parameter under scenario 1-0. Furthermore, this approach allowed testing of the sensitivity of individual damage models to traffic input. As mentioned earlier, the life predictions in these two tables were obtained under an assumed annual AADTT growth rate of 4 percent. For each of the 30 sites analyzed, the results were summarized by plotting pavement life versus traffic data collection scenario by confidence level (figures 10 through 14).

**Table 25. Scenario 1-0: Life prediction and critical distress, flexible pavement sites.**

| Site | AADTT Level | Life (years) | Critical Distress |
|---|---|---|---|
| 091803 | AADTT ≤ 800 | > 99 | No distresses |
| 261004 | | 30 | Rut > 10 mm (0.4 inch) |
| 271019 | | 44 | Rut > 10 mm (0.4 inch) |
| 282807 | | 5.9 | Longitudinal cracking > 20 percent length |
| 531007 | | < 3 | Premature failure |
| 182008 | | > 99 | No distresses |
| 182009 | | > 99 | No distresses |
| 261010 | | 41 | Rut > 10 mm (0.4 inch) |
| 536048 | | 9.8 | Rut > 10 mm (0.4 inch) |
| 261012 | AADTT > 800 | 16.08 | Longitudinal cracking > 20 percent length |
| 181028 | | 30 | Rut > 10 mm (0.4 inch) |
| 186012 | | 26 | Rut > 10 mm (0.4 inch) |
| 261013 | | 26 | Rut > 10 mm (0.4 inch) |
| 283081 | | 6.8 | Longitudinal cracking > 20 percent length |
| 283093 | | < 3 | Premature failure |

**Table 26. Scenario 1-0: Life prediction and critical distress, rigid pavement sites.**

| Site | Configuration | AADTT Level | Life (years) | Critical Distress |
|---|---|---|---|---|
| 094020 | JRCP | AADTT ≤ 1200 | > 99 | No distresses |
| 263069 | JRCP | | > 99 | No distresses |
| 284024 | JRCP | | > 99 | No distresses |
| 501682 | JRCP | | 23.6 | Cracking > 50 percent slabs |
| 533813 | JRCP | | 18.7 | Cracking > 50 percent slabs |
| 185022 | CRCP | | 20.7 | Punchouts > 19/km (30/mile) |
| 94008 | JRCP | AADTT > 1200 | 5.6 | Cracking > 50 percent slabs |
| 265363 | CRCP | | 45 | Cracking > 50 percent slabs |
| 274055 | JRCP | | > 99 | No distresses |
| 275076 | CRCP | | 20.7 | Punchouts > 19/km (30/mile) |
| 95001 | CRCP | | < 3 | Premature failure |
| 185518 | CRCP | | 11.7 | Punchouts > 19/km (30/mile) |
| 264015 | JRCP | | > 99 | No distress |
| 285006 | CRCP | | < 3 | Premature failure |
| 285805 | CRCP | | < 3 | Premature failure |

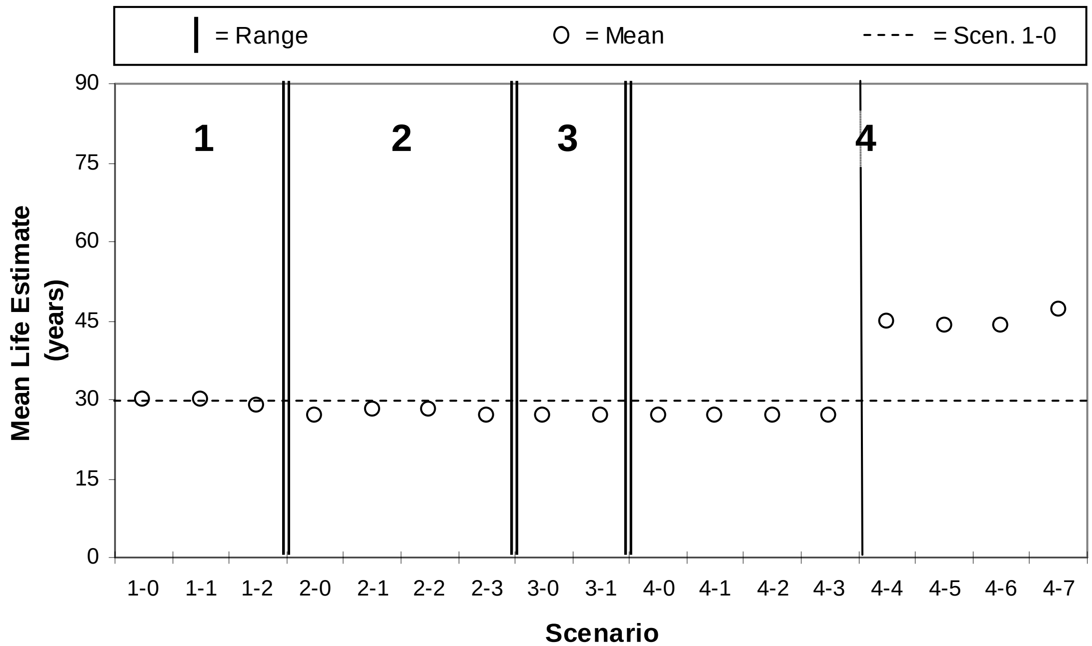



**Figure 10. Summary of mean in life predictions, site 181028 in Indiana, confidence 50 percent.**

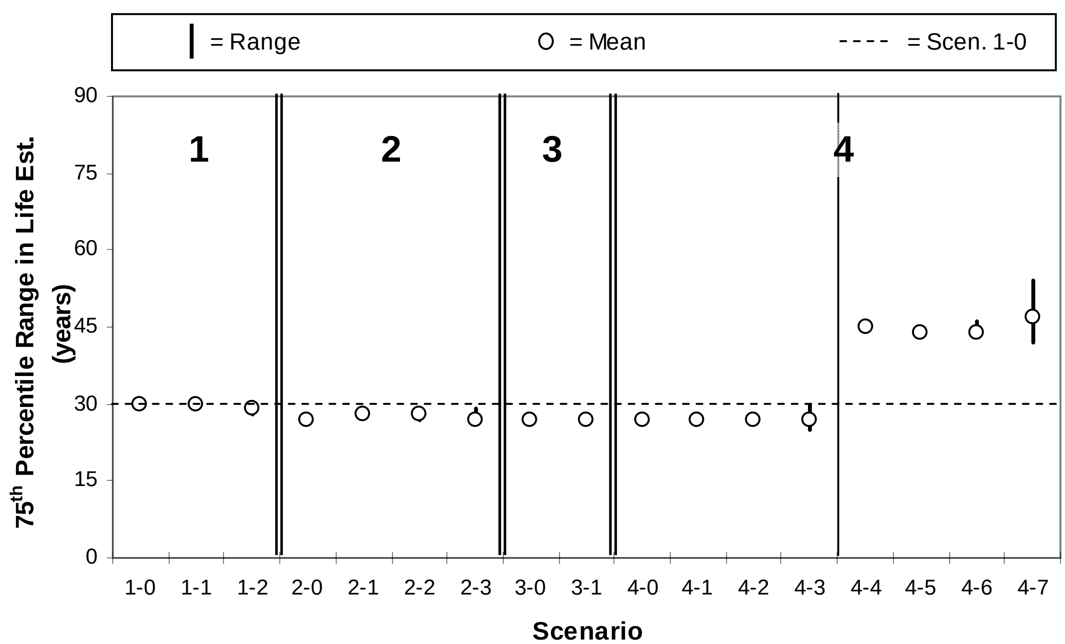



**Figure 11. Summary of the range in predictions, site 181028 in Indiana, confidence 75 percent.**

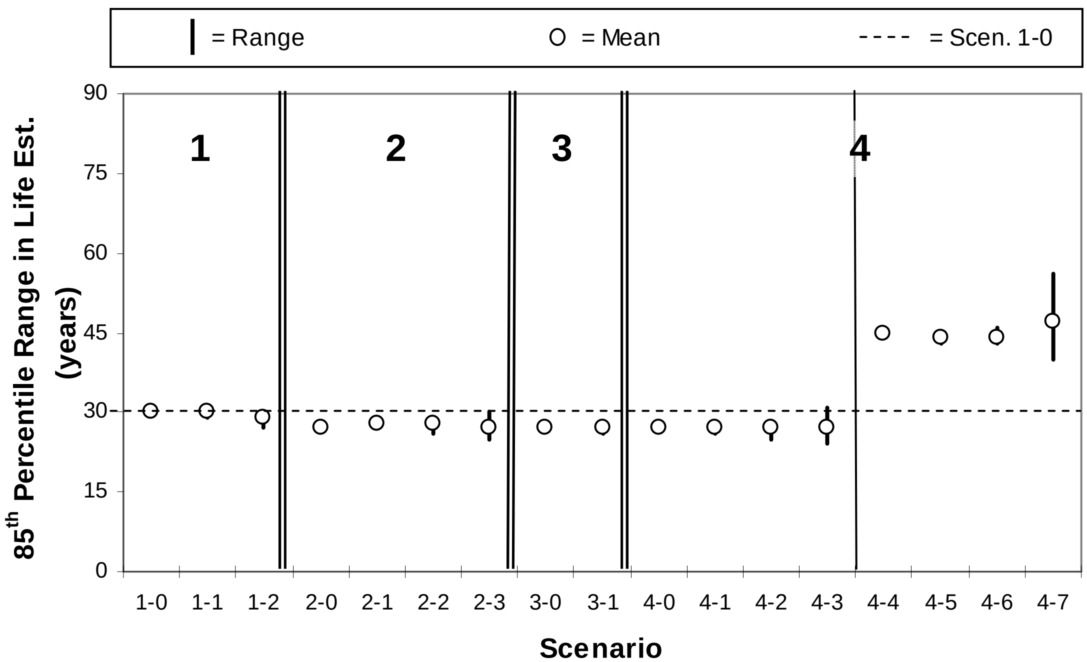



**Figure 12. Summary of the range in predictions, site 181028 in Indiana, confidence 85 percent.**

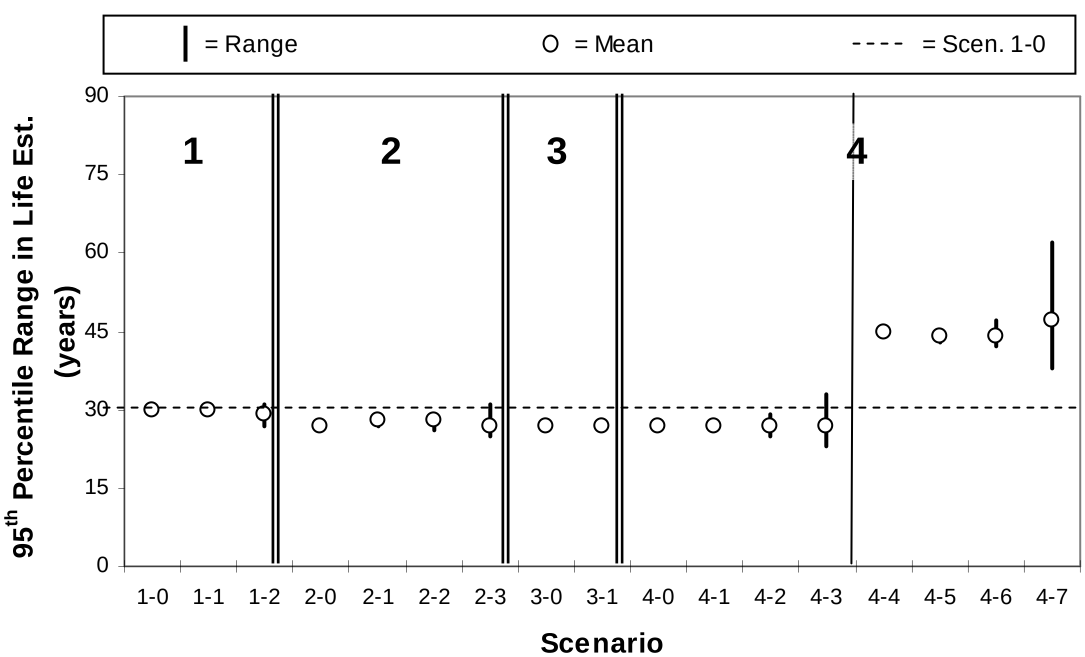



**Figure 13. Summary of the range in predictions, site 181028 in Indiana, confidence 95 percent.**

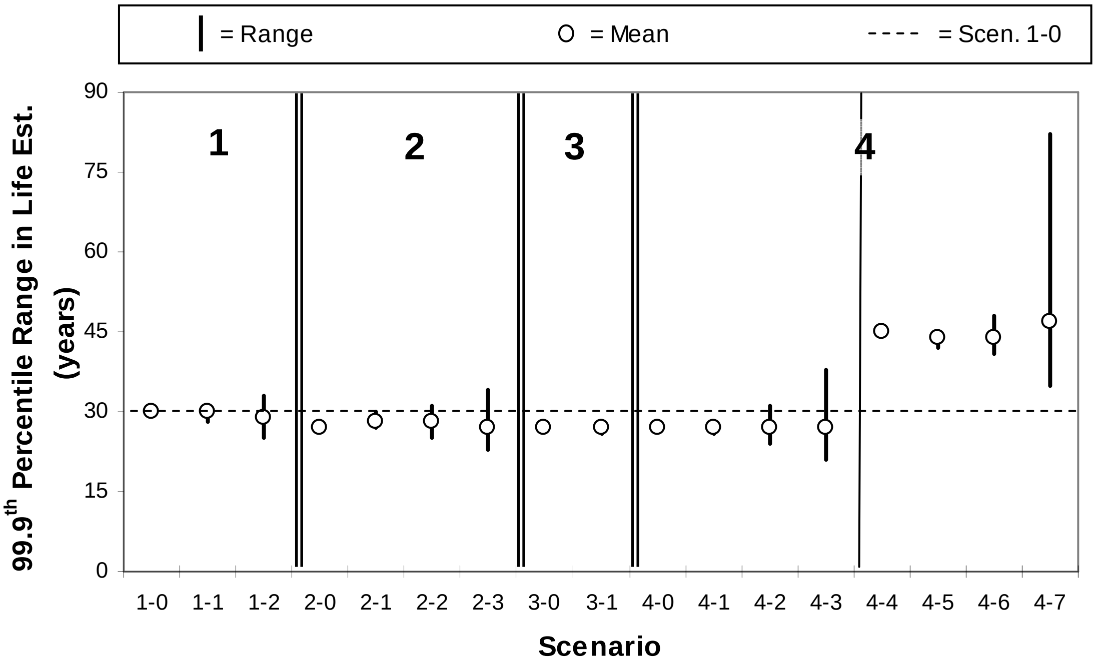



**Figure 14. Summary of the range in predictions, site 181028 in Indiana, confidence 99.9 percent.**

These plots show life predictions for both ends of the confidence interval to offer an idea of the range in pavement life predictions obtained from the discontinuous data coverage scenarios. Appendix D contains a series of tables summarizing the estimated lives by section for all scenarios and confidence levels.

## EFFECT OF AADTT GROWTH RATE

The sensitivity analysis conducted so far considered that the annual growth rate in AADTT was 4 percent for all of the scenarios simulated. Additional analyses were conducted to establish the actual annual growth rate in AADTT for the sections that had multiple traffic data years. A compound traffic formula was used for this purpose. Pavement life predictions were obtained with the NCHRP 1-37A design guide software using the actual AADTT growth rate under scenario 1-0 input. The actual growth rates calculated and the resulting pavement life predictions are shown in tables 27 and 28 for the flexible and rigid sections, respectively. In general, the actual annual AADTT growth rates differed significantly from the assumed value of 4 percent, ranging from −29 percent to +28 percent. Where actual annual AADTT growth rates were estimated to be negative, they were assumed to be equal to zero in predicting pavement performance. Furthermore, it was not possible to capacity constrain future AADTT, where the calculated annual AADTT growth rates were unusually high (i.e., the NCHRP 1-37A design guide software does not allow changing of the traffic growth rates during the analysis period). A comparison of the resulting pavement life predictions between scenario 1-0 with the assumed 4 percent annual AADTT growth rate and the actual annual AADTT growth rate are shown in figures 15 and 16, respectively.

**Table 27. Summary of computed AADTT growth rates and corresponding scenario 1-0 pavement lives, flexible pavement sites.**

| Site | Compound Annual Growth Rate in AADTT for Truck Classes 4 Through 13 (percentage) | Life (years) |
|---|---|---|
| 091803 | 18.6 | 21.8 |
| 261004 | 28.1 | 11.8 |
| 271019 | 6.2 | 32.4 |
| 282807 | 6.3 | 5.1 |
| 531007 | 9.4 | Premature failure |
| 182008 | 11.5 | No distress |
| 182009 | – | – |
| 261010 | 11.2 | 23 |
| 536048 | – | – |
| 261012 | 13.9 | 10.8 |
| 181028 | 28.1 | 11.7 |
| 186012 | 1.8 | No distress |
| 261013 | 22.5 | 11.8 |
| 283081 | – | – |
| 283093 | 9.1 | Premature failure |

– Indicates only one data year available.

**Table 28. Summary of computed AADTT growth rates and corresponding scenario 1-0 pavement lives, rigid pavement sites.**

| Site | Compound Annual Growth Rate in AADTT for Truck Classes 4 Through 13 (percentage) | Life (years) |
|---|---|---|
| 094020 | – | – |
| 263069 | 15.6 | No distress |
| 284024 | −29.3 (assumed to be 0.0) | No distress |
| 501682 | 3.8 | 23.9 |
| 533813 | 8.7 | 14.0 |
| 185022 | – | – |
| 94008 | 3.7 | 5.6 |
| 265363 | −4.1 (assumed to be 0.0) | No distress |
| 274055 | 2.9 | 21.8 |
| 275076 | – | – |
| 095001 | – | – |
| 185518 | 6.8 | 8.3 |
| 264015 | 10.0 | No distress |
| 285006 | 7.9 | Premature failure |
| 285805 | 6.0 | Premature failure |

– Indicates only one data year available.

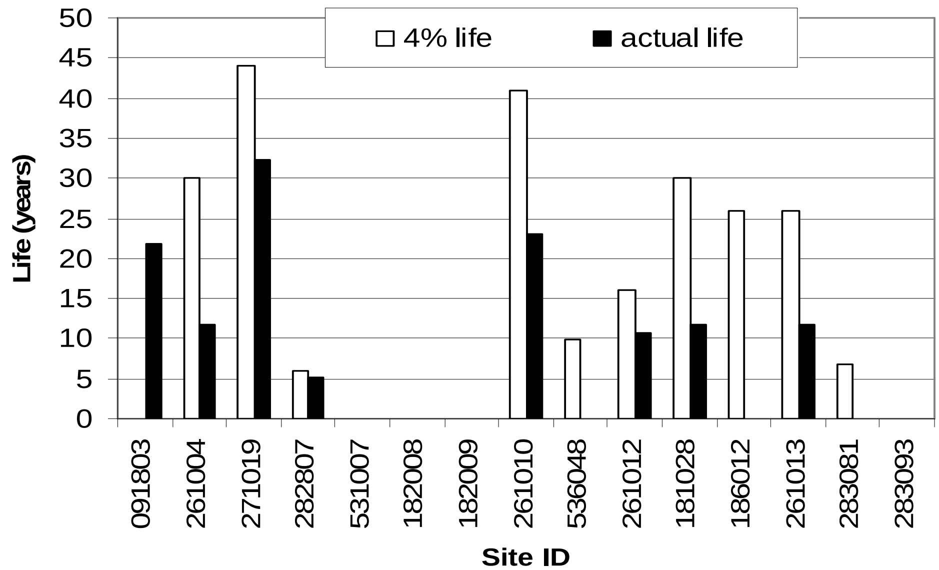



**Figure 15. Pavement life prediction comparison between actual annual AADTT growth rate and 4 percent annual AADTT growth rate, flexible pavement sites.**

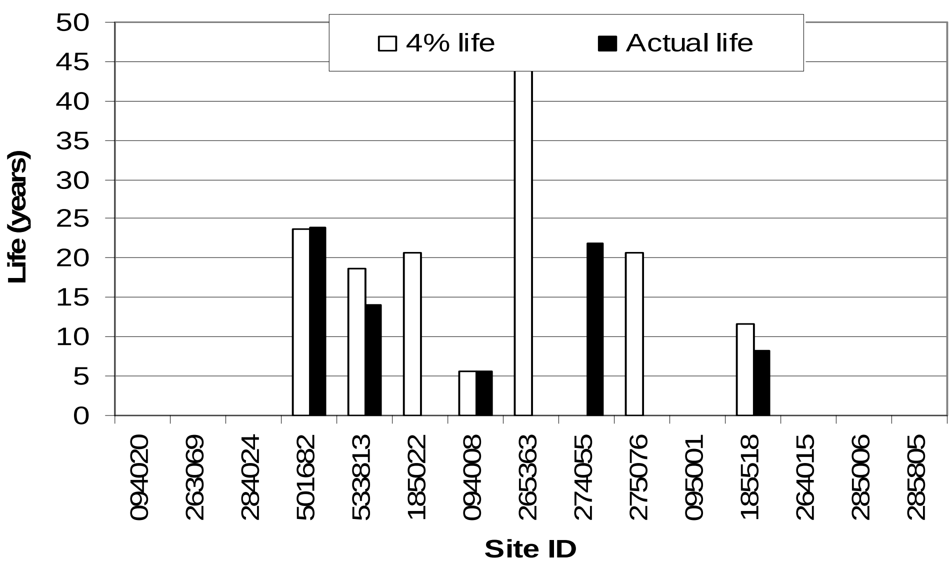



**Figure 16. Pavement life prediction comparison between actual annual AADTT growth rate and 4 percent annual AADTT growth rate, rigid pavement sites.**

As anticipated, the greater the difference between the annual AADTT growth rate and the assumed 4 percent value, the greater the difference in estimated pavement lives. These differences in pavement life were as high as 256 percent (i.e., for flexible section 181028).

## CHAPTER 6. DEFINE TRAFFIC COLLECTION REQUIREMENTS

From a pavement design point of view, traffic data collection requirements need to be established as a function of the tolerable error and the desirable confidence in NCHRP 1-37A design guide life predictions. The error is defined as the difference between pavement life predictions obtained under a particular scenario and those obtained under true traffic (scenario 1-0). This error, expressed in percentage, was determined from the series of pavement life prediction plots presented in appendix D. It comprises two components, as shown schematically in figure 17, which are labeled as “A” and “B.” “A” is the estimated error from the traffic input of a continuous scenario or the mean traffic input of a discontinuous time-coverage scenario. “B” is the additional error possible in discontinuous-coverage scenarios by considering the lowest percentile input for all traffic input estimates simultaneously. Although doing so is very conservative, it allows establishment of the statistical maximum error in predicting pavement life, and therefore, it answers the question of reliability, as explained earlier.

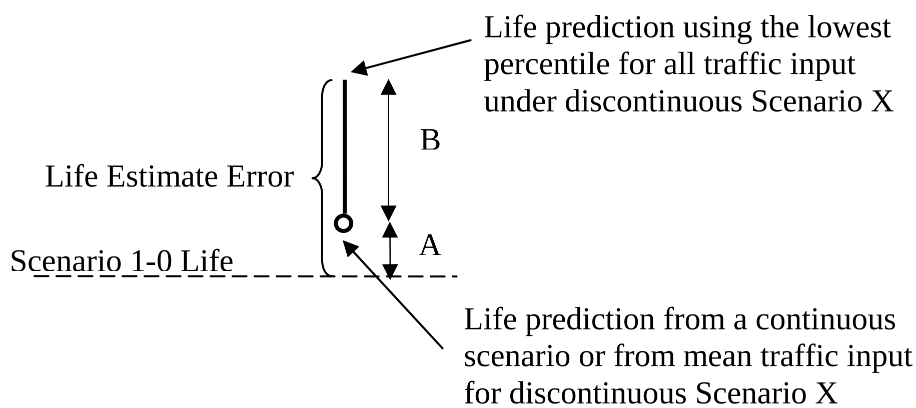



**Figure 17. Components of the percentage difference between pavement life predictions for scenario X and those for scenario 1-0.**

Statistics for quantity “A” were computed by scenario type using the NCHRP 1-37A design guide performance predictions for the sites analyzed. These results are plotted by pavement type and traffic level in figures 18 through 21. In interpreting these results, consideration was given to the source of traffic input for each scenario, as outlined in table 22. To facilitate interpretation, the scenarios in these figures were arranged in three groups:

- SS AVC, SS, or R WIM, which indicates site-specific vehicle classification distribution data combined with site-specific or regional axle-load distribution data.
- R AVC, R WIM, which indicates regional vehicle classification distribution data combined with regional axle-load distribution data.
- R or N AVC, N WIM, which indicates regional or national vehicle classification distribution data combined with national axle-load distribution data.

Analysis of figures 18 through 21 reveals the following information:

- For scenarios 1-1 through 2-3 (i.e., site-specific AVC, site-specific or regional WIM), the mean errors are relatively small and, in general, increase as site-specific information and time coverage decreases. They range from −10.8 percent to +9.9 percent.
- For the remaining scenarios (i.e., 3-0 through 4-7), the mean errors are considerably larger. This is not surprising because they rely increasingly on regional or national vehicle classification and axle-load distribution data.
- The sign of the mean errors seems random (i.e., some scenarios underpredict pavement life, while others overpredict it). For scenarios 1-1 through 2-3, this largely depends on whether the estimated MAFs resulted in higher or lower seasonal damage accumulation, respectively, than the actual MAFs. For scenarios 3-0 through 4-7, this depends on whether the regional or national vehicle classification and axle-load distributions used were heavier or lighter, respectively, than the actual ones. Given the random nature of the signs of these mean errors, it is anticipated that if a considerably larger sample of pavement-performance predictions was available, the mean errors for all of the scenarios would become negligible.
- Overall, it is observed that the standard deviation in the errors decreases as the truck traffic volumes increase (i.e., the AADTT > 800 and AADTT > 1,200 sections exhibit lower error variation than the AADTT ≤ 800 and AADTT ≤ 1,200 sections, respectively). This is not surprising, considering that short-term sampling yields more accurate AADTT estimates where traffic volumes are high.
- For scenarios 1-1 through 2-3, the standard deviation in the errors increases as site-specific information and time coverage decreases. In general, it ranges from 1.8 percent to 23 percent.
- For the remaining scenarios (i.e., 3-0 through 4-7), the standard deviation in the errors is considerably higher and, in general, it increases as site-specific information and time coverage decreases. In general, it ranges from 14.3 percent to as high as 70 percent.

Statistics for pavement prediction error component "A" were computed for all 17 sites analyzed (table 29).

Indeed, the mean values of this error component are negligible. Ranges in these errors were estimated as a function of the selected level of confidence (i.e., 100 percent minus the probability of exceeding that error), assuming that the mean error values are zero. Because the sample size is small, the Student's t-standard deviate was used. The values corresponding to one-sided probabilities of 75 percent, 85 percent, and 95 percent for 17 observations are 0.69, 1.07, and 1.74, respectively. The error ranges obtained as a function of the probability of exceeding them are listed in table 29 and plotted in figure 22.

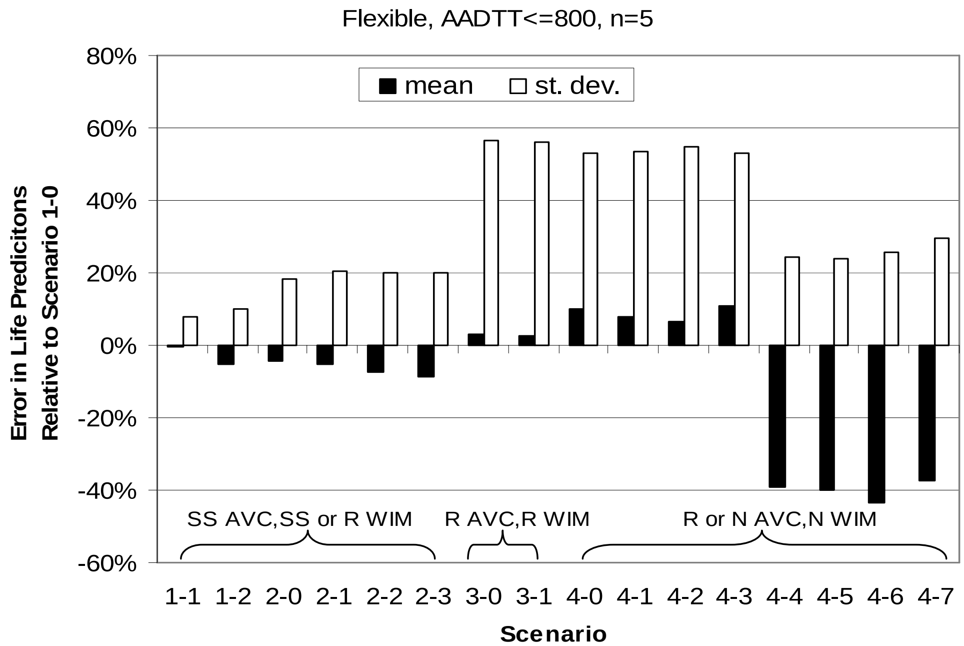



**Figure 18. Statistics for error component "A" in life predictions (percent), flexible pavement sites with AADTT ≤ 800 trucks/day/lane.**

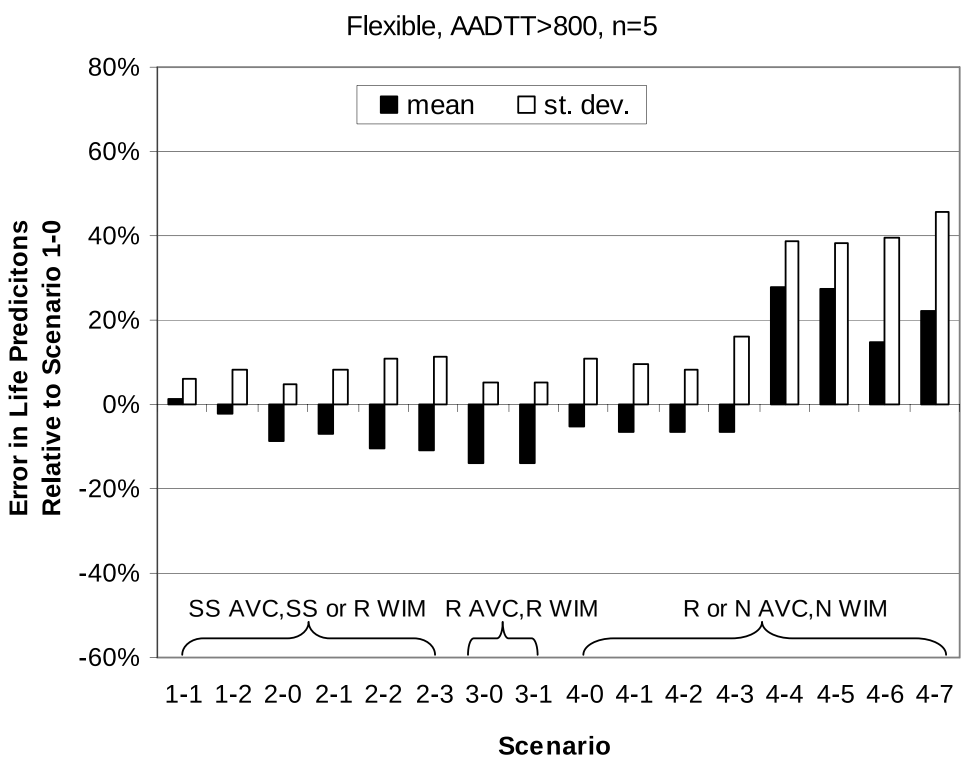



**Figure 19. Statistics for error component "A" in life predictions (percentage), flexible pavement sites with AADTT > 800 trucks/day/lane.**

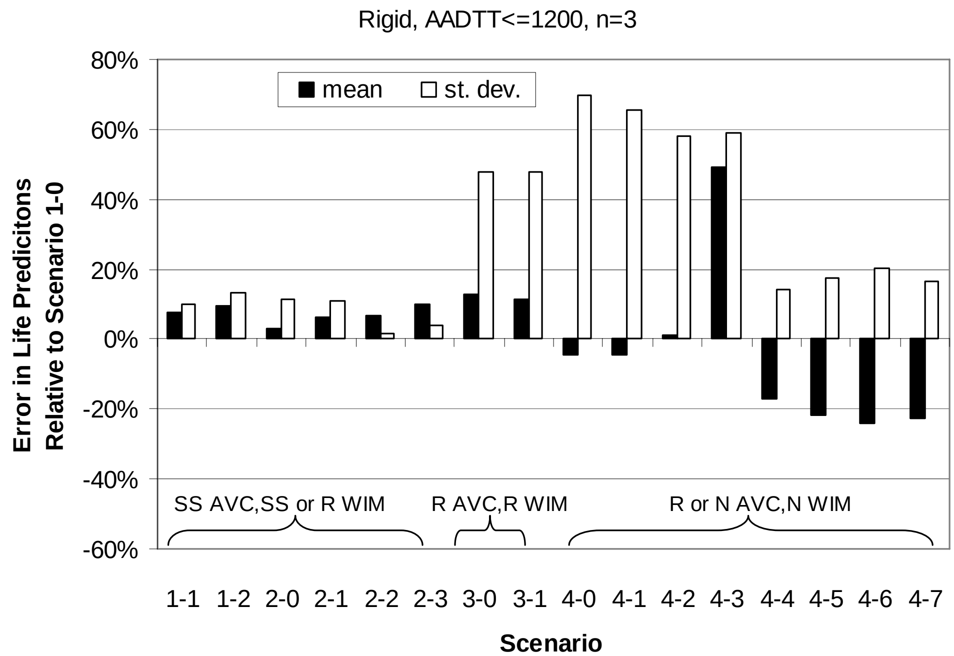



**Figure 20. Statistics for error component "A" in life predictions (percentage), rigid pavement sites with AADTT ≤ 1,200 trucks/day/lane.**

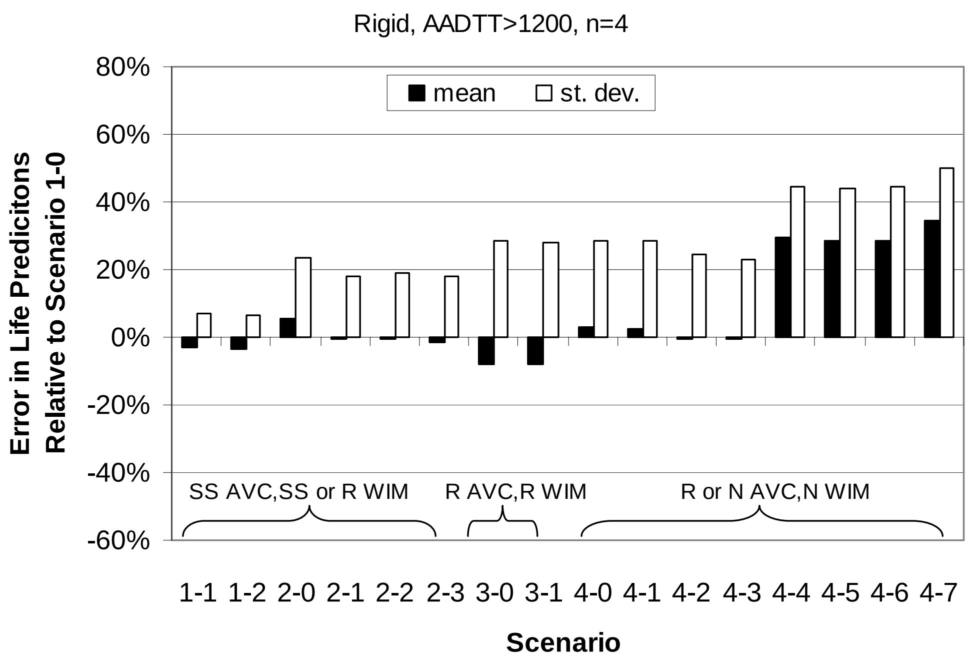



**Figure 21. Statistics for error component "A" in life predictions (percentage), rigid pavement sites with AADTT > 1,200 trucks/day/lane.**

**Table 29. Statistics and ranges for the percentage life prediction errors from mean traffic input (i.e., quantity "A"), n=17.**

| | Error Statistics | | Error Range by Probability of Exceeding Them | | |
|---|---|---|---|---|---|
| **Scenario** | **Mean** | **SD** | **25 percent** | **15 percent** | **5 percent** |
| 1-1 | 1 | 8 | 5.32 | 8.26 | 13.42 |
| 1-2 | −1 | 10 | 6.87 | 10.66 | 17.33 |
| 2-0 | −2 | 16 | 10.74 | 16.65 | 27.08 |
| 2-1 | −3 | 15 | 10.28 | 15.94 | 25.91 |
| 2-2 | −4 | 16 | 10.72 | 16.62 | 27.03 |
| 2-3 | −4 | 16 | 10.94 | 16.97 | 27.59 |
| 3-0 | −3 | 37 | 25.29 | 39.22 | 63.78 |
| 3-1 | −3 | 36 | 25.00 | 38.77 | 63.05 |
| 4-0 | 1 | 39 | 27.08 | 41.99 | 68.29 |
| 4-1 | 0 | 38 | 26.38 | 40.90 | 66.51 |
| 4-2 | 0 | 36 | 25.11 | 38.94 | 63.32 |
| 4-3 | 10 | 41 | 28.48 | 44.17 | 71.83 |
| 4-4 | 1 | 44 | 30.17 | 46.78 | 76.08 |
| 4-5 | −1 | 44 | 30.38 | 47.10 | 76.60 |
| 4-6 | −6 | 44 | 30.12 | 46.71 | 75.96 |
| 4-7 | 0 | 47 | 32.49 | 50.39 | 81.94 |

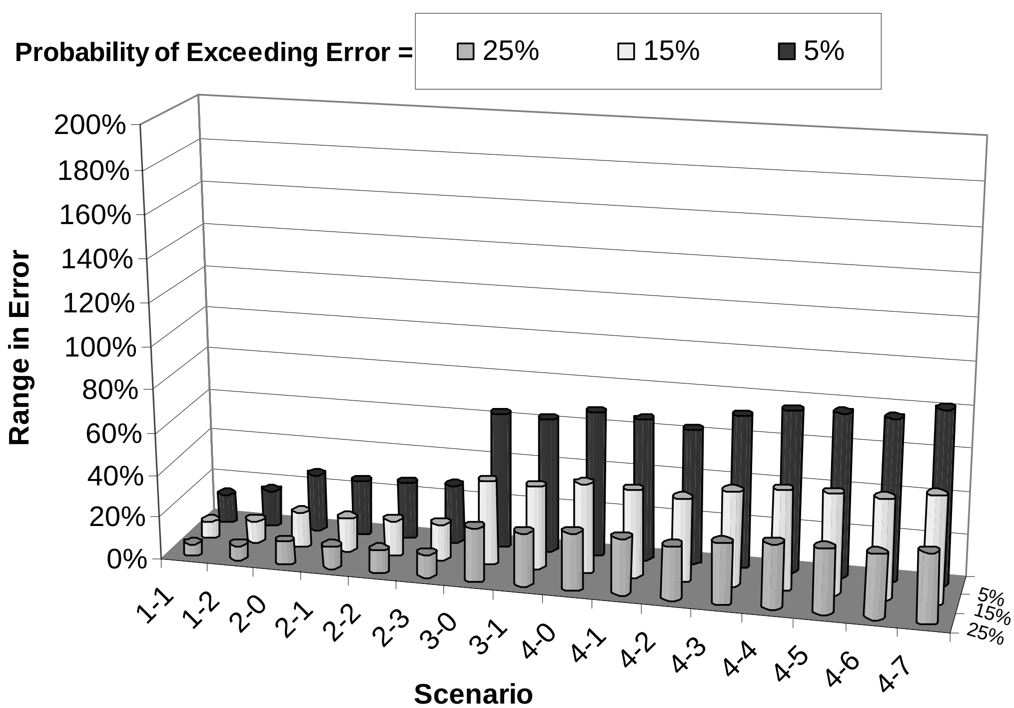



**Figure 22. Estimated range in NCHRP 1-37A design guide pavement life prediction errors from mean traffic input.**

Assuming mean traffic input, figure 22 can be used to establish the least effort traffic data collection scenario that will provide a maximum acceptable pavement life prediction error under a selected level of confidence. For example, scenarios 3-0, 3-1, and 4-2 are among the least effort scenarios capable of a 25-percent maximum error in predicting pavement life (e.g., 3.5 years in a 14-year design period) with a 75-percent confidence. A better traffic data collection scenario would be needed to either decrease the level of the acceptable error or increase the confidence that it will not be exceeded.

The error ranges described above were obtained assuming mean traffic input for each discontinuous traffic data collection scenario. Additional errors were computed because of the variation in traffic input resulting from the sampling scheme used within each of the traffic data collection scenarios that involved discontinuous time coverage. These reflect the error component "B" defined in figure 17. As described earlier, this error component in predicting pavement life was computed from the NCHRP 1-37A design guide life estimates obtained by inputting the low percentile for all of the traffic elements simultaneously. Table 30 shows the mean and the standard deviation of these errors by traffic input percentile level. It also shows the standard deviation in the mean errors computed by dividing the standard deviation of the errors by the square root of the number of degrees of freedom (i.e., $\sqrt{16}=4$), according to the central limit theorem. Table 31 gives the ranges in the mean error component "B" by traffic input percentile level. These were computed from the data in table 30 by summing the mean error plus the product of the standard deviation of the mean error multiplied by the Student's t-deviate (i.e., 0.69, 1.07, and 1.74, as described earlier).

The combined range in the two error components "A" and "B" was computed by percentile level by adding the range in the error component "A" to the range in the mean of the error of component "B." The results are shown in table 32 and plotted in figure 23. Figure 23 was compiled assuming that the lowest percentile of all of the traffic input for a discontinuous-coverage scenario could be input simultaneously during design. As mentioned earlier, this is very conservative; however, it addresses the question of reliability to guarantee the designer that a particular error level will not be exceeded given a level of confidence.

Assuming low-percentile traffic input, figure 23 can be used to establish the least-effort traffic data collection scenario that will provide a maximum acceptable pavement life prediction error under a selected level of confidence. Compared to the earlier example, scenario 3-0 is the only one among the least effort scenarios identified earlier capable of a 25-percent minimum error in predicting pavement life with a 75-percent confidence. A better traffic data collection scenario would be needed to either decrease the level of the acceptable error or increase the confidence that it will not be exceeded.

The main observations drawn from figure 23 are summarized below:

- Discontinuous traffic data collection scenarios involving site-specific WIM data (scenarios 1-1 and 1-2) are inferior to continuous-coverage, site-specific AVC data (scenario 2-0). This is because partial WIM coverage does not yield site-specific MAFs, which are necessary for accurately modeling seasonal damage in the NCHRP 1-37A design guide.

- Scenario 2-0 is capable of predicting pavement life with an error lower than 10 percent, 16 percent, and 27 percent for confidence levels of 75 percent, 85 percent, and 95 percent, respectively.
- Where continuous site-specific truck counts are combined with regional load and classification data (scenario 3-0), life prediction errors may range from 25 percent to 64 percent, depending on the desired confidence level.
- Where continuous site-specific truck counts are combined with regional classification and national load data (scenario 4-0), life prediction errors may range from 27 percent to 68 percent, depending on the desired confidence level.
- Where continuous site-specific truck counts are combined with national axle-load and classification data (scenario 4-4), life prediction errors may range from 30 percent to 76 percent, depending on the desired confidence level.

**Table 30. Statistics for percentage additional error in life predictions from lowest percentile traffic input (i.e., quantity "B").**

| | Mean Error by Traffic Input Percentile | | | Stand. Dev. of Error by Traffic Input Percentile | | | Stand. Dev. in Mean Error by Traffic Input Percentile | | |
|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | **25th** | **15th** | **5th** | **25th** | **15th** | **5th** | **25th** | **15th** | **5th** |
| 1-1 | 12.69 | 15.79 | 23.74 | 16.65 | 19.72 | 25.52 | 4.16 | 4.93 | 6.38 |
| 1-2 | 17.75 | 20.00 | 2.80 | 22.99 | 30.50 | 32.94 | 5.75 | 7.63 | 8.24 |
| 2-0 | – | – | – | – | – | – | – | – | – |
| 2-1 | 19.17 | 21.40 | 27.82 | 30.49 | 30.81 | 30.30 | 7.62 | 7.70 | 7.57 |
| 2-2 | 11.24 | 16.89 | 15.31 | 10.62 | 17.61 | 11.42 | 2.65 | 4.40 | 2.85 |
| 2-3 | 22.82 | 29.75 | 51.49 | 20.19 | 29.38 | 62.59 | 5.05 | 7.35 | 15.65 |
| 3-0 | – | – | – | – | – | – | – | – | – |
| 3-1 | 4.32 | 6.06 | 9.53 | 4.33 | 5.49 | 8.31 | 1.08 | 1.37 | 2.08 |
| 4-0 | – | – | – | – | – | – | – | – | – |
| 4-1 | 4.91 | 5.38 | 8.59 | 4.92 | 6.94 | 9.59 | 1.23 | 1.74 | 2.40 |
| 4-2 | 18.83 | 28.31 | 36.16 | 19.05 | 30.77 | 35.84 | 4.76 | 7.69 | 8.96 |
| 4-3 | 30.37 | 41.31 | 68.03 | 27.84 | 40.35 | 69.18 | 6.96 | 10.09 | 17.30 |
| 4-4 | – | – | – | – | – | – | – | – | – |
| 4-5 | 4.08 | 5.99 | 8.40 | 5.21 | 7.34 | 10.24 | 1.30 | 1.84 | 2.56 |
| 4-6 | 34.55 | 55.29 | 81.06 | 31.88 | 59.85 | 102.17 | 7.97 | 14.96 | 25.54 |
| 4-7 | 45.22 | 74.99 | 110.08 | 35.48 | 80.46 | 85.41 | 8.87 | 20.11 | 21.35 |

[a]16 degrees of freedom
– Indicates no data available.

**Table 31. Range in mean "B" errors.**

| | Range in Mean "B" Errors by Traffic Input Percentile | | |
|---|---|---|---|
| **Scenario** | **25th** | **15th** | **5th** |
| 1-1 | 15.56 | 19.19 | 28.15 |
| 1-2 | 21.72 | 25.26 | 38.48 |
| 2-0 | – | – | – |
| 2-1 | 24.43 | 26.72 | 33.05 |
| 2-2 | 13.07 | 19.93 | 17.28 |
| 2-3 | 26.30 | 34.82 | 62.28 |
| 3-0 | – | – | – |
| 3-1 | 5.07 | 7.00 | 10.96 |
| 4-0 | – | – | – |
| 4-1 | 5.76 | 6.57 | 10.24 |
| 4-2 | 22.11 | 33.62 | 42.35 |
| 4-3 | 35.17 | 48.27 | 79.96 |
| 4-4 | – | – | – |
| 4-5 | 4.98 | 7.26 | 10.17 |
| 4-6 | 40.05 | 65.61 | 98.69 |
| 4-7 | 51.34 | 88.87 | 124.81 |

**Table 32. Overall range in pavement life prediction errors ("A" plus "B" components) by probability of exceeding them.**

| Range in Combined "A" and "B" Errors by Percentile of Probability of Exceeding Them | | | |
|---|---|---|---|
| **Scenario** | **25 percent** | **15 percent** | **5 percent** |
| 1-1 | 20.89 | 27.45 | 41.57 |
| 1-2 | 28.59 | 35.91 | 55.81 |
| 2-0 | 10.74 | 16.65 | 27.08 |
| 2-1 | 34.70 | 42.65 | 58.96 |
| 2-2 | 23.79 | 36.55 | 44.31 |
| 2-3 | 37.24 | 51.79 | 89.88 |
| 3-0 | 25.29 | 39.22 | 63.78 |
| 3-1 | 30.07 | 45.78 | 74.02 |
| 4-0 | 27.08 | 41.99 | 68.29 |
| 4-1 | 32.14 | 47.47 | 76.75 |
| 4-2 | 47.22 | 72.55 | 105.66 |
| 4-3 | 63.66 | 92.44 | 151.79 |
| 4-4 | 30.17 | 46.78 | 76.08 |
| 4-5 | 35.36 | 54.36 | 86.77 |
| 4-6 | 70.17 | 112.32 | 174.65 |
| 4-7 | 83.84 | 139.25 | 206.75 |

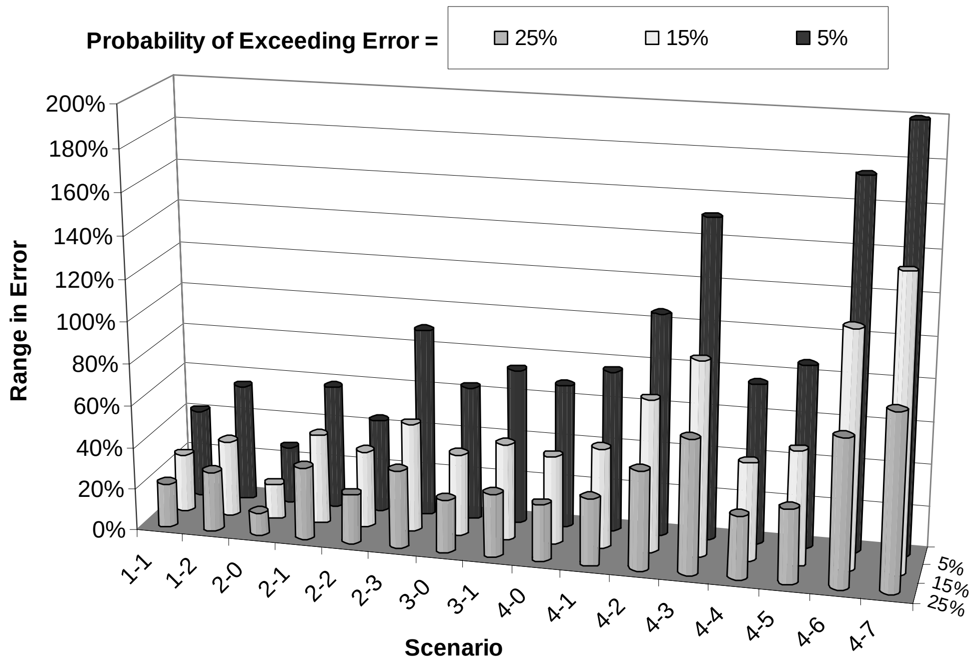



**Figure 23. Estimated range in NCHRP 1-37A design guide pavement life prediction errors from low-percentile traffic input.**

# CHAPTER 7. SUMMARY

This study presented a comprehensive approach for establishing the minimum traffic data collection effort required for pavement design applications satisfying a maximum acceptable error under a prescribed confidence level. This approach consists of simulating the traffic data input to the new NCHRP 1-37A design guide for 17 distinct traffic data collection scenarios using extended-coverage WIM data from the LTPP database.

Extended coverage was defined as 299 or more days per year of level E WIM data. Analysis of Data Release 16.0 revealed a total of 178 GPS sites that satisfied this requirement. For all of these sites, CTDB data were extracted in the form of daily summaries (level 3). From these sites, a total of 30 sites (15 flexible and 15 rigid) were selected for NCHRP 1-37A design guide simulation. The selection was based on the widest possible distribution of AADTT volumes and structural thicknesses.

A number of the traffic data collection scenarios simulated involved continuous site-specific data coverage for axle loads, classification, or counts, while others involved discontinuous site-specific data coverage (e.g., 1 month per season, 1 week per season, and so on). Data elements that were assumed to be unavailable at a site for simulation purposes were estimated from regional data. Regional vehicle classification and load data were obtained from the remaining LTPP sites identified using clustering techniques. Scenarios involving national data used the default traffic input in the NCHRP 1-37A design guide. For each of the traffic data collection scenarios involving discontinuous coverage of site-specific data, statistics for each traffic data element were computed by considering all possible time-coverage combinations. This allowed establishment of the lowest percentiles for each of these input to simulate underestimation of the actual traffic volumes/loads at a site. This was considered to be critical because it would result in thinner pavement designs that failed prematurely. Three confidence levels were selected: 75 percent, 85 percent, and 95 percent. Traffic inputs for the continuous-coverage traffic data collection scenarios involved no variation because of the sampling scheme used. All scenarios were simulated using a 4-percent annual growth in AADTT. Additional analyses were conducted to compute the annual growth rate in AADTT and its effect on pavement life predictions.

The NCHRP 1-37A design guide pavement life predictions for each scenario were analyzed to compute percentage errors in pavement life predictions with respect to the life predictions obtained under continuous site-specific WIM data (scenario 1-0). Reasonable life predictions were obtained for 17 of the 30 sections analyzed (the remainder experienced either premature failures or no failure at all). Two error components were identified:

- “A” is the estimated error from the traffic input of a continuous scenario or from the mean traffic input of a discontinuous time-coverage scenario.
- “B” is the additional error possible in discontinuous-coverage scenarios by inputting the lowest percentile input for all of the traffic input estimates simultaneously.

Computing statistics for error component “A” for all 17 sections revealed that its mean is negligible for all of the scenarios analyzed. Its standard deviation allowed for the establishment of a range of errors by confidence level (table 29 and figure 22). Statistics for error component “B” were processed to yield the mean error and the standard deviation in the mean error by traffic data collection scenario. This allowed computation of the range in mean error resulting from specifying the lowest percentile for all of the traffic input simultaneously. It was noted that this is very conservative; however, it addresses the question of reliability, guaranteeing the designer that given a level of confidence, a particular error level will not be exceeded. Overall error was computed by adding the range in error from component "A" to the range in mean error from component "B." The results were plotted in a three-dimensional plot, indicating the maximum error by confidence level for each of the traffic data collection scenarios analyzed (table 32 and figure 23). Figure 23 can be used to establish the minimum required traffic data collection effort given the acceptable error and the desirable level of confidence.

# APPENDIX A. CARD-4 AND CARD-7 DESCRIPTIONS

**Table 33. Card-4: Vehicle classification record.**

| Columns | Width | Description |
|---:|:---:|---|
| 1 | 1 | Vehicle classification record code (4) |
| 2–3 | 2 | State code |
| 4−5 | 2 | Functional classification |
| 6−8 | 3 | Station identification number |
| 9 | 1 | Direction of travel |
| 10−11 | 2 | Year of data |
| 12−13 | 2 | Month of data |
| 14−15 | 2 | Date of month |
| 16−17 | 2 | Hour of day |
| 18−19 | 2 | Number of motorcycles (optional) |
| 20−23 | 4 | Number of passenger cars or all two-axle, four-tire, single-unit vehicles |
| 24−26 | 3 | Number of other two-axle, four-tire, single-unit vehicles |
| 27−28 | 2 | Number of buses |
| 29−31 | 3 | Number of two-axle, six-tire, single-unit trucks |
| 32−33 | 2 | Number of three-axle, single-unit trucks |
| 34−35 | 2 | Number of four- or more axle, single-unit trucks |
| 36−37 | 2 | Number of four- or less axle, single-trailer trucks |
| 38−40 | 3 | Number of five-axle, single-trailer trucks |
| 41−42 | 2 | Number of six- or more axle, single-trailer trucks |
| 43−44 | 2 | Number of five- or less axle, multi-trailer trucks |
| 45−46 | 2 | Number of six-axle, multi-trailer trucks |
| 47−48 | 2 | Number of seven- or more axle, multi-trailer trucks |
| 49 | 1 | Motorcycle reporting indicator |
| 50 | 1 | Vehicle class combination indicator |
| 51 | 1 | Lane of travel: 0 = combined lanes, 1 = outside (rightmost) lane, 2 through 9 = other lanes in order toward innermost lane |
| 52−80 | 31 | Blank or optional State data |

## Table 34. Card-7: Truck weight record.

| Columns | Width | Description |
|---|---|---|
| | | **FACE RECORD** |
| 1 | 1 | Truck weight record code (7) |
| 2−3 | 2 | State code |
| 4−5 | 2 | Functional classification |
| 6−8 | 3 | Station identification number |
| 9 | 1 | Direction of travel |
| 10−11 | 2 | Year of data |
| 12−13 | 2 | Month of data |
| 14−15 | 2 | Date of month |
| 16−17 | 2 | Hour of day |
| 18−23 | 6 | Vehicle type code |
| 24−27 | 4 | (open) |
| 28 | 1 | Day of week (optional) |
| 29−34 | 6 | (open) |
| 35 | 1 | Lane of travel |
| 36−41 | 6 | (open) |
| 42−45 | 4 | Total weight of truck or combination |
| 46−48 | 3 | A axle weight (hundreds of pounds) |
| 49−51 | 3 | B axle weight (hundreds of pounds) |
| 52−54 | 3 | C axle weight (hundreds of pounds) |
| 55−57 | 3 | D axle weight (hundreds of pounds) |
| 58−60 | 3 | E axle weight (hundreds of pounds) |
| 61−63 | 3 | A-B axle spacing (feet and tenths) |
| 64−66 | 3 | B-C axle spacing (feet and tenths) |
| 67−69 | 3 | C-D axle spacing (feet and tenths) |
| 70−72 | 3 | D-E axle spacing (feet and tenths) |
| 73−76 | 4 | Total wheelbase (feet and tenths) |
| 77−79 | 3 | Record serial number |
| 80 | 1 | Continuation indicator: 0 = no continuation record,<br>1 = has a continuation record |
| | | **CONTINUATION RECORD*** |
| 1−23 | 23 | Same as columns 1 through 23 of the face record |
| 23−28 | 5 | (open) |
| 29−31 | 3 | F axle weight (hundreds of pounds) |
| 32−34 | 3 | G axle weight (hundreds of pounds) |
| 35−37 | 3 | H axle weight (hundreds of pounds) |
| 38−40 | 3 | I axle weight (hundreds of pounds) |
| 41−43 | 3 | J axle weight (hundreds of pounds) |
| 44−46 | 3 | K axle weight (hundreds of pounds) |
| 47−49 | 3 | L axle weight (hundreds of pounds) |
| 50−52 | 3 | M axle weight (hundreds of pounds) |
| 53−55 | 3 | E-F axle spacing (feet and tenths) |
| 56−58 | 3 | F-G axle spacing (feet and tenths) |
| 59−61 | 3 | G-H axle spacing (feet and tenths) |
| 62−64 | 3 | H-I axle spacing (feet and tenths) |
| 65−67 | 3 | I-J axle spacing (feet and tenths) |
| 68−70 | 3 | J-K axle spacing (feet and tenths) |
| 71−73 | 3 | K-L axle spacing (feet and tenths) |
| 74−76 | 3 | L-M axle spacing (feet and tenths) |

**Table 34. Card-7: Truck weight record (continued).**

| CONTINUATION RECORD* | | |
|---|---|---|
| **Columns** | **Width** | **Description** |
| 77–79 | 3 | Record serial number (same as face record) |
| 80 | 1 | Continuation indicator: 2 = first continuation record for a vehicle with more than 13 axles, 9 = last continuation record |

[a] Used only for truck combinations having six or more axles. Immediately follows the face record.

## APPENDIX B. CLUSTER ANALYSIS RESULTS

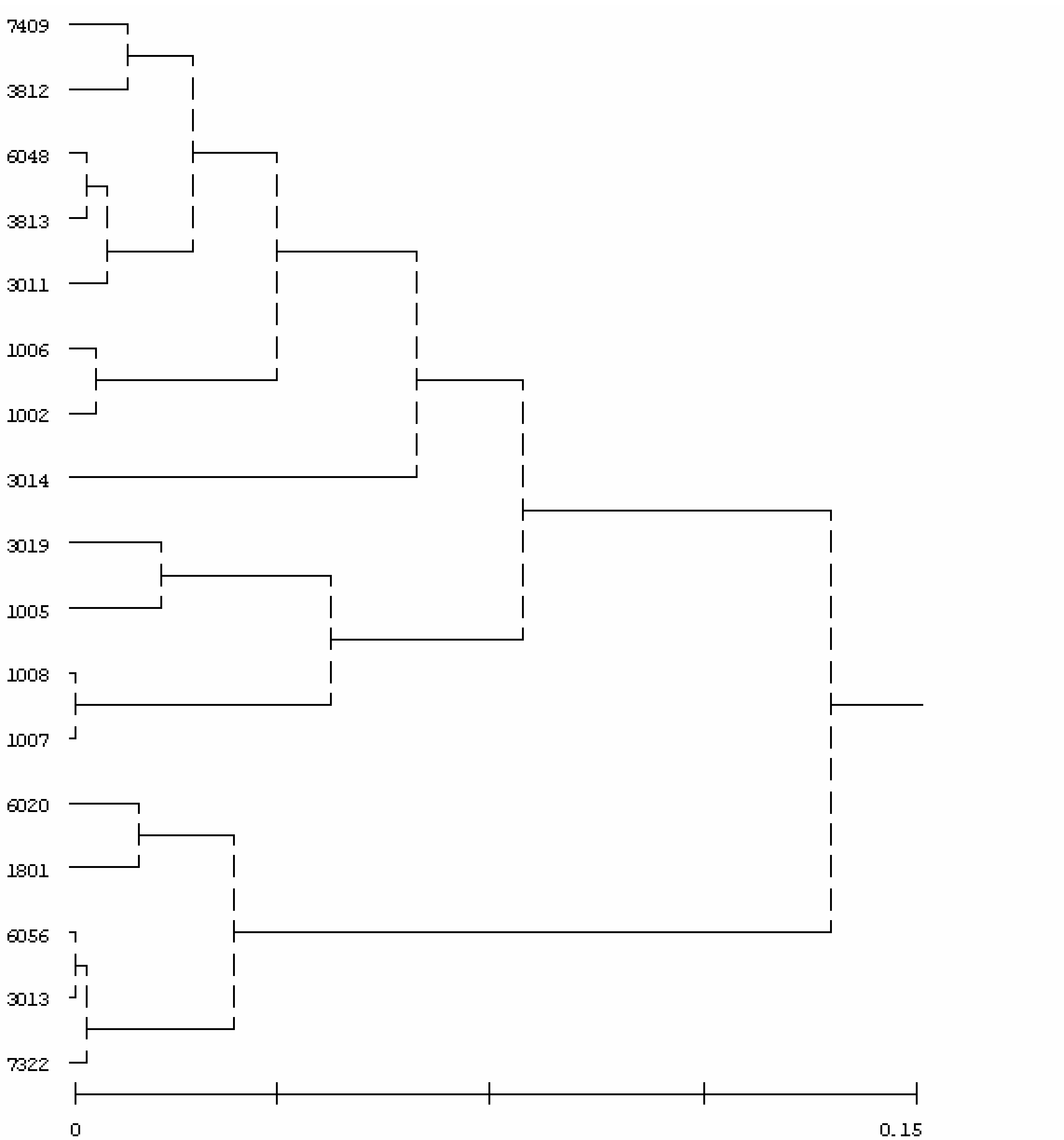



**Figure 24. Clusters of LTPP sites by annual tandem-axle load distribution, Washington State.**

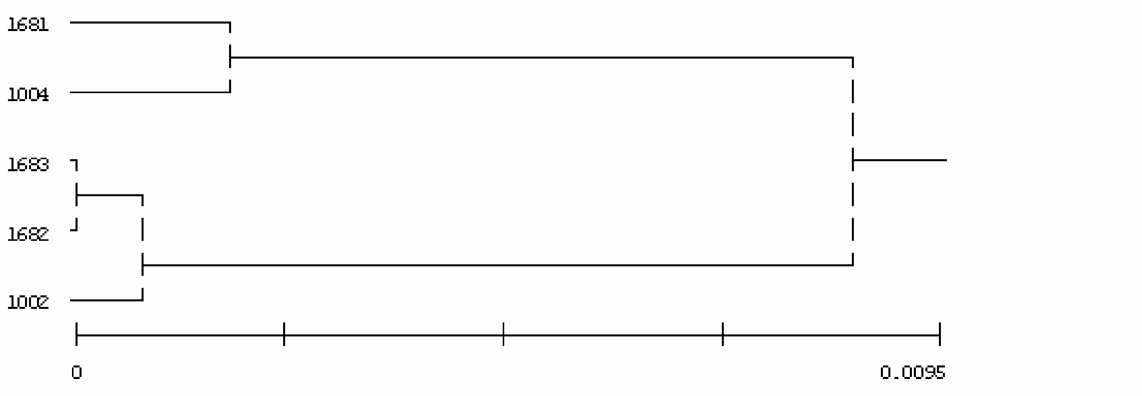



Figure 25. Clusters of LTPP sites by annual tandem-axle load distribution, Vermont.

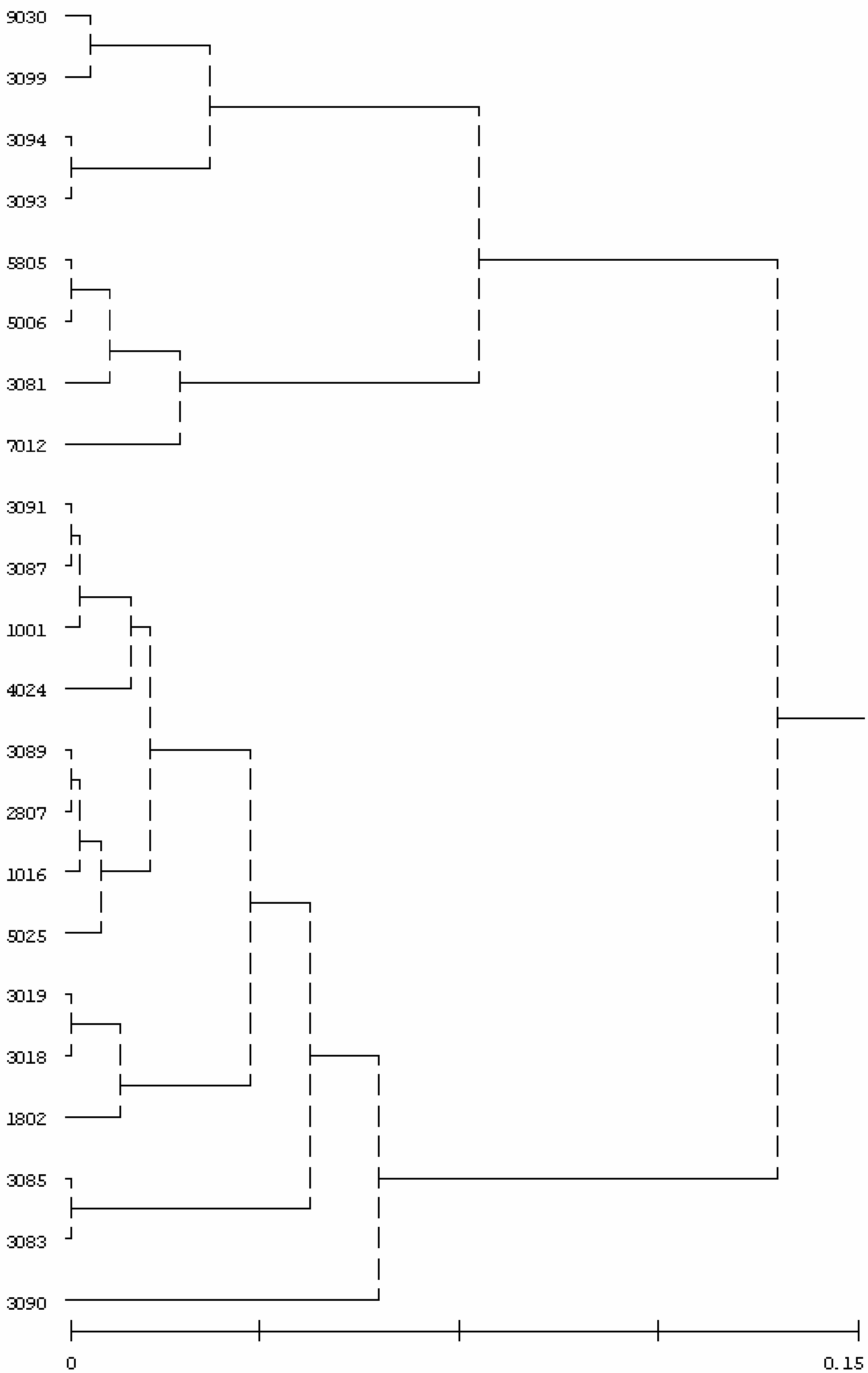



**Figure 26. Clusters of LTPP sites by annual tandem-axle load distribution, Mississippi.**

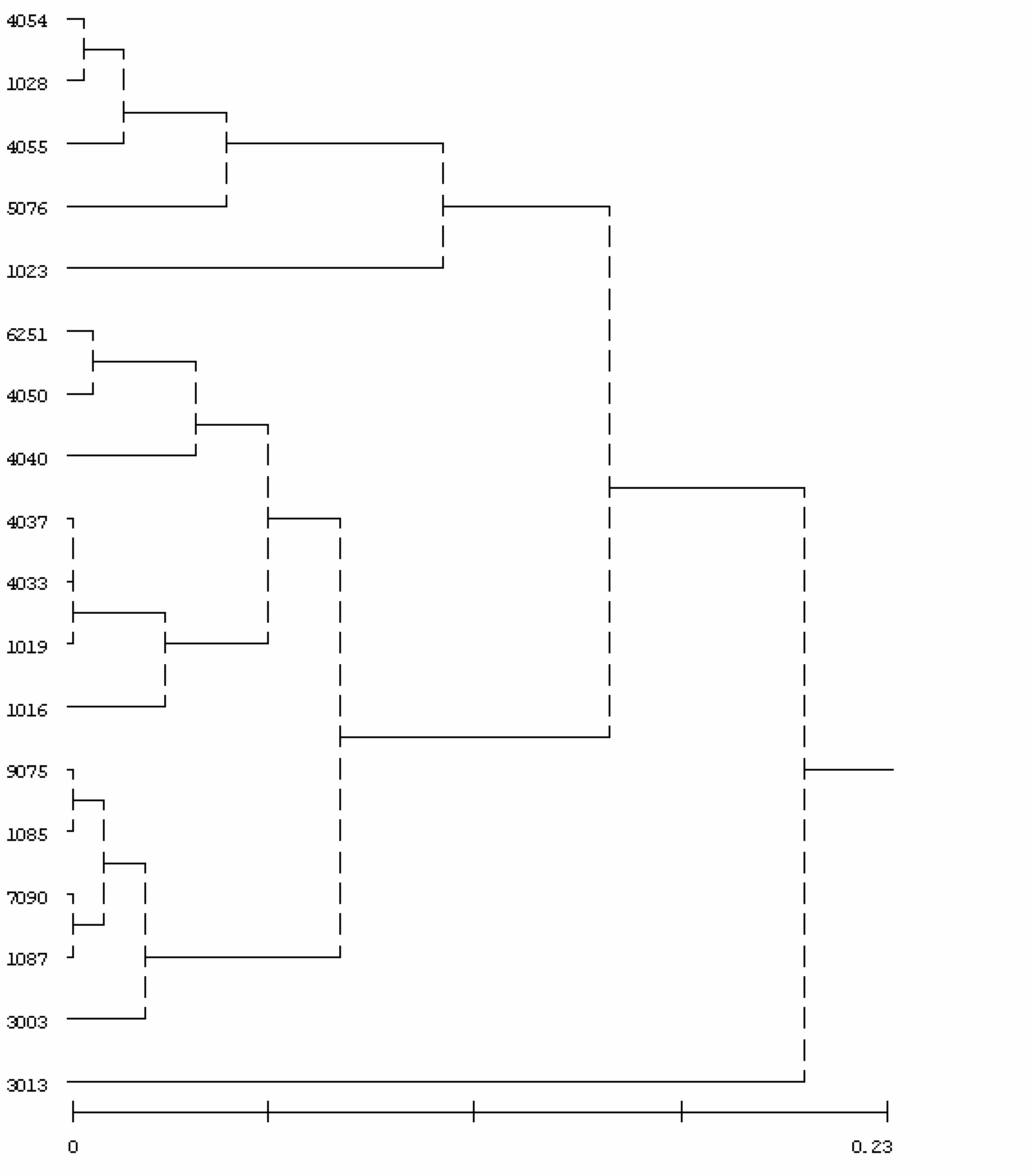



**Figure 27. Clusters of LTPP sites by annual tandem-axle load distribution, Minnesota.**

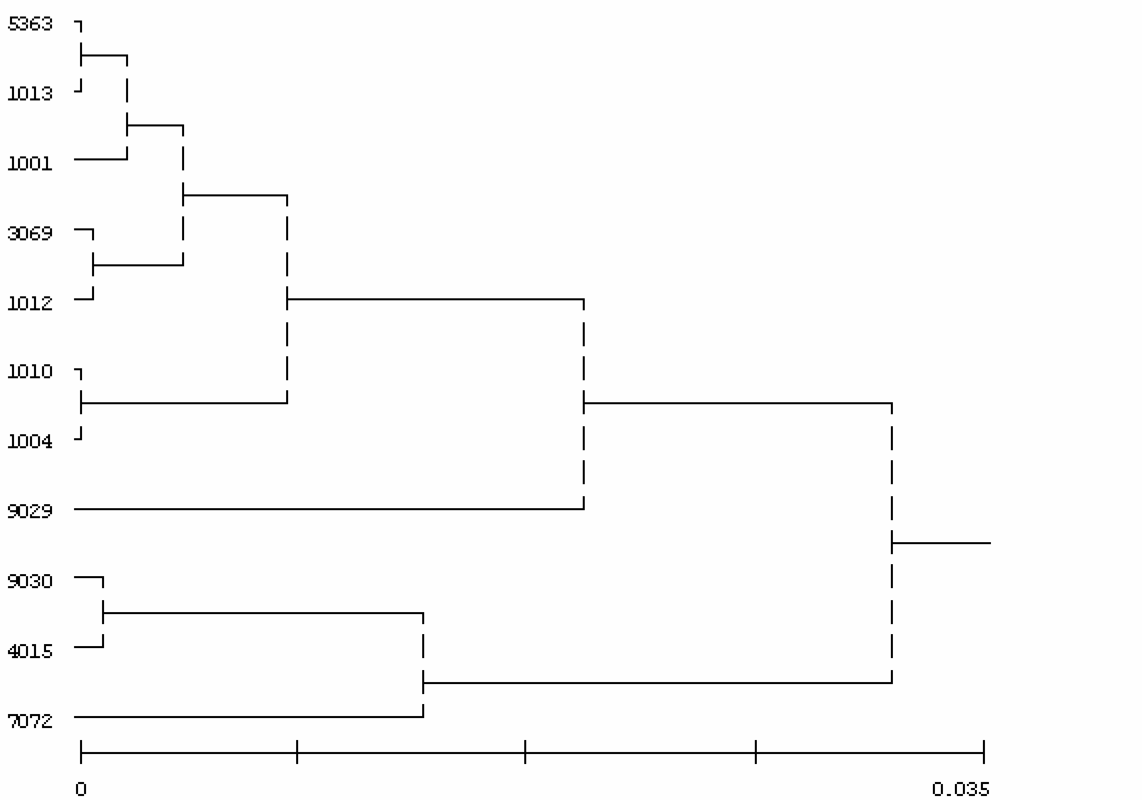



**Figure 28. Clusters of LTPP sites by annual tandem-axle load distribution, Michigan.**

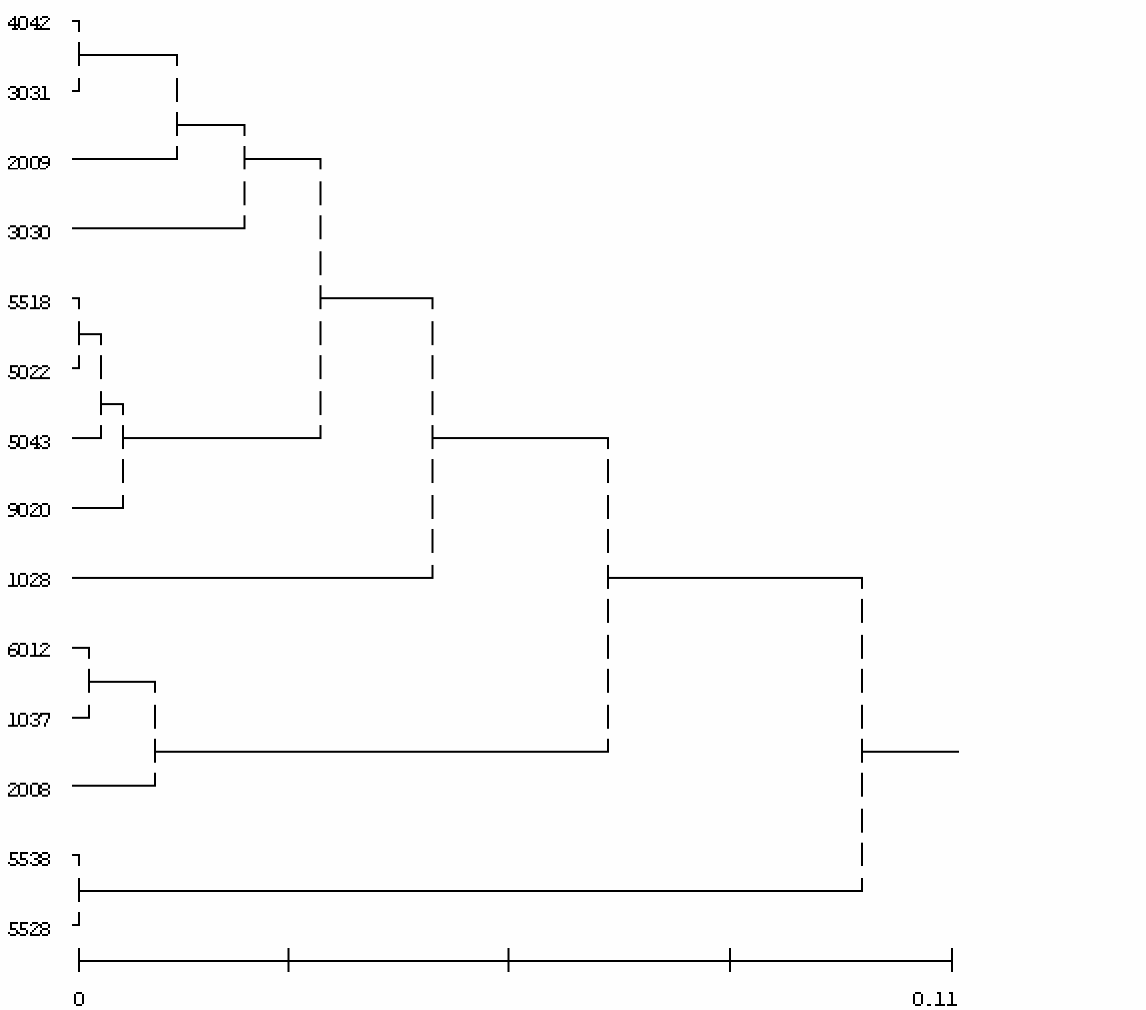



**Figure 29. Clusters of LTPP sites by annual tandem-axle load distribution, Indiana.**

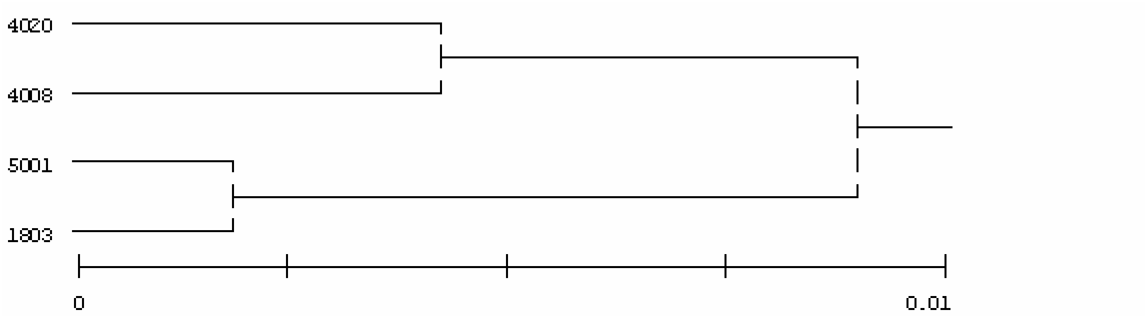



**Figure 30. Clusters of LTPP sites by annual tandem-axle load distribution, Connecticut.**

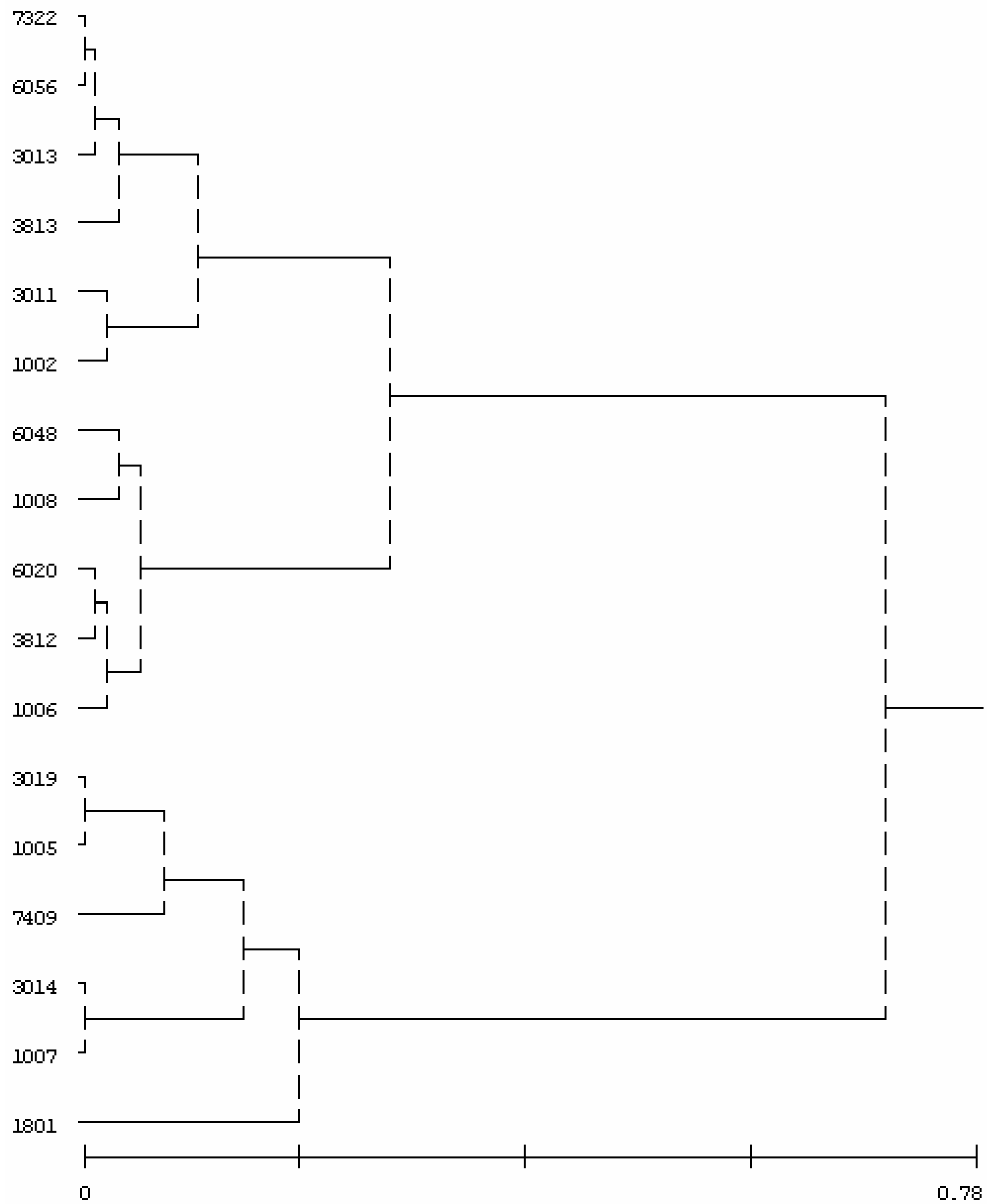



**Figure 31. Clusters of LTPP sites by annual average truck class distribution, Washington State.**

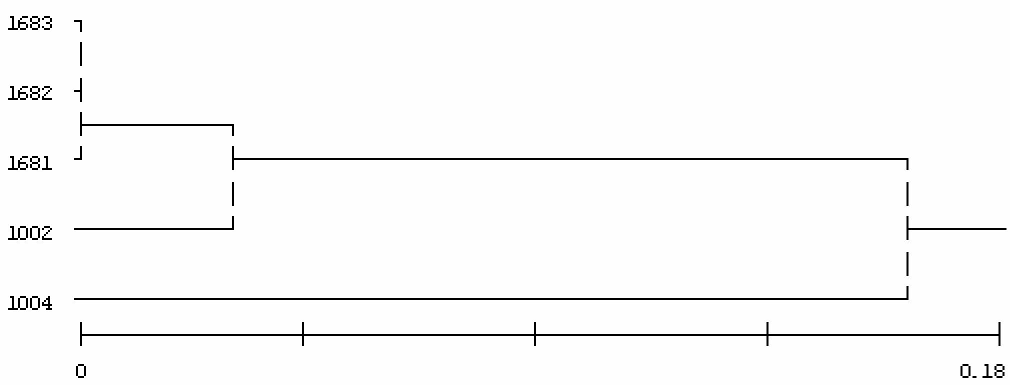



**Figure 32. Clusters of LTPP sites by annual average truck class distribution, Vermont.**

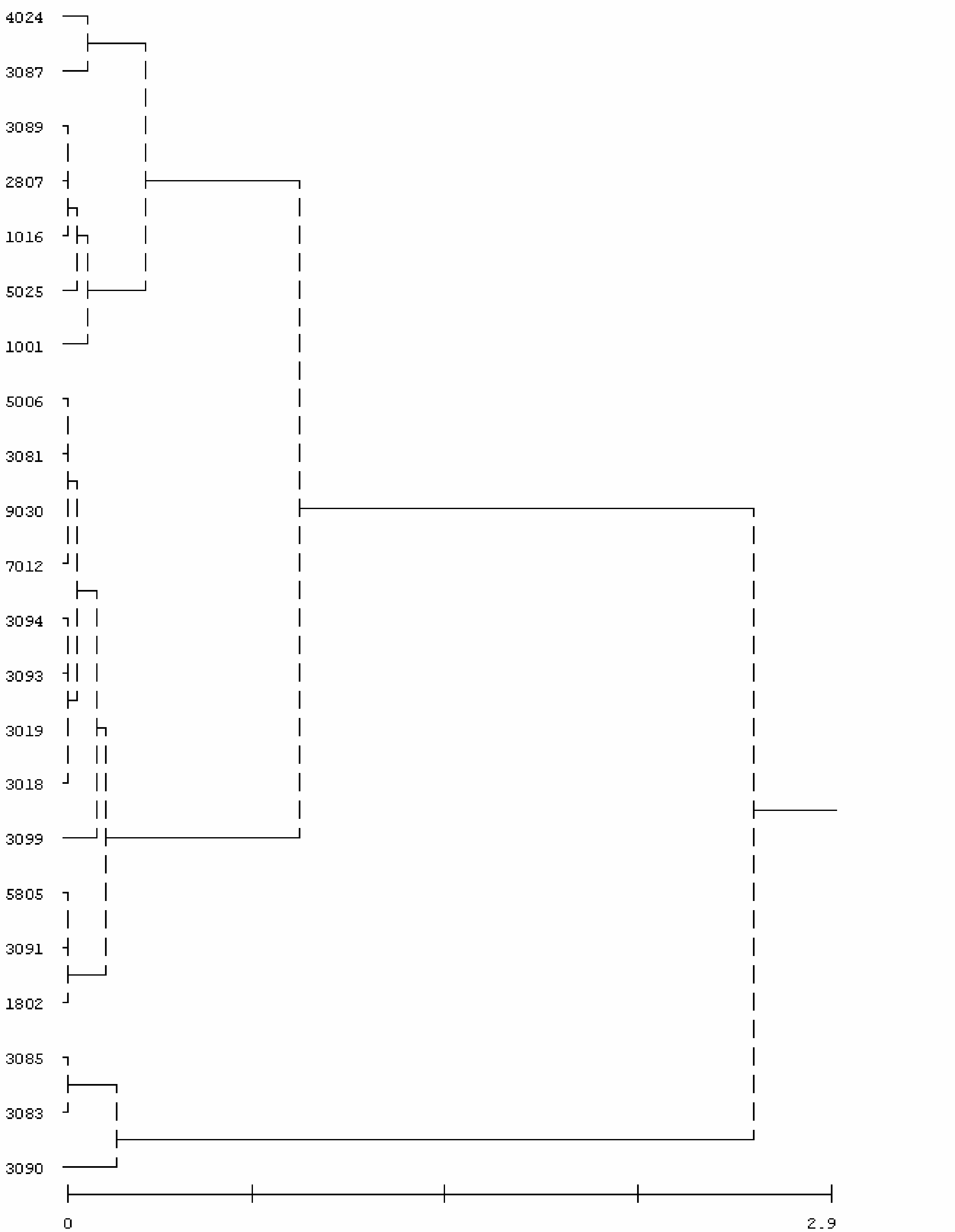



**Figure 33. Clusters of LTPP sites by annual average truck class distribution, Mississippi.**

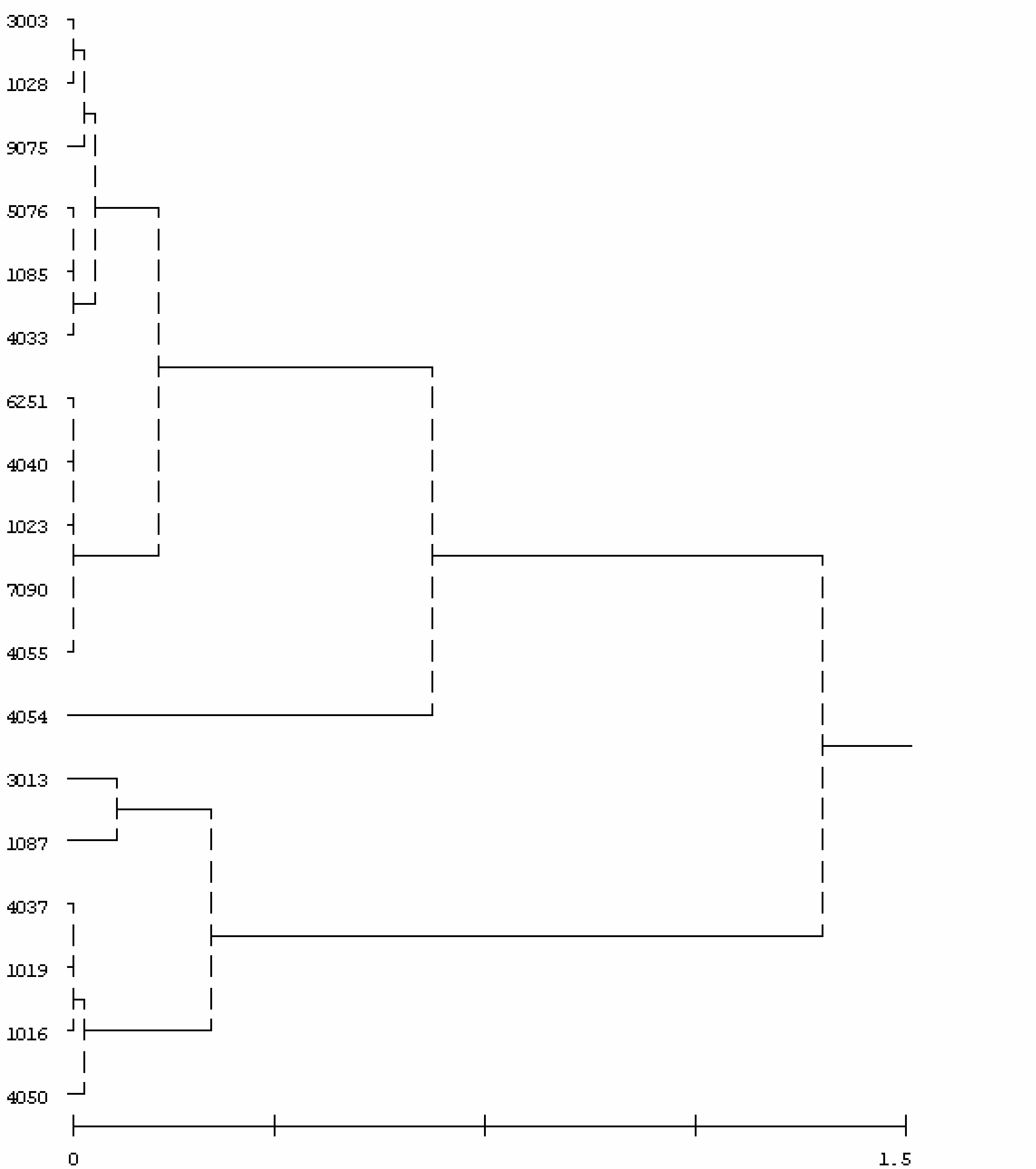



**Figure 34. Clusters of LTPP sites by annual average truck class distribution, Minnesota.**

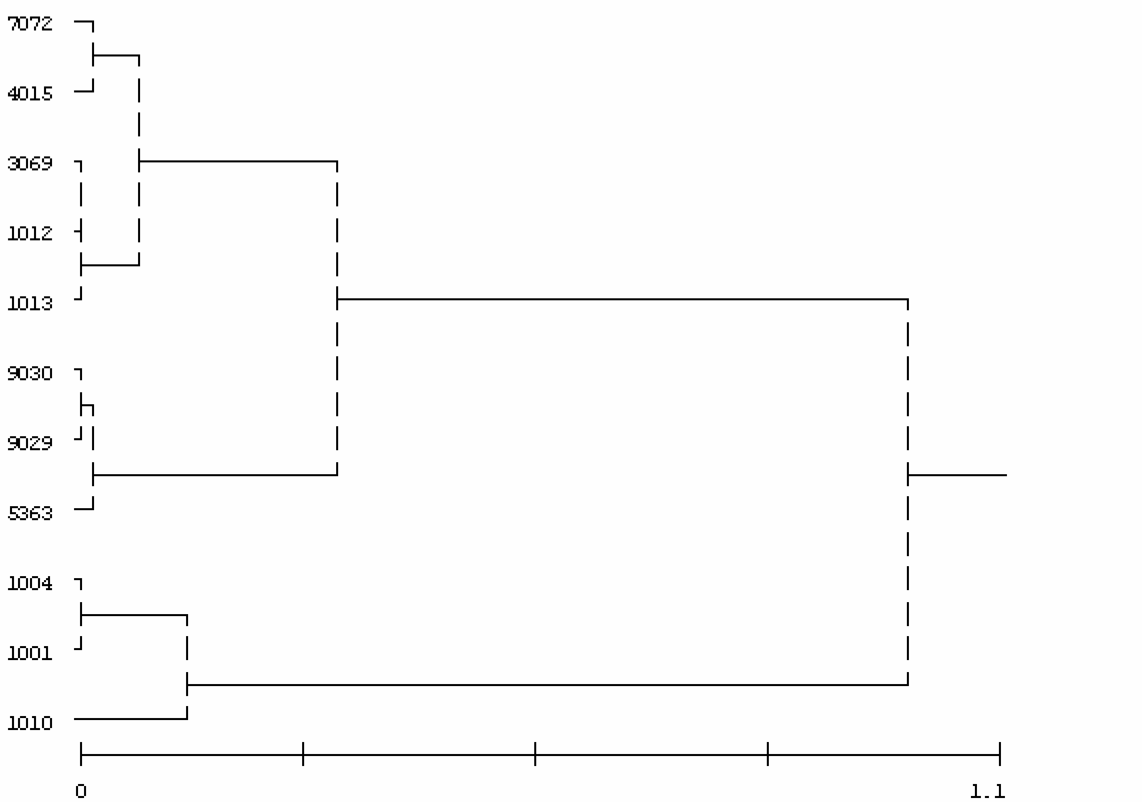



**Figure 35. Clusters of LTPP sites by annual average truck class distribution, Michigan.**

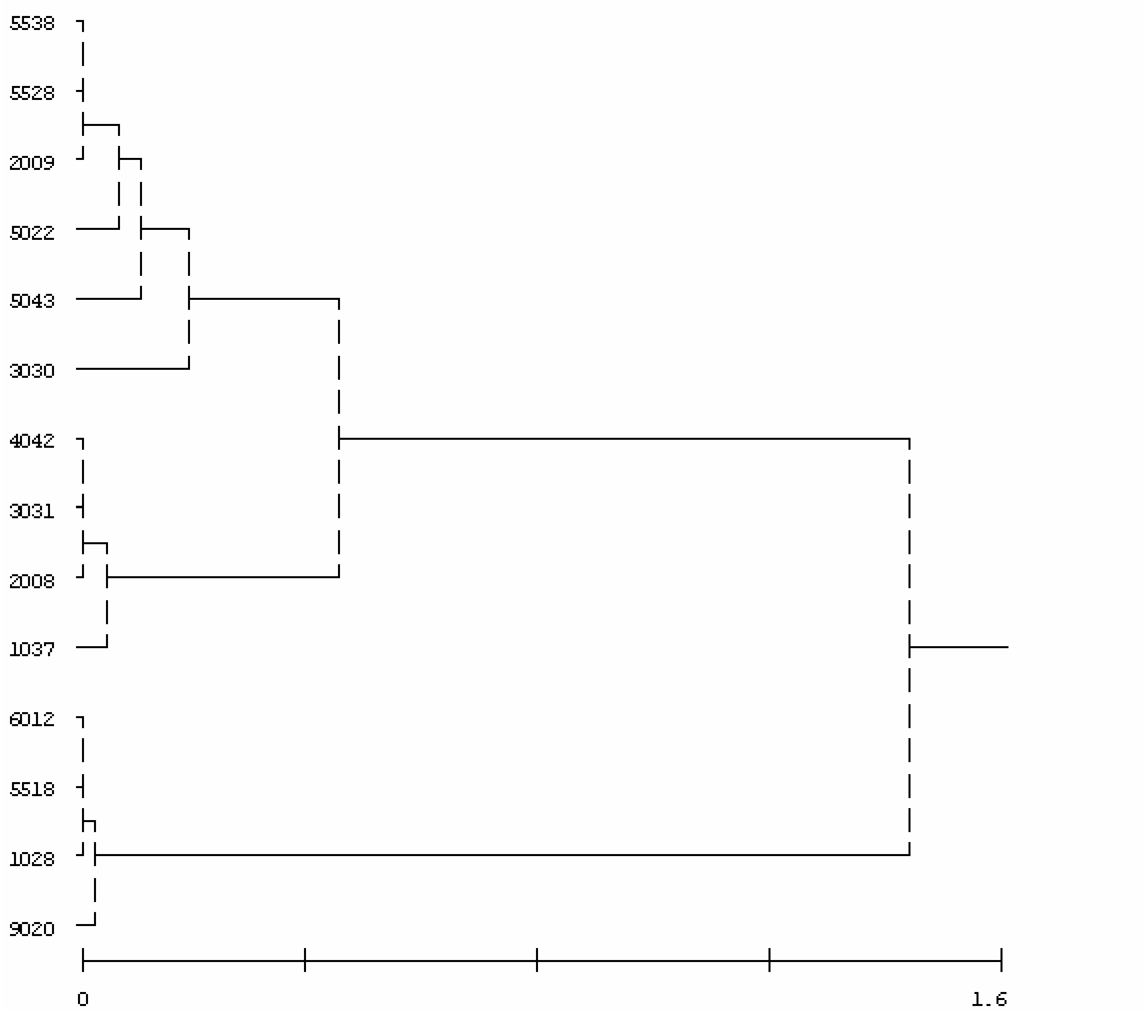



**Figure 36. Clusters of LTPP sites by annual average truck class distribution, Indiana.**

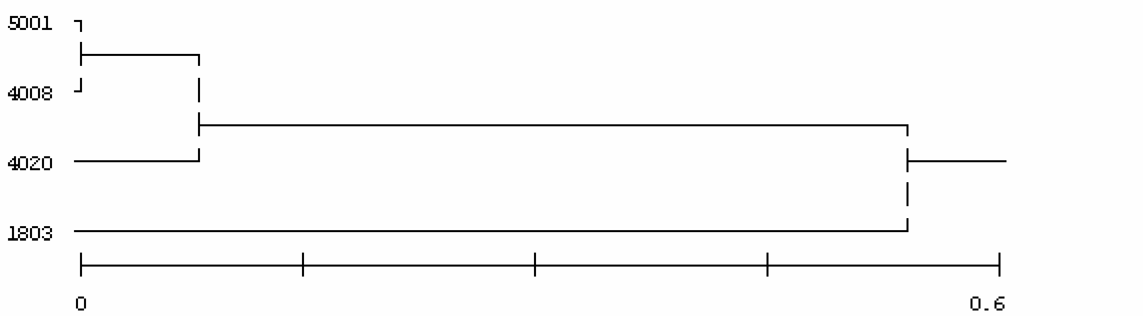



**Figure 37. Clusters of LTPP sites by annual average truck class distribution, Connecticut.**

# APPENDIX C. STRUCTURAL AND CLIMATIC INPUT

This appendix lists the structural and climatic input values used for the *2002 Pavement Design Guide* (PDG) for the detailed sensitivity analysis LTPP sites. The structural input is listed in the order in which it is entered into the PDG.

## STRUCTURE: JOINTED PORTLAND CEMENT CONCRETE PAVEMENT

1) Design features
   a) Slab thickness: Variable (table 9)
   b) Permanent curl/warp effective temperature difference: 23.3 degrees Celsius (ºC) (75 degrees Fahrenheit (°F))
   c) Joint spacing: 3.7 m (12 ft)
   d) Sealant type: Liquid
   e) Doweled transverse joints
   f) Dowel diameter: 32 mm (1.25 inches)
   g) Dowel bar spacing: 305 mm (12 inches)
   h) Edge support: None
   i) Base type: Granular
   j) PCC-base interface: Bonded
   k) Erodibility index: Erosion resistant (3)
   l) Loss of bond age (months): 60
2) Drainage and surface properties
   a) Surface shortwave absorptivity: 0.85
   b) Infiltration: Minor (10 percent)
   c) Drainage path length: 3.7 m (12 ft)
      i) Pavement cross slope (percent): 2
3) Layers
   a) PCC
      i) Thermal
         (1) PCC material: JPCP
         (2) Layer thickness: Variable (table 9)
         (3) Unit weight: 2400 kilograms per cubic meter ($kg/m^3$) (159 pounds per cubic foot ($lb/ft^3$))
         (4) Poisson's ratio: 0.20
         (5) Coefficient of thermal expansion: $9.9 \times 10^{-6}$ $ºC^{-1}$ ($5.5 \times 10^{-6}$ $ºF^{-1}$)
         (6) Thermal conductivity: 2.16 watts (W)/m-ºC (1.25 British thermal units (BTU)/h-ft-ºF)
         (7) Heat capacity: 0.33 W-h/kg-ºC (0.28 BTU/lb-ºF)
      ii) Mix
         (1) Cement type: Type II
         (2) Cementitious material content: 178 $kg/m^3$ (600 pounds per cubic yard ($lb/yd^3$))
         (3) Water-cement ratio: 0.4
         (4) Aggregate type: Gabbro
         (5) PCC zero-stress temperature (ºF): Computed by PDG

(6) Ultimate shrinkage at 40 percent relative humidity (RH) (microstrain): Computed by PDG
(7) Reversible shrinkage (percent of ultimate shrinkage): Computed by PDG
(8) Time to develop 50 percent of ultimate shrinkage (days): Computed by PDG
(9) Curing method: Curing compound

iii) Strength: Level 2 (table C.1)

**Table 35. PC strength properties for level 2 input.**

| Time | Compressive Strength (kilopascals (kPa)) | Compressive Strength (pounds force per square inch ($lbf/inch^2$)) |
|---|---|---|
| 7 days | 24,500 | 3560 |
| 14 days | 26,900 | 3900 |
| 28 days | 29,000 | 4200 |
| 90 days | 32,500 | 4700 |
| 20 years/28 days | | 1.44 |

## STRUCTURE: CONTINUOUSLY REINFORCED CONCRETE PAVEMENT

1) Design features
   a) Slab thickness: Variable (table 9)
   b) Shoulder type: Asphalt
      i) Permanent curl/warp effective temperature difference: 23.3 ºC (−10 ºF)
   c) Steel reinforcement
      i) Percent steel (percent): 0.7
      ii) Bar diameter: 16 mm (0.625 inch)
      iii) Steel depth: 356 mm (4 inches)
   d) Base properties
      i) Base type: Granular
      ii) Erodibility index: Erosion resistant (3)
      iii) Base/slab friction coefficient: 4
   e) Crack spacing: Generate using model
2) Drainage and surface properties
   a) Surface shortwave absorptivity: 0.85
   b) Infiltration: Minor (10 percent)
   c) Drainage path length: 3.7 m (12 ft)
      i) Pavement cross slope (percent): 2
3) Layers
   a) PCC
      i) Thermal
         (1) PCC material: CRCP
         (2) Layer thickness: Variable (table 9)
         (3) Unit weight: 2400 $kg/m^3$ (150 $lb/ft^3$)
         (4) Poisson's ratio: 0.20
         (5) Coefficient of thermal expansion: 9.9 x $10^{-6}$ $ºC^{-1}$ (5.5 x $10^{-6}$ $ºF^{-1}$)

(6) Thermal conductivity: 2.16 W/m-ºC (1.25 BTU/h-ft-ºF)
(7) Heat capacity: 0.33 W-h/kg-ºC (0.28 BTU/lb-ºF)

ii) Mix
(1) Cement type: Type II
(2) Cementitious material content: 178 kg/$m^3$ (600 lb/$yd^3$)
(3) Water-cement ratio: 0.4
(4) Aggregate Type: Gabbro
(5) PCC zero-stress temperature (ºF): Computed by PDG
(6) Ultimate shrinkage at 40 percent RH (microstrain): Computed by PDG
(7) Reversible shrinkage (percent of ultimate shrinkage): Computed by PDG
(8) Curing method: Curing compound

iii) Strength: Level 2 (table 35)

## STRUCTURE: ASPHALT CONCRETE PAVEMENT

1) Drainage and surface properties
   a) Surface shortwave absorptivity: 0.85
2) Layers
   a) AC
      i) Input level: 3
      ii) Asphalt material type: Asphalt concrete
      iii) Layer thickness: Variable (table 36)

**Table 36. Layer types and thicknesses for all sites.**

| Site | Layer 1 (Surface) | $h_1$ (mm (inches)) | LAYER 2 (USCS)[a] | $h_2$ (mm (inches)) | Layer 3 (USCS)[a] | $h_3$ (mm (inches)) | Layer 4 (USCS)[a] | $h_4$ (mm (inches)) |
|---|---|---|---|---|---|---|---|---|
| 181028 | AC | 401 (15.8) | CL | 305 (12.0) | CL | ∞ | – | – |
| 261010 | AC | 58 (2.3) | GW | 279 (11.0) | SW | 508 (20.0) | ML | ∞ |
| 282807 | AC | 267 (10.5) | GW | 762 (30.0) | ML | ∞ | – | – |
| 531007 | AC | 4.6 (1.8) | GW | 335 (13.2) | MH | ∞ | – | – |
| 536048 | AC | 152 (6.0) | GW | 86 (3.4) | GW | 254 (10.0) | GW | ∞ |
| 091803 | **AC** | 178 (7.0) | GW | 254 (10.0) | ML | ∞ | – | – |
| 182008 | AC | 401 (15.8) | ML | ∞ | – | – | – | – |
| 182009 | AC | 450 (17.7) | SW | 610 (24.0) | ML | ∞ | – | – |
| 186012 | AC | 523 (20.6) | GW | | CL | ∞ | – | – |
| 261004 | AC | 64 (2.5) | GW | 102 (4.0) | ML | ∞ | – | – |
| 261012 | AC | 152 (6.0) | GW | 114 (4.5) | SW | ∞ | – | – |
| 261013 | AC | 191 (7.5) | GW | 114 (4.5) | SW | ∞ | – | – |
| 271019 | AC | 122 (4.8) | GW | 152 (6.0) | ML | ∞ | – | – |
| 283081 | AC | 229 (9.0) | GW | ∞ | – | – | – | – |
| 283093 | AC | 305 (12.0) | GW | ∞ | – | – | – | – |

[a] Codes based on Unified Soil Classification System (USCS) standards.[(19)]

iv) Asphalt mix
   (1) Cumulative percent retained on the 19.0-mm (0.75-inch) sieve: 0
   (2) Cumulative percent retained on the 12.5-mm (0.375-inch) sieve: 5
   (3) Cumulative percent retained on the 4.75-mm (#4) sieve: 30
   (4) Percent passing the 0.075-mm (#200) sieve: 5
v) Asphalt binder
   (1) Conventional viscosity grade: AC 20
vi) Asphalt general
   (1) Reference temperature: 21.1 ºC (70 Fº)
   (2) Volumetric properties: As built
      (a) Effective binder content (percent): 11.0
      (b) Air voids (percent): 8.5
      (c) Total unit weight: 2370 kg/m$^3$ (148 lb/ft$^3$)
   (3) Poisson's ratio: 0.35
   (4) Thermal properties
      (a) Thermal conductivity of asphalt: 1.16 W/m-ºC (0.67 BTU/h-ft ºF)
      (b) Heat capacity of asphalt: 0.27 W-h/kg-ºC (0.23 BTU/lb-ºF)

**STRUCTURE: UNBOUND BASE**

1) Unbound material: Variable (table 37)

**Table 37. Assumed layer moduli.**

| Layer Type (USCS)[a] | Layer Description | Modulus (megapascals (MPa) (kips per square inch (ksi)) |
|---|---|---|
| GW | Gravel | 690 (100) |
| SW | Sand | 276 (40) |
| SM | Silty Sand | 138 (20) |
| CL | Silty Clay | 138 (20) |
| ML | Clayey Silt | 138 (20) |
| MH | Silt | 138 (20) |

[a] Codes based on Unified Soil Classification System (USCS) standards. (19)

2) Thickness: Variable (table 36)
3) Strength properties
   a) Input level: 3
   b) Poisson's ratio: 0.35
   c) Coefficient of lateral earth pressure: K=0.5
   d) Material property
      i) Modulus: Variable (table 37)

e) Analysis type:
    i) Integrated Climatic Model (ICM) calculated modulus: ICM input
4) Integrated Climate Model (ICM)
    a) Gradation and plasticity index: Computed by PDG
    b) Calculated/Derived parameters: Computed by PDG
    c) Soil characteristic curve fit parameters: Computed by PDG

Compacted, unbound materials

**CLIMATE**

The climatic data for the detailed analysis sites were computed by the PDG as a function of the latitude/longitude of each site (table 38). Weather station data from the nearest three or four weather sites were used to estimate the site-specific weather data. The actual elevation of each site was used; however, all groundwater table elevations were set at 30.5 m (100 ft) to eliminate the resulting variations in pavement performance.

**Table 38. Site locations used for interpolation of weather station data.**

| Site | Longitude (decimal of degree) | Latitude (decimal of degree) | Elevation (m (ft)) |
|---|---|---|---|
| 094008 | −72.558 | 41.798 | 47 (155) |
| 181028 | −87.016 | 38.196 | 134 (441) |
| 185518 | −86.853 | 40.477 | 20 (65) |
| 261010 | −83.656 | 43.179 | 241 (792) |
| 274055 | −94.074 | 45.424 | 299 (980) |
| 275076 | −92.975 | 45.034 | 300 (985) |
| 282807 | −89.655 | 34.356 | 90 (295) |
| 284024 | −91.041 | 33.359 | 300 (125) |
| 501682 | −73.241 | 44.326 | 122 (400) |
| 531007 | −119.602 | 46.048 | 275 (903) |
| 536048 | −122.138 | 47.788 | 37 (120) |
| 091803 | −72.0273 | 41.3949 | 50 (165) |
| 094020 | −72.5677 | 41.7020 | 61 (201) |
| 095001 | −72.4399 | 41.8485 | 163 (534) |
| 182008 | −85.0578 | 40.9456 | 242 (793) |
| 182009 | −86.0046 | 40.0308 | 239 (785) |
| 185022 | −86.0719 | 39.6278 | 255 (836) |
| 186012 | −87.4925 | 38.1673 | 144 (472) |
| 261004 | −88.6100 | 47.1000 | 300 (984) |
| 261012 | −83.5300 | 43.7100 | 315 (1032) |
| 261013 | −85.4918 | 43.4408 | 274 (900) |
| 263069 | −84.8745 | 43.8713 | 285 (935) |
| 264015 | −82.7996 | 42.9779 | 238 (780) |
| 265363 | −83.3915 | 42.1866 | 195 (640) |
| 271019 | −93.6021 | 45.5909 | 300 (980) |
| 283081 | −88.4405 | 34.2400 | 97 (317) |
| 283093 | −88.6736 | 30.4327 | 7 (24) |
| 285006 | −88.8100 | 34.3300 | 100 (329) |
| 285805 | −89.0600 | 30.4400 | 9 (30) |
| 533813 | −122.4600 | 45.5800 | 134 (440) |

# APPENDIX D. PAVEMENT-PERFORMANCE RESULTS

All pavement sections were analyzed using the 2002 PDG. This section contains the life of the pavement sections in absolute terms (years).

**Table 39. Life prediction estimates by scenario and traffic input percentile level, section 181028.**

| Site | Scenario | Traffic Input Percentile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% | 75% | 85% | 95% | 99.9% |
| | | Life to Rutting Failure (years) | | | | | | | | |
| 181028 | 1-0 | 30.0 | – | – | – | – | – | – | – | – |
| | 1-1 | 30.0 | 30.0 | 29.0 | 30.0 | 30.0 | 29.0 | 29.0 | 29.0 | 28.0 |
| | 1-2 | 29.0 | 30.0 | 30.0 | 31.0 | 32.0 | 28.0 | 27.0 | 27.0 | 25.0 |
| | 2-0 | 27.0 | – | – | – | – | – | – | – | – |
| | 2-1 | 28.0 | 28.0 | 28.0 | 29.0 | 29.0 | 28.0 | 28.0 | 27.0 | 27.0 |
| | 2-2 | 27.0 | 28.0 | 29.0 | 29.0 | 30.0 | 27.0 | 26.0 | 26.0 | 25.0 |
| | 2-3 | 27.0 | 29.0 | 29.0 | 30.0 | 32.0 | 26.0 | 25.0 | 25.0 | 23.0 |
| | 3-0 | 27.0 | – | – | – | – | – | – | – | – |
| | 3-1 | 27.0 | 27.0 | 27.0 | 27.0 | 27.0 | 26.0 | 26.0 | 26.0 | 26.0 |
| | 4-0 | 27.0 | – | – | – | – | – | – | – | – |
| | 4-1 | 27.0 | 27.0 | 27.0 | 28.0 | 28.0 | 26.0 | 26.0 | 26.0 | 26.0 |
| | 4-2 | 27.0 | 28.0 | 28.0 | 29.0 | 30.0 | 26.0 | 25.0 | 25.0 | 24.0 |
| | 4-3 | 27.0 | 29.0 | 30.0 | 31.0 | 34.0 | 25.0 | 24.0 | 23.0 | 21.0 |
| | 4-4 | 45.0 | – | – | – | – | – | – | – | – |
| | 4-5 | 44.0 | 44.0 | 44.0 | 45.0 | 45.0 | 43.0 | 43.0 | 43.0 | 42.0 |
| | 4-6 | 44.0 | 45.0 | 45.0 | 45.0 | 46.0 | 43.0 | 43.0 | 42.0 | 41.0 |
| | 4-7 | 46.0 | 49.0 | 50.0 | 52.0 | 58.0 | 42.0 | 40.0 | 38.0 | 35.0 |

– Indicates no data available.

**Table 40. Life prediction estimates by scenario and traffic input percentile level, section 261010.**

| Site | Scenario | Traffic Input Percentile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% | 75% | 85% | 95% | 99.9% |
| | | Life to Rutting Failure (years) | | | | | | | | |
| 261010 | 1-0 | 41.0 | – | – | – | – | – | – | – | – |
| | 1-1 | 46.0 | 51.0 | 52.0 | 52.0 | 56.0 | 44.0 | 43.0 | 43.0 | 38.0 |
| | 1-2 | 46.0 | 55.0 | 57.0 | 60.0 | 49.0 | 41.0 | 40.0 | 37.0 | 34.0 |
| | 2-0 | 44.0 | – | – | – | – | – | – | – | – |
| | 2-1 | 43.0 | 45.0 | 45.0 | 47.0 | 49.0 | 39.0 | 39.0 | 38.0 | 35.0 |
| | 2-2 | 42.0 | 46.0 | 47.0 | 49.0 | 54.0 | 37.0 | 36.0 | 35.0 | 31.0 |
| | 2-3 | 41.0 | 48.0 | 51.0 | 56.0 | 100.0 | 35.0 | 33.0 | 31.0 | 27.0 |
| | 3-0 | 33.0 | – | – | – | – | – | – | – | – |
| | 3-1 | 33.0 | 34.0 | 34.0 | 35.0 | 36.0 | 32.0 | 32.0 | 31.0 | 30.0 |
| | 4-0 | 38.0 | – | – | – | – | – | – | – | – |
| | 4-1 | 37.0 | 39.0 | 40.0 | 41.0 | 43.0 | 35.0 | 34.0 | 33.0 | 31.0 |
| | 4-2 | 37.0 | 42.0 | 44.0 | 47.0 | 61.0 | 31.0 | 30.0 | 28.0 | 25.0 |
| | 4-3 | 37.0 | 46.0 | 49.0 | 57.0 | 100.0 | 29.0 | 28.0 | 26.0 | 22.0 |
| | 4-4 | 25.0 | – | – | – | – | – | – | – | – |
| | 4-5 | 24.0 | 26.0 | 27.0 | 28.0 | 31.0 | 22.0 | 22.0 | 21.0 | 18.8 |
| | 4-6 | 24.0 | 29.0 | 31.0 | 34.0 | 44.0 | 19.9 | 18.9 | 17.6 | 15.0 |
| | 4-7 | 24.0 | 31.0 | 33.0 | 37.0 | 100.0 | 18.9 | 17.9 | 16.8 | 13.9 |

– Indicates no data available.

**Table 41. Life prediction estimates by scenario and traffic input percentile level, section 282807.**

| Site | Scenario | Traffic Input Percentile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% | 75% | 85% | 95% | 99.9% |
| | | Life to Longitudinal Cracking Failure (years) | | | | | | | | |
| 282807 | 1-0 | 5.9 | | | | | | | | |
| | 1-1 | 5.9 | 7.9 | 8.0 | 8.9 | 9.9 | 4.9 | 5.0 | 4.9 | 4.1 |
| | 1-2 | 5.1 | 8.9 | 10.0 | 10.8 | 10.0 | 4.8 | 6.8 | 4.0 | 5.0 |
| | 2-0 | 7.0 | – | – | – | – | – | – | – | – |
| | 2-1 | 6.9 | 7.1 | 7.1 | 7.9 | 12.0 | 6.8 | 6.1 | 6.0 | 5.9 |
| | 2-2 | 6.8 | 7.9 | 8.0 | 8.9 | 10.1 | 5.9 | 5.9 | 5.1 | 4.9 |
| | 2-3 | 6.8 | 9.0 | 9.9 | 15.8 | 21.0 | 5.0 | 5.0 | 4.8 | 3.9 |
| | 3-0 | 12.0 | – | – | – | – | – | – | – | – |
| | 3-1 | 11.9 | 12.1 | 12.8 | 12.9 | 13.8 | 11.8 | 11.8 | 11.0 | 10.9 |
| | 4-0 | 12.0 | – | – | – | – | – | – | – | – |
| | 4-1 | 11.9 | 12.1 | 12.9 | 13.0 | 14.0 | 10.9 | 10.9 | 10.8 | 9.9 |
| | 4-2 | 11.9 | 14.0 | 14.9 | 16.8 | 22.0 | 9.9 | 9.0 | 8.9 | 7.1 |
| | 4-3 | 12.0 | 14.9 | 16.0 | 18.1 | 25.0 | 9.9 | 9.0 | 8.9 | 7.0 |
| | 4-4 | 6.1 | | | | | | | | |
| | 4-5 | 6.0 | 6.8 | 6.9 | 7.0 | 8.0 | 5.8 | 5.1 | 5.0 | 4.9 |
| | 4-6 | 5.9 | 7.9 | 8.8 | 9.9 | 15.0 | 4.9 | 4.9 | 4.0 | 3.9 |
| | 4-7 | 6.8 | 10.0 | 11.8 | 15.0 | 100.0 | 4.9 | 4.1 | 4.0 | 3.0 |

– Indicates no data available.

**Table 42. Life prediction estimates by scenario and traffic input percentile level, section 536048.**

| Site | Scenario | Traffic Input Percentile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% | 75% | 85% | 95% | 99.9% |
| | | Life to Rutting Failure (years) | | | | | | | | |
| 536048 | 1-0 | 9.8 | – | – | – | – | – | – | – | – |
| | 1-1 | 9.1 | 11.9 | 12.9 | 14.0 | 17.1 | 7.8 | 7.0 | 7.0 | 5.9 |
| | 1-2 | 9.2 | 14.0 | 15.1 | 18.1 | 24.0 | 6.8 | 6.1 | 6.0 | 5.0 |
| | 2-0 | 6.9 | – | – | – | – | – | – | – | – |
| | 2-1 | 6.1 | 7.0 | 7.1 | 7.9 | 8.9 | 5.9 | 5.9 | 5.7 | 5.0 |
| | 2-2 | 6.1 | 7.1 | 7.9 | 8.0 | 9.9 | 5.8 | 5.5 | 5.0 | 4.8 |
| | 2-3 | 6.0 | 8.2 | 9.0 | 10.8 | 16.0 | 5.0 | 4.9 | 4.1 | 3.9 |
| | 3-0 | 6.1 | – | – | – | – | – | – | – | – |
| | 3-1 | 6.0 | 6.1 | 6.2 | 6.7 | 6.8 | 6.0 | 6.0 | 6.0 | 5.9 |
| | 4-0 | 6.8 | – | – | – | – | – | – | – | – |
| | 4-1 | 6.8 | 6.9 | 6.9 | 7.0 | 7.2 | 6.1 | 6.1 | 6.0 | 5.9 |
| | 4-2 | 6.1 | 7.1 | 7.8 | 8.0 | 10.0 | 5.8 | 5.6 | 5.0 | 4.8 |
| | 4-3 | 6.8 | 7.9 | 8.0 | 9.0 | 11.9 | 5.8 | 5.4 | 5.0 | 4.7 |
| | 4-4 | 4.2 | – | – | – | – | – | – | – | – |
| | 4-5 | 4.1 | 4.5 | 4.7 | 4.8 | 4.9 | 4.0 | 4.0 | 4.0 | 3.9 |
| | 4-6 | 4.1 | 4.8 | 4.9 | 5.0 | 5.9 | 3.9 | 3.9 | 3.8 | 3.3 |
| | 4-7 | 4.9 | 7.8 | 8.9 | 12.8 | 100.0 | 3.8 | 3.2 | 2.9 | 2.5 |

– Indicates no data available.

**Table 43. Life prediction estimates by scenario and traffic input percentile level, section 185518.**

| Site | Scenario | Traffic Input Percentile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% | 75% | 85% | 95% | 99.9% |
| | | Life to Punchout Failure (years) | | | | | | | | |
| 185518 | 1-0 | 11.7 | – | – | – | – | – | – | – | – |
| | 1-1 | 11.8 | 13.8 | 14.4 | 15.2 | 18.3 | 10.5 | 10.3 | 10.2 | 9.3 |
| | 1-2 | 11.8 | 15.4 | 17.2 | 20.7 | 26.7 | 9.9 | 9.5 | 9.4 | 8.4 |
| | 2-0 | 10.3 | – | – | – | – | – | – | – | – |
| | 2-1 | 9.7 | 10.7 | 11.3 | 11.7 | 13.3 | 9.3 | 8.8 | 8.7 | 8.3 |
| | 2-2 | 9.5 | 10.3 | 11.4 | 11.8 | 13.7 | 8.8 | 8.7 | 7.8 | 7.7 |
| | 2-3 | 9.4 | 12.4 | 13.3 | 15.5 | 23.7 | 8.3 | 7.7 | 7.4 | 6.6 |
| | 3-0 | 9.8 | – | – | – | – | – | – | – | – |
| | 3-1 | 9.8 | 10.3 | 10.3 | 10.4 | 10.8 | 9.4 | 9.4 | 9.4 | 9.3 |
| | 4-0 | 11.4 | – | – | – | – | – | – | – | – |
| | 4-1 | 11.3 | 11.8 | 12.2 | 12.3 | 13.6 | 10.6 | 10.5 | 10.4 | 10.3 |
| | 4-2 | 11.3 | 13.3 | 15.2 | 15.7 | 23.7 | 9.5 | 9.3 | 8.8 | 8.1 |
| | 4-3 | 11.3 | 13.7 | 14.3 | 17.0 | 23.7 | 9.6 | 9.3 | 8.7 | 7.8 |
| | 4-4 | 18.7 | | | | | | | | |
| | 4-5 | 18.5 | 18.7 | 19.4 | 19.6 | 22.7 | 18.1 | 17.7 | 17.6 | 17.3 |
| | 4-6 | 18.5 | 21.7 | 23.7 | 22.7 | 24.7 | 16.5 | 15.8 | 15.3 | 13.9 |
| | 4-7 | 19.2 | 23.7 | 23.7 | 24.7 | 25.7 | 16.3 | 15.5 | 14.6 | 13.3 |

– Indicates no data available.

**Table 44. Life prediction estimates by scenario and traffic input percentile level, section 275076.**

| Site | Scenario | Traffic Input Percentile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% | 75% | 85% | 95% | 99.9% |
| | | Life to Punchout Failure (years) | | | | | | | | |
| 275076 | 1-0 | 20.7 | – | – | – | – | – | – | – | – |
| | 1-1 | 20.7 | 23.7 | 23.7 | 24.7 | 26.7 | 18.8 | 18.9 | 18.8 | 17.8 |
| | 1-2 | 20.7 | 24.7 | 25.7 | 26.7 | 27.7 | 18.8 | 18.8 | 18.1 | 16.9 |
| | 2-0 | 17.8 | – | – | – | – | – | – | – | – |
| | 2-1 | 17.8 | 18.7 | 22.7 | 19.3 | 20.7 | 16.8 | 16.8 | 16.3 | 15.4 |
| | 2-2 | 17.7 | 18.8 | 19.3 | 21.7 | 21.7 | 17.8 | 16.3 | 15.8 | 14.7 |
| | 2-3 | 17.7 | 20.7 | 21.7 | 22.7 | 23.7 | 15.5 | 15.2 | 14.3 | 13.0 |
| | 3-0 | 11.5 | – | – | – | – | – | – | – | – |
| | 3-1 | 11.8 | 12.2 | 12.3 | 12.4 | 13.1 | 11.7 | 11.7 | 11.5 | 11.2 |
| | 4-0 | 13.9 | – | – | – | – | – | – | – | – |
| | 4-1 | 13.8 | 14.6 | 14.7 | 14.9 | 15.7 | 13.8 | 13.7 | 13.4 | 12.8 |
| | 4-2 | 13.8 | 15.5 | 16.1 | 16.8 | 19.3 | 12.8 | 12.8 | 12.4 | 11.7 |
| | 4-3 | 14.1 | 16.3 | 16.8 | 18.2 | 21.7 | 12.8 | 12.5 | 11.8 | 10.9 |
| | 4-4 | 15.6 | – | – | – | – | – | – | – | – |
| | 4-5 | 15.3 | 15.6 | 15.7 | 15.8 | 16.5 | 14.8 | 14.7 | 14.6 | 14.3 |
| | 4-6 | 15.3 | 16.8 | 16.9 | 17.8 | 19.8 | 13.8 | 13.8 | 13.8 | 12.6 |
| | 4-7 | 15.8 | 19.7 | 21.7 | 23.7 | 25.7 | 13.5 | 12.8 | 12.3 | 10.8 |

– Indicates no data available.

**Table 45. Life prediction estimates by scenario and traffic input percentile level, section 094008.**

| Site | Scenario | Traffic Input Percentile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% | 75% | 85% | 95% | 99.9% |
| | | Life to Slab Cracking Failure (years) | | | | | | | | |
| 094008 | 1-0 | 5.8 | – | – | – | – | – | – | – | – |
| | 1-1 | 5.0 | 6.1 | 6.8 | 7.6 | 9.7 | 4.7 | 4.6 | 4.0 | 3.8 |
| | 1-2 | 5.0 | 6.8 | 6.9 | 8.0 | 11.7 | 4.6 | 4.0 | 3.9 | 3.7 |
| | 2-0 | 7.8 | – | – | – | – | – | – | – | – |
| | 2-1 | 6.8 | 8.1 | 6.8 | 9.7 | 11.8 | 6.0 | 5.8 | 5.8 | 5.0 |
| | 2-2 | 6.9 | 8.1 | 8.8 | 9.8 | 11.8 | 6.1 | 5.9 | 5.8 | 5.1 |
| | 2-3 | 6.7 | 12.0 | 14.8 | 23.6 | 36.6 | 4.6 | 4.0 | 3.8 | 3.0 |
| | 3-0 | 6.8 | – | – | – | – | – | – | – | – |
| | 3-1 | 6.8 | 7.0 | 7.1 | 7.7 | 7.9 | 6.6 | 6.1 | 5.9 | 5.8 |
| | 4-0 | 7.8 | – | – | – | – | – | – | – | – |
| | 4-1 | 7.8 | 8.6 | 7.1 | 7.7 | 9.6 | 7.7 | 7.6 | 7.0 | 6.8 |
| | 4-2 | 7.1 | 10.8 | 12.8 | 15.7 | 100.0 | 5.8 | 5.1 | 4.8 | 3.9 |
| | 4-3 | 7.0 | 12.2 | 15.1 | 24.6 | 100.0 | 5.0 | 4.8 | 4.7 | 3.8 |
| | 4-4 | 9.8 | – | – | – | – | – | – | – | – |
| | 4-5 | 9.8 | 9.8 | 9.9 | 10.1 | 10.8 | 9.6 | 9.2 | 9.0 | 8.8 |
| | 4-6 | 9.8 | 11.0 | 11.8 | 12.7 | 15.7 | 8.7 | 8.6 | 7.8 | 7.0 |
| | 4-7 | 10.7 | 14.8 | 16.1 | 20.6 | 35.6 | 8.1 | 7.8 | 7.1 | 6.0 |

– Indicates no data available.

**Table 46. Life prediction estimates by scenario and traffic input percentile level, section 501682.**

| Site | Scenario | Traffic Input Percentile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% | 75% | 85% | 95% | 99.9% |
| | | Life to Slab Cracking Failure (years) | | | | | | | | |
| 501682 | 1-0 | 23.6 | – | – | – | – | – | – | – | – |
| | 1-1 | 24.6 | 27.6 | 28.6 | 29.6 | 31.6 | 22.6 | 21.6 | 21.6 | 19.7 |
| | 1-2 | 24.6 | 30.6 | 31.6 | 32.6 | 34.6 | 19.8 | 19.0 | 19.1 | 15.8 |
| | 2-0 | 26.6 | – | – | – | – | – | – | – | – |
| | 2-1 | 26.6 | 26.6 | 26.6 | 27.6 | 27.6 | 25.6 | 25.6 | 24.6 | 24.6 |
| | 2-2 | 25.6 | 26.6 | 27.6 | 27.6 | 28.6 | 24.6 | 24.6 | 23.6 | 22.6 |
| | 2-3 | 25.6 | 28.6 | 28.6 | 29.6 | 31.6 | 23.6 | 23.6 | 22.6 | 20.6 |
| | 3-0 | 27.6 | – | – | – | – | – | – | – | – |
| | 3-1 | 26.6 | 26.6 | 26.6 | 27.6 | 27.6 | 26.6 | 26.6 | 26.6 | 26.6 |
| | 4-0 | 40.6 | – | – | – | – | – | – | – | – |
| | 4-1 | 39.6 | 39.6 | 39.6 | 39.6 | 40.6 | 36.6 | 36.6 | 36.6 | 35.6 |
| | 4-2 | 39.6 | 40.6 | 40.6 | 41.6 | 42.6 | 35.6 | 33.6 | 32.6 | 31.6 |
| | 4-3 | 39.6 | 42.6 | 43.6 | 44.6 | 100.0 | 33.6 | 32.6 | 30.6 | 27.6 |
| | 4-4 | 22.6 | – | – | – | – | – | – | – | – |
| | 4-5 | 21.6 | 22.6 | 22.6 | 23.6 | 23.6 | 21.6 | 21.6 | 20.6 | 20.6 |
| | 4-6 | 21.6 | 23.6 | 23.6 | 24.6 | 26.6 | 20.6 | 19.8 | 19.6 | 18.0 |
| | 4-7 | 22.6 | 27.6 | 28.6 | 30.6 | 35.6 | 18.7 | 17.8 | 16.7 | 14.1 |

– Indicates no data available.

**Table 47. Life prediction estimates by scenario and traffic input percentile level, section 186012.**

| Site | Scenario | Traffic Input Percentile | | | | |
|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% |
| | | Life to Rutting Failure (years) | | | | |
| 186012 | 1-0 | 28.0 | – | – | – | – |
| | 1-1 | 26.0 | 31.0 | 32.0 | 36.0 | – |
| | 1-2 | 26.0 | 28.0 | 30.0 | 33.0 | – |
| | 2-0 | 26.0 | – | – | – | – |
| | 2-1 | 24.0 | 28.0 | 29.0 | 31.0 | – |
| | 2-2 | 24.0 | 26.0 | 27.0 | 28.0 | – |
| | 2-3 | 23.0 | 29.0 | 31.0 | 34.0 | – |
| | 3-0 | 26.0 | – | – | – | – |
| | 3-1 | 26.0 | 27.0 | 27.0 | 28.0 | – |
| | 4-0 | 31.0 | – | – | – | – |
| | 4-1 | 30.0 | 32.0 | 32.0 | 34.0 | – |
| | 4-2 | 29.0 | 34.0 | 36.0 | 39.0 | – |
| | 4-3 | 33.0 | 43.0 | 48.0 | 60.0 | – |
| | 4-4 | 50.0 | – | – | – | – |
| | 4-5 | 50.0 | 50.0 | 50.0 | 50.0 | – |
| | 4-6 | 45.0 | 53.0 | 54.0 | 59.0 | – |
| | 4-7 | 51.0 | 65.0 | 72.0 | 85.0 | – |

– Indicates no data available.

**Table 48. Life prediction estimates by scenario and traffic input percentile level, section 261004.**

| Site | Scenario | Traffic Input Percentile | | | | |
|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% |
| | | Life to Rutting Failure (years) | | | | |
| 261004 | 1-0 | 30.0 | – | – | – | – |
| | 1-1 | 28.0 | 29.0 | 30.0 | 31.0 | – |
| | 1-2 | 27.0 | 30.0 | 32.0 | 34.0 | – |
| | 2-0 | 27.0 | – | – | – | – |
| | 2-1 | 29.0 | 32.0 | 33.0 | 35.0 | – |
| | 2-2 | 29.0 | 31.0 | 31.0 | 30.0 | – |
| | 2-3 | 28.0 | 37.0 | 38.0 | 99.0 | – |
| | 3-0 | 26.0 | – | – | – | – |
| | 3-1 | 26.0 | 27.0 | 28.0 | 28.0 | – |
| | 4-0 | 29.0 | – | – | – | – |
| | 4-1 | 29.0 | 32.0 | 33.0 | 36.0 | – |
| | 4-2 | 29.0 | 42.0 | 50.0 | 99.0 | – |
| | 4-3 | 31.0 | 58.0 | 99.0 | 99.0 | – |
| | 4-4 | 15.9 | – | – | – | – |
| | 4-5 | 15.9 | 15.9 | 15.9 | 15.9 | – |
| | 4-6 | 13.0 | 23.0 | 27.0 | 46.0 | – |
| | 4-7 | 14.0 | 33.0 | 57.0 | 99.0 | – |

– Indicates no data available.

**Table 49. Life prediction estimates by scenario and traffic input percentile level, section 261012.**

| Site | Scenario | Traffic Input Percentile | | | | |
|---|---|---|---|---|---|---|
| | | **50%** | **−75%** | **−85%** | **−95%** | **−99.9%** |
| | | **Life to Longitudinal Cracking Failure (years)** | | | | |
| 261012 | 1-0 | 16.1 | – | – | – | – |
| | 1-1 | 17.1 | 19.7 | 20.0 | 21.0 | – |
| | 1-2 | 16.9 | 17.7 | 18.0 | 18.8 | – |
| | 2-0 | 15.6 | – | – | – | – |
| | 2-1 | 16.5 | 17.6 | 17.8 | 18.1 | – |
| | 2-2 | 16.0 | 16.1 | 16.1 | 16.0 | – |
| | 2-3 | 16.0 | 17.3 | 17.6 | 17.3 | – |
| | 3-0 | 13.0 | – | – | – | – |
| | 3-1 | 13.0 | 13.3 | 13.6 | 13.7 | – |
| | 4-0 | 14.0 | – | – | – | – |
| | 4-1 | 13.9 | 14.7 | 14.8 | 14.9 | – |
| | 4-2 | 13.6 | 16.1 | 16.9 | 18.7 | – |
| | 4-3 | 12.2 | 16.1 | 17.6 | 21.0 | – |
| | 4-4 | 14.6 | – | – | – | – |
| | 4-5 | 14.6 | 14.6 | 14.6 | 14.6 | – |
| | 4-6 | 11.9 | 16.3 | 18.0 | 23.0 | – |
| | 4-7 | 13.0 | 17.2 | 18.8 | 23.0 | – |

– Indicates no data available.

**Table 50. Life prediction estimates by scenario and traffic input percentile level, section 261013.**

| Site | Scenario | Traffic Input Percentile | | | | |
|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% |
| | | Life to Rutting Failure (years) | | | | |
| 261013 | 1-0 | 26.0 | – | – | – | – |
| | 1-1 | 28.0 | 37.0 | 39.0 | 48.0 | – |
| | 1-2 | 28.0 | 31.0 | 31.0 | 29.0 | – |
| | 2-0 | 24.0 | – | – | – | – |
| | 2-1 | 26.0 | 34.0 | 37.0 | 41.0 | – |
| | 2-2 | 26.0 | 29.0 | 29.0 | 30.0 | – |
| | 2-3 | 26.0 | 40.0 | 43.0 | 99.0 | – |
| | 3-0 | 21.0 | – | – | – | – |
| | 3-1 | 21.0 | 24.0 | 25.0 | 27.0 | – |
| | 4-0 | 22.0 | – | – | – | – |
| | 4-1 | 22.0 | 26.0 | 27.0 | 30.0 | – |
| | 4-2 | 23.0 | 39.0 | 49.0 | 99.0 | – |
| | 4-3 | 22.0 | 41.0 | 55.0 | 99.0 | – |
| | 4-4 | 23.0 | – | – | – | – |
| | 4-5 | 23.0 | 23.0 | 23.0 | 23.0 | – |
| | 4-6 | 20.0 | 42.0 | 63.0 | 99.0 | – |
| | 4-7 | 20.0 | 44.0 | 71.0 | 99.0 | – |

– Indicates no data available.

**Table 51. Life prediction estimates by scenario and traffic input percentile level, section 271019.**

| Site | Scenario | Traffic Input Percentile | | | | |
|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% |
| | | Life to Rutting Failure (years) | | | | |
| 271019 | 1-0 | 44.0 | – | – | – | – |
| | 1-1 | 44.0 | 51.0 | 53.0 | 59.0 | – |
| | 1-2 | 41.0 | 45.0 | 43.0 | 45.0 | – |
| | 2-0 | 41.0 | – | – | – | – |
| | 2-1 | 41.0 | 48.0 | 50.0 | 55.0 | – |
| | 2-2 | 38.0 | 41.0 | 42.0 | 43.0 | – |
| | 2-3 | 38.0 | 46.0 | 47.0 | 46.0 | – |
| | 3-0 | 37.0 | – | – | – | – |
| | 3-1 | 37.0 | 39.0 | 39.0 | 40.0 | – |
| | 4-0 | 39.0 | – | – | – | – |
| | 4-1 | 36.0 | 39.0 | 39.0 | 40.0 | – |
| | 4-2 | 36.0 | 41.0 | 42.0 | 46.0 | – |
| | 4-3 | 39.0 | 52.0 | 59.0 | 78.0 | – |
| | 4-4 | 20.0 | – | – | – | – |
| | 4-5 | 20.0 | 20.0 | 20.0 | 20.0 | – |
| | 4-6 | 16.9 | 22.0 | 24.0 | 29.0 | – |
| | 4-7 | 19.0 | 30.0 | 36.0 | 56.0 | – |

– Indicates no data available.

**Table 52. Life prediction estimates by scenario and traffic input percentile level, section 283081.**

| Site | Scenario | Traffic Input Percentile | | | | |
|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% |
| | | Life to Longitudinal Cracking Failure (years) | | | | |
| 283081 | 1-0 | 6.8 | – | – | – | – |
| | 1-1 | 6.8 | 6.8 | 6.8 | 6.8 | – |
| | 1-2 | 6.0 | 6.4 | 6.8 | 6.8 | – |
| | 2-0 | 5.8 | – | – | – | – |
| | 2-1 | 5.8 | 5.9 | 5.9 | 5.9 | – |
| | 2-2 | 5.0 | 5.1 | 5.1 | 5.1 | – |
| | 2-3 | 5.1 | 5.9 | 5.9 | 5.9 | – |
| | 3-0 | 5.8 | – | – | – | – |
| | 3-1 | 5.8 | 5.9 | 5.9 | 5.9 | – |
| | 4-0 | 6.9 | – | – | – | – |
| | 4-1 | 6.8 | 7.0 | 7.0 | 7.1 | – |
| | 4-2 | 6.8 | 7.7 | 7.9 | 8.0 | – |
| | 4-3 | 6.8 | 8.9 | 9.8 | 12.0 | – |
| | 4-4 | 9.0 | – | – | – | – |
| | 4-5 | 9.0 | 9.0 | 9.0 | 9.0 | – |
| | 4-6 | 7.9 | 10.9 | 12.8 | 15.1 | – |
| | 4-7 | 8.0 | 11.8 | 12.9 | 15.8 | – |

– Indicates no data available.

**Table 53. Life prediction estimates by scenario and traffic input percentile level, section 185022.**

| Site | Scenario | Traffic Input Percentile | | | | |
|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% |
| | | Life to Punchout Failure (years) | | | | |
| 185022 | 1-0 | 20.7 | – | – | – | – |
| | 1-1 | 24.7 | 44.7 | 44.7 | 44.7 | – |
| | 1-2 | 25.7 | 44.7 | 44.7 | 44.7 | – |
| | 2-0 | 18.8 | – | – | – | – |
| | 2-1 | 19.3 | 38.7 | 44.7 | 44.7 | – |
| | 2-2 | 21.7 | 29.7 | 34.7 | 24.7 | – |
| | 2-3 | 23.7 | 44.7 | 44.7 | 44.7 | – |
| | 3-0 | 32.7 | – | – | – | – |
| | 3-1 | 32.7 | 36.7 | 37.7 | 40.7 | – |
| | 4-0 | 44.7 | – | – | – | – |
| | 4-1 | 44.7 | 44.7 | 44.7 | 44.7 | – |
| | 4-2 | 44.7 | 44.7 | 44.7 | 44.7 | – |
| | 4-3 | 40.7 | 44.7 | 44.7 | 44.7 | – |
| | 4-4 | 17.7 | – | – | – | – |
| | 4-5 | 17.5 | 19.6 | 20.7 | 22.7 | – |
| | 4-6 | 17.3 | 24.7 | 29.7 | 44.7 | – |
| | 4-7 | 15.3 | 20.1 | 22.7 | 34.7 | – |

– Indicates no data available.

**Table 54. Life prediction estimates by scenario and traffic input percentile level, section 265363.**

| Site | Scenario | Traffic Input Percentile | | | | |
|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% |
| | | Life to Slab Cracking Failure (years) | | | | |
| 265363 | 1-0 | 45.0 | – | – | – | – |
| | 1-1 | 45.0 | 99.0 | 45.0 | 99.0 | – |
| | 1-2 | 44.0 | 99.0 | 32.0 | 99.0 | – |
| | 2-0 | 99.0 | – | – | – | – |
| | 2-1 | 99.0 | 99.0 | 99.0 | 99.0 | – |
| | 2-2 | 99.0 | 99.0 | 99.0 | 99.0 | – |
| | 2-3 | 99.0 | 99.0 | 99.0 | 99.0 | – |
| | 3-0 | 99.0 | – | – | – | – |
| | 3-1 | 99.0 | 99.0 | 99.0 | 99.0 | – |
| | 4-0 | 99.0 | – | – | – | – |
| | 4-1 | 99.0 | 99.0 | 99.0 | 99.0 | – |
| | 4-2 | 99.0 | 99.0 | 99.0 | 99.0 | – |
| | 4-3 | 99.0 | 99.0 | 99.0 | 99.0 | – |
| | 4-4 | 99.0 | – | – | – | – |
| | 4-5 | 99.0 | 99.0 | 99.0 | 99.0 | – |
| | 4-6 | 99.0 | 99.0 | 99.0 | 99.0 | – |
| | 4-7 | 99.0 | 99.0 | 99.0 | 99.0 | – |

– Indicates no data available.

**Table 55. Life prediction estimates by scenario and traffic input percentile level, section 533813.**

| Site | Scenario | Traffic Input Percentile | | | | |
|---|---|---|---|---|---|---|
| | | 50% | −75% | −85% | −95% | −99.9% |
| | | Life to Slabs Cracking Failure (years) | | | | |
| 533813 | 1-0 | 18.7 | – | – | – | – |
| | 1-1 | 18.7 | 22.0 | 23.0 | 24.0 | – |
| | 1-2 | 18.6 | 23.0 | 24.0 | 23.0 | – |
| | 2-0 | 19.8 | – | – | – | – |
| | 2-1 | 21.0 | 22.0 | 23.0 | 24.0 | – |
| | 2-2 | 19.9 | 22.0 | 22.0 | 23.0 | – |
| | 2-3 | 19.9 | 24.0 | 25.0 | 28.0 | – |
| | 3-0 | 11.8 | – | – | – | – |
| | 3-1 | 11.8 | 12.1 | 12.7 | 12.8 | – |
| | 4-0 | 14.8 | – | – | – | – |
| | 4-1 | 14.7 | 15.8 | 16.6 | 17.0 | – |
| | 4-2 | 14.0 | 17.6 | 18.6 | 21.0 | – |
| | 4-3 | 15.6 | 24.0 | 28.0 | 48.0 | – |
| | 4-4 | 12.6 | – | – | – | – |
| | 4-5 | 10.8 | 11.8 | 12.6 | 12.8 | – |
| | 4-6 | 9.8 | 19.9 | 28.0 | 50.0 | – |
| | 4-7 | 11.8 | 21.0 | 25.0 | 50.0 | – |

– Indicates no data available.

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