

**A PRACTICAL GUIDE TO LOW-VOLUME ROAD
PERPETUAL PAVEMENT DESIGN**

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ABSTRACT

Perpetual pavement structural design for high volume roads hinges on limiting the strains caused by the vast majority of heavy vehicles. Using this approach allows for the use of the endurance limit concept which implies that structural damage due to bottom-up fatigue cracking and rutting deep in the pavement will not occur if certain levels of critical strains in the structure are not exceeded. The resulting pavement structure is thick enough to ensure long-life while it is economically attractive because it avoids over-design. Low-volume pavements designed in this manner would be too thick to be economically viable because infrequent heavy vehicles such as garbage trucks, busses, and delivery vans would dictate the strains according to the endurance limits. However, when examining the rate of damage accumulation on low-volume roads, it is possible to design long-life asphalt structures by ensuring that damage accumulation remains low over a long period of time (i.e., 30 years). This paper presents a practical approach to perpetual pavement design for low-volume roads. It includes simple design equations, based on results from PerRoad analyses, to facilitate low-volume road design.

INTRODUCTION

Long-life pavements are often associated with high traffic volume facilities, and in such situations, perpetual pavements make good engineering and economic sense. By avoiding expensive reconstruction, future costs in terms of agency expenditures and traveling inconvenience are minimized. In these situations, the design strategy is to make sure that damage from the heaviest vehicles is minimal. Since heavy vehicles tend to have a high frequency, this approach results in relatively thick sections of hot mix asphalt (HMA).

Low volume roads (LVR's) can also benefit from the application of perpetual pavement design. By ensuring proper design and construction, it would be possible to avoid pavement reconstruction, and while traffic delay is not usually an overriding consideration, local businesses and residents will not be inconvenienced if future work is confined to resurfacing the existing pavement structure. Muench et al. (1) investigated the economics of long-life low-volume asphalt pavements in Washington State. According to their research, perpetual pavements for low-volume roads can be 25% more economical than conventional low-volume asphalt pavement design.

Pavement design software (PerRoad) has been developed to facilitate perpetual pavement design following mechanistic-empirical principles (2). While it has been primarily used to design structures for high traffic volumes, there is a need to investigate its applicability in low-volume scenarios. This is of particular importance since it is estimated that 86% of the developing world's road network consists of low-volume roads (3). Further, approximately 69% of U.S. federal-aid road centerline miles have an average daily traffic below 5,000 (1). From an economic standpoint, in the U.S., low-volume road maintenance and rehabilitation account for \$82,000,000 per year, or about 54% of the annual investment in roads (3). Clearly, low-volume roads are an important part of the worldwide transportation infrastructure and even small improvements in their design can have significant impacts on the economy.

OBJECTIVES AND SCOPE OF STUDY

The primary objective of this study was to develop simple equations to facilitate the design of LVR's using mechanistic principles. Within the paper, the PerRoad software is first described, followed by recommendations for LVR input parameters to be used within the software. A numerical study is then presented from which simple design equations were developed for LVR design.

PERROAD

Before discussing the use of PerRoad in the context of LVR's, a general description of the program is presented below. Following this section are recommendations regarding input parameters and analysis for LVR's.

Materials and Performance Criteria

PerRoad is a mechanistic-based pavement design and analysis program that utilizes layered elastic analysis and Monte Carlo simulation to develop probability-based flexible pavement designs (2). Figure 1 illustrates the structural input window for the program. As shown in the figure, PerRoad can design up to five-layer structures and consider a maximum of five seasons. Seasonal air temperatures can be entered and the program will automatically calculate HMA stiffness as a function of pavement temperature and performance-graded (PG)

binder. Alternatively, designers can enter stiffnesses manually based upon more specific information that may be available.

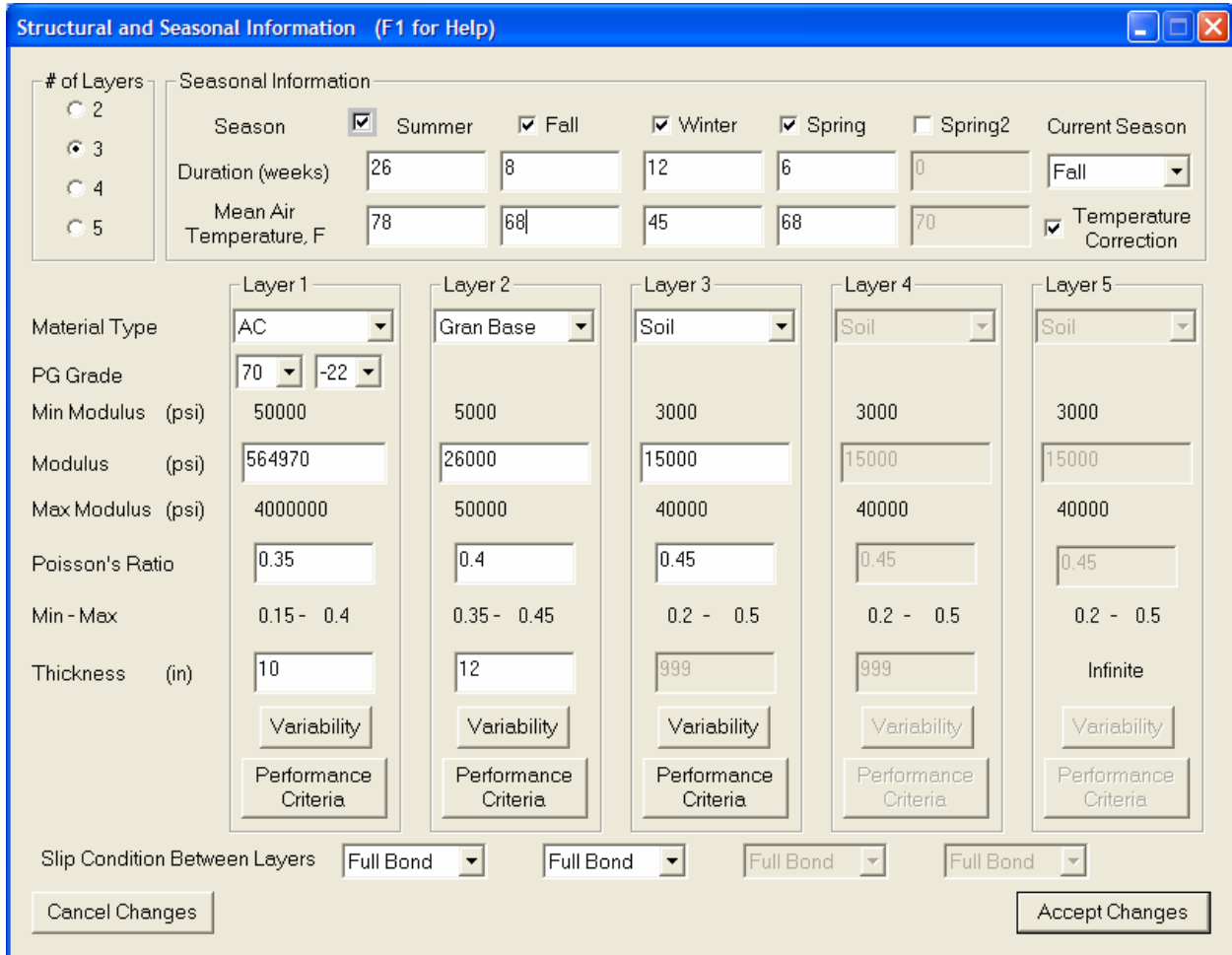


FIGURE 1 PerRoad Structural Input Window.

The variability of individual layer thicknesses and stiffnesses can be incorporated in design. The “Variability” buttons shown in Figure 1 allow the designer to characterize the variability as either normally or log-normally distributed with default coefficient of variation values recommended within the software. This feature allows designers to rationally consider the impact of improved construction practices and specifications on required pavement thickness.











The “Performance Criteria” buttons shown in Figure 1 enable the designer to input performance thresholds and transfer functions for each layer. The top, middle or bottom of each layer can be selected and various pavement responses (e.g., deflection, stress, strain) can be specified. However, typical perpetual pavement design relies upon controlling the horizontal tensile strain at the bottom of the HMA layer and the vertical compressive strain at the top of the subgrade. Further, damage resulting from responses exceeding the threshold can be computed using common fatigue and rutting algorithms that will be discussed further below.

Load Spectra Characterization

The second input for PerRoad is load characterization. Figures 2 and 3 illustrate the main windows for entering the traffic loadings. The designer can select a default vehicle classification based upon the functional classification of the roadway. The defaults are based upon data available from the ME Pavement Design Guide software (4), an FHWA study (5) and data available from the Long Term Pavement Performance (LTPP) database, Datapave 3.0. The program will then automatically load the representative load spectra (single, tandem and tridem axle weights) that correspond to the vehicle type distribution as shown in Figure 3. The designer also enters traffic volume, percent trucks, truck growth rate, percent trucks in the design lane and the directional distribution.

Vehicle Type Distribution (Press F1 for Help)

Roadway Functional Classification: Rural Local Collector

Vehicle Classification	% AADTT	Average Number of Axles Per Vehicle		
		Single	Tandem	Tridem
 4	3.5	1.62	0.39	0
 5	48.4	2	0	0
 6	9.2	1.02	0.99	0
 7	0	1	0.26	0.83
 8	6.6	2.38	0.67	0
 9	29.1	1.13	1.93	0
 10	3.2	1.19	1.09	0.89
 11	0	4.29	0.26	0.06
 12	0	3.52	1.14	0.06
 13	0	2.15	2.13	0.35
Total	100			

Cancel Changes Accept Changes

FIGURE 2 Vehicle Type Distribution.

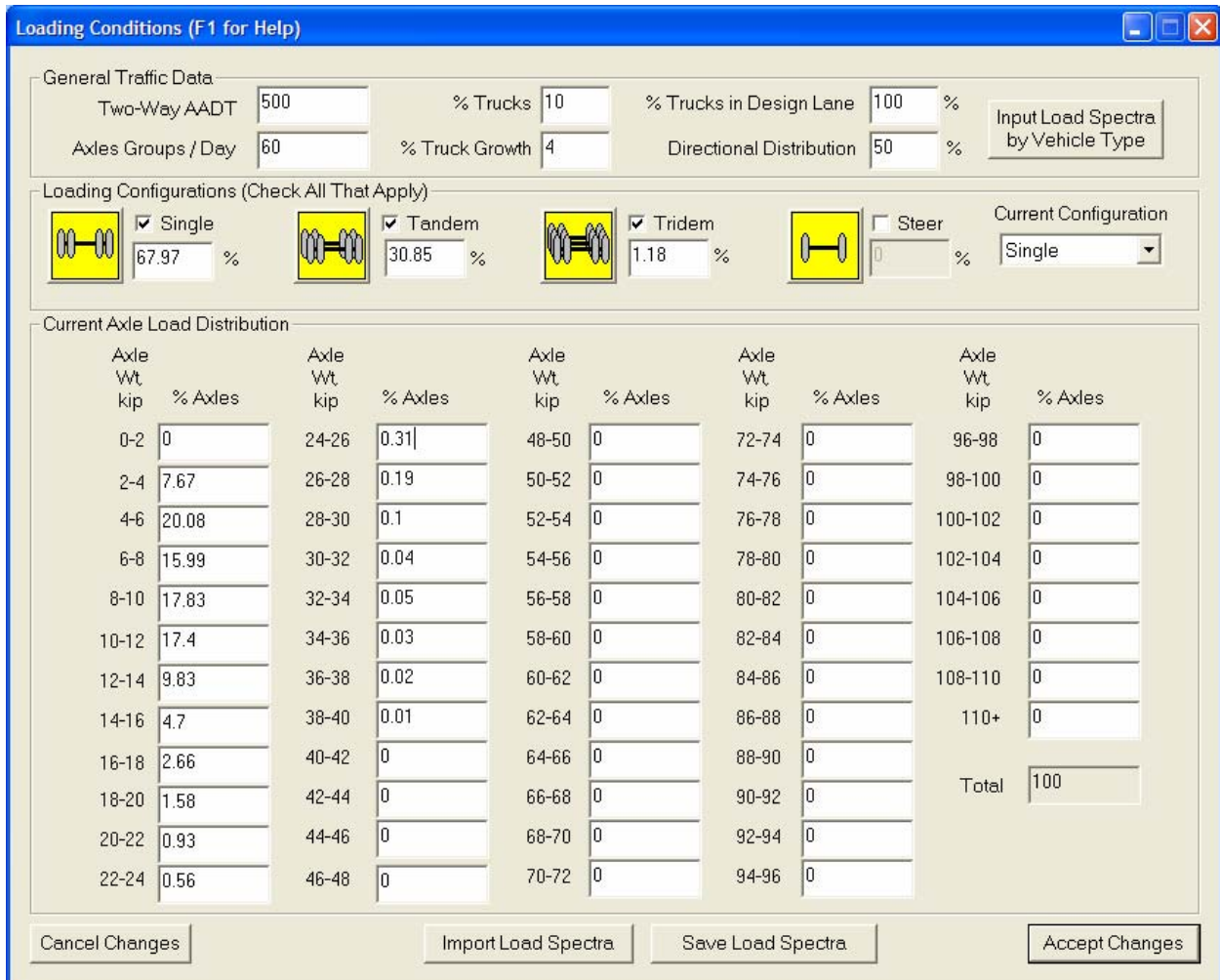


FIGURE 3 Axle Load Spectra.

Analysis and Design

After the structural cross section, materials, performance criteria and traffic have been defined, the designer proceeds to analysis and design. Within the window shown in Figure 4, the designer can alter the pavement cross-section and evaluate the results of the Monte Carlo-based M-E analysis. A full discussion regarding the Monte Carlo M-E procedure in PerRoad is documented elsewhere (2). The three primary outputs are the percent below the threshold criteria, the damage accumulation per million axle and the estimated number of years until damage equals 0.1. The damage computations are based upon Miner's Hypothesis, a standard damage accumulation model used in M-E design. In conventional M-E design, pavement sections are designed to a damage of 1.0 which corresponds to a terminal level of pavement distress. It was decided, for perpetual pavement design, to lower the damage value to 0.1 since the objective is to observe no structural distress at the end of the design period. For high-volume perpetual pavement design it is recommended that damage equal 0.1 after 35 years.

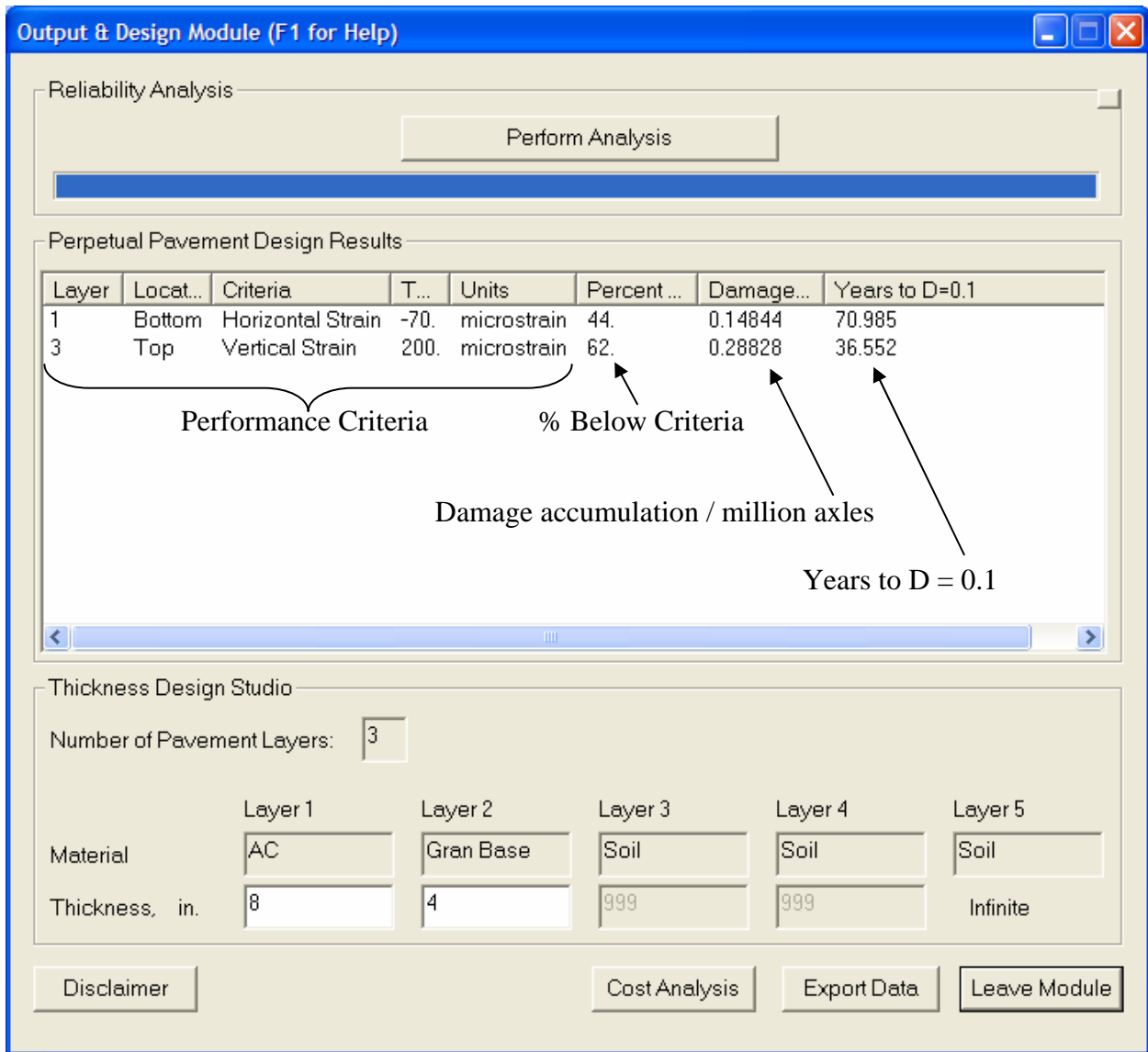


FIGURE 4 Analysis and Design.

LOW-VOLUME ROADS - DEFINED

There are a number of definitions for low-volume roads as demonstrated by a list compiled by Muench et al. (1) in Table 1. Rather than define low-volume roads as done in Table 1, for the purposes of this design method, low-volume roads are defined as those whose traffic conditions require a thickness of less than 8 in. (200 mm). As discussed below, it is recommended that if designs require greater than 8 in. (200 mm), a more detailed analysis using PerRoad or another design approach be utilized.

TABLE 1 Low Volume Road Definitions (after 12)

Organization	Definition	Reference
Transportation Research Board	Road located in a rural environment that supports automobile operation with less than 500 vehicles/day	(3)
American Association of State Highway and Transportation Officials (AASHTO)	0.7 to 1 million ESAL in a given performance period with 500,000 ESAL as a practical maximum	(6)
Washington State DOT	< 50,000 ESALs in 20 years	(7)

METHODOLOGY

When considering the design of LVR's, it is important to maintain the basic principles of simplicity and efficiency. Simplicity is needed because the input parameters are often based upon local experience rather than extensive laboratory testing or data collection efforts and a more sophisticated analysis is not justified. Efficiency is required since time-consuming design simulations are not warranted for LVR design. These principles are embodied in the methodology below and were certainly recognized by earlier design procedures developed for LVR's (*e.g.*, 6, 8). In developing the PerRoad LVR framework, a number of simulations were run within a fixed set of conditions to establish simple equations that can be used for design. The following subsections first detail the design parameters, then the development of the equations.

Traffic

It is recommended that LVR design be limited to either rural local collectors or urban collectors. Figure 5 illustrates the vehicle type distribution assumed within PerRoad for these two functional classifications. Of particular importance, as will be discussed later, is the prevalence of Class 9 vehicles on rural collectors when compared to urban collectors. Figure 6a and 6b show the corresponding axle weight distributions for single and tandem axles, respectively. From the figures, it is apparent that the Class 9 vehicles have much heavier single and tandem axles when compared to the other dominant vehicle type (Class 5). In terms of traffic volume, a range of conditions were considered and are listed in Table 2. It should be noted that some combinations of traffic in Table 2 will result in relatively large traffic volumes. For example, 5,000 AADT with 3% growth, 20% trucks and 50% directional distribution results in over eight million trucks during the 30 year design period. This would likely exceed the definition of low volume roads for most agencies. However, for the purposes of this investigation, it was decided to execute the full matrix of pavement designs derived, in part, from the design parameters shown in Table 2.

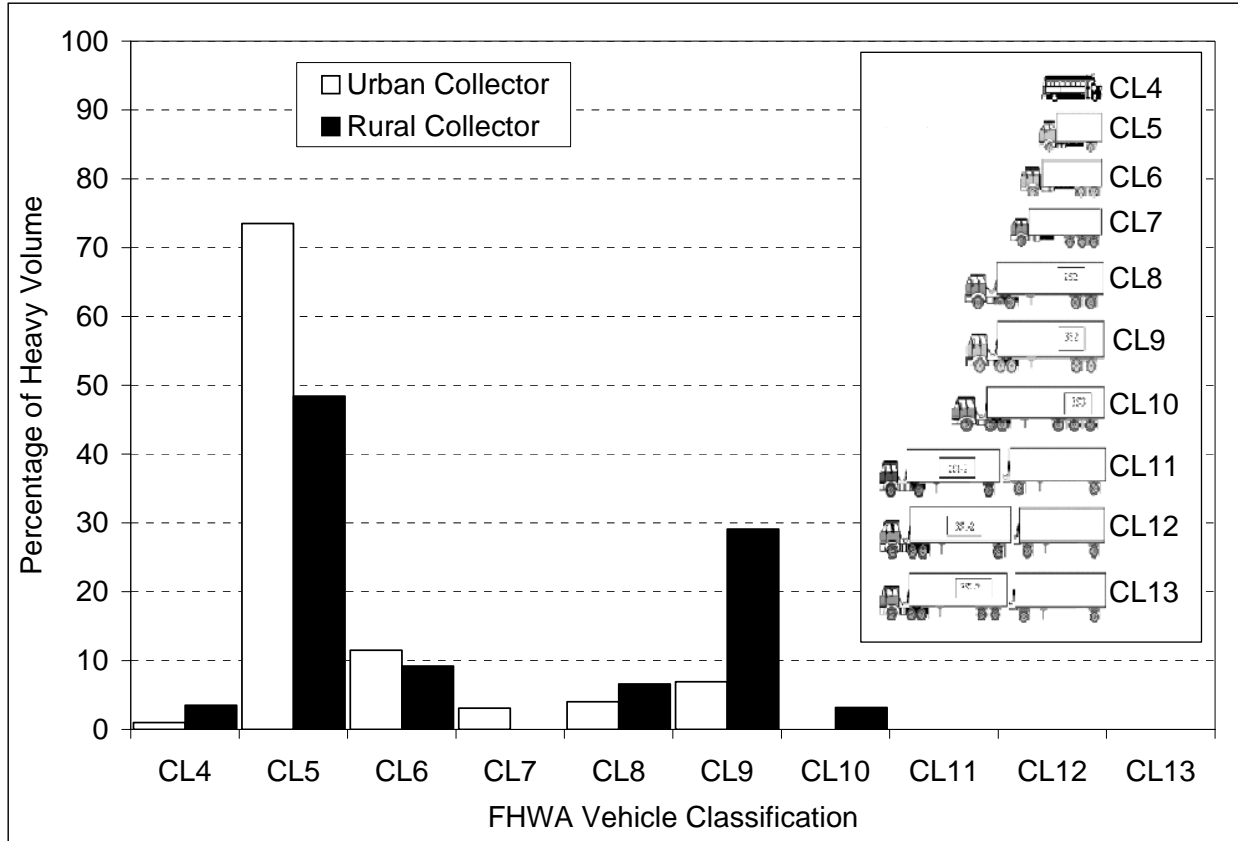
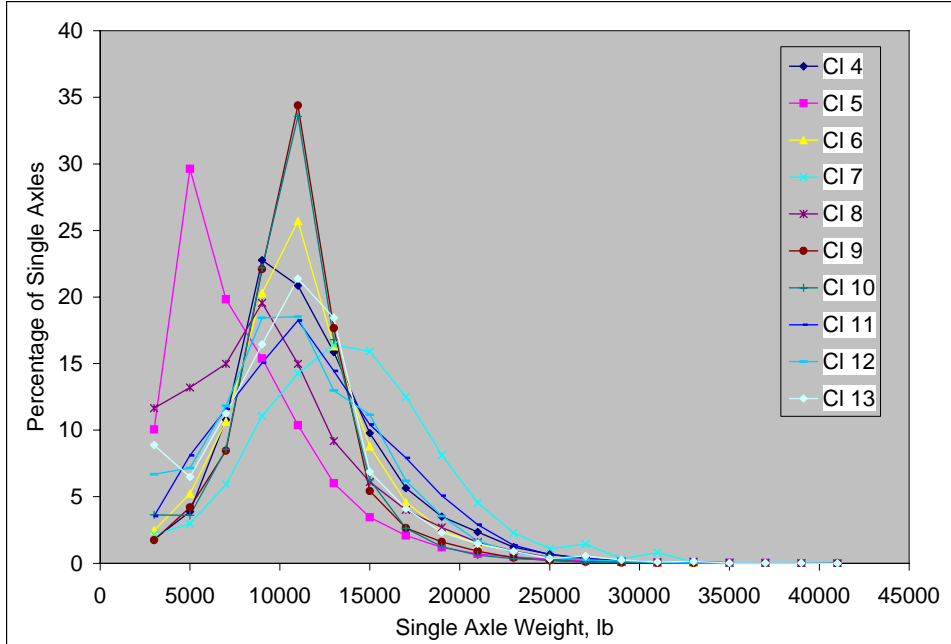
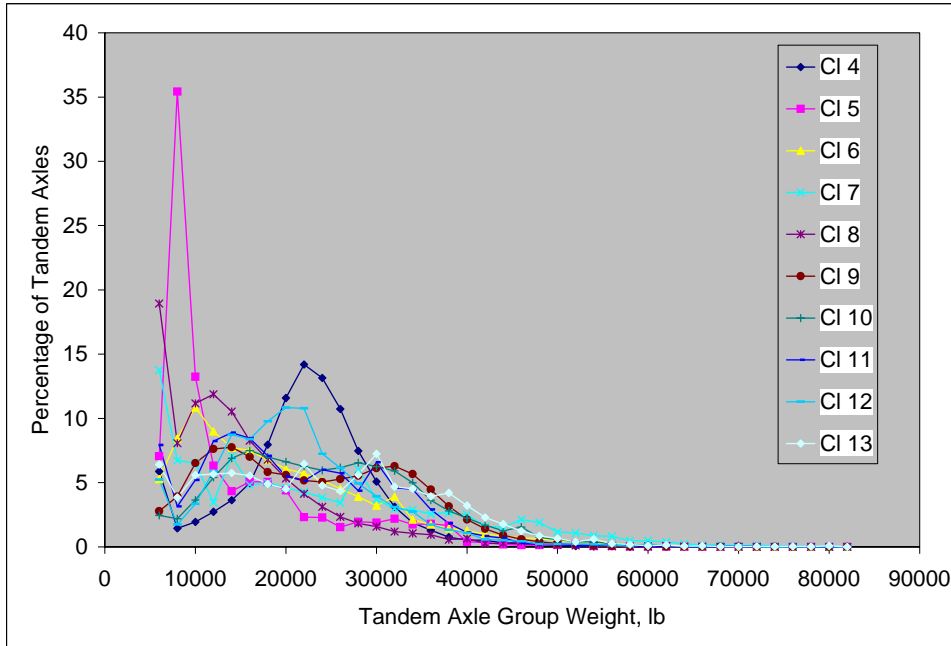


FIGURE 5 LVR Vehicle Type Distributions.



a) Single Axles



b) Tandem Axles

FIGURE 6 Axle Load Distributions.

TABLE 2 Traffic Volume Parameters

Parameter	Range
Volume	500 – 5,000 AADT
Growth	0% – 3%
Percent Trucks	5% – 20%
Directional Distribution	50%

Pavement Cross-Section and Materials

To act as a construction platform, it is recommended that a 4 in. (100 mm) aggregate base layer be placed on top of the subgrade soil, as shown in Figure 7. The subgrade soil, within the PerRoad LVR framework, can range from 10,000 psi to 30,000 psi (70 MPa to 210 MPa). It is assumed that the granular base will be of reasonable quality having a design modulus of 20,000 psi (137 MPa). The levels of variability, not described herein, were based on PerRoad default values and consistent with other studies of pavement variability (9).

The hot-mix asphalt (HMA) overlying the aggregate base layer was assumed to have a modulus ranging from 400,000 psi to 1,000,000 psi (2,760 MPa to 6,895 MPa). This range captures moduli values for most Superpave-designed mixtures and the designer should select a value representative of a particular mix in a given climate. The HMA thickness, of course, must be determined as an output of the design process.

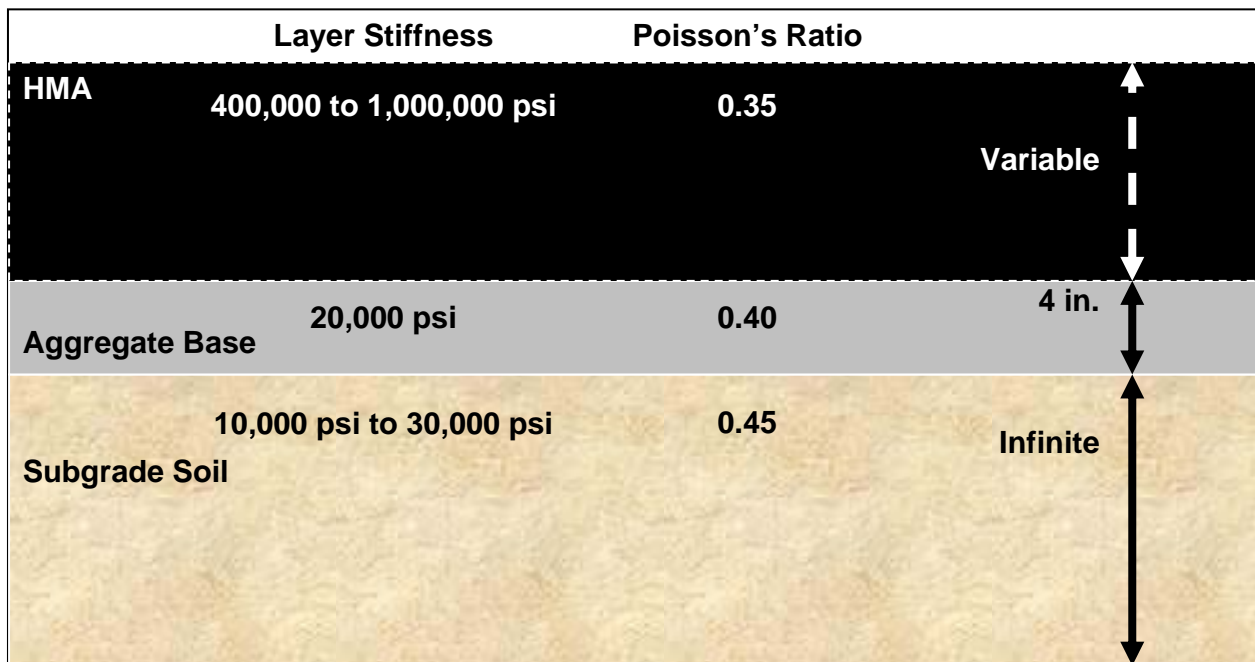


FIGURE 7 Structural Cross Section and Material Properties.

Performance

The Asphalt Pavement Alliance currently considers a pavement life exceeding 35 years, with no structural deterioration, to be perpetual for high-volume roadways (10). For LVR design, it is reasonable to somewhat reduce this lifespan to 30 years since there is less overall demand on the structure. In terms of pavement response criteria, 70 $\mu\epsilon$ at the bottom of the asphalt layer for fatigue and 200 $\mu\epsilon$ at the top of the subgrade for rutting were selected, respectively, based upon previous studies (11, 12). Further, fatigue and rutting algorithms developed at Mn/ROAD (13) were used to predict pavement damage in cases where pavement responses exceeded the thresholds. They are:

$$N_f = 2.83 * 10^{-6} \left(\frac{1}{\varepsilon_t} \right)^{3.148} \quad (\text{fatigue}) \quad (1)$$

$$N_r = 6.026 * 10^{-8} \left(\frac{1}{\varepsilon_v} \right)^{3.87} \quad (\text{rutting}) \quad (2)$$

where:

N_f = number of load repetitions until fatigue failure

N_r = number of load repetitions until rutting failure

ε_t = horizontal tensile strain at the bottom of the HMA

ε_v = vertical compressive strain at the top of the subgrade

As discussed above, Miner's Hypothesis is used in conjunction with the transfer functions within PerRoad to compute the number of years until the pavement damage equals 0.1.

Development of Design Equations

A total of 486 pavement designs, using PerRoad 3.01, were developed within the range of variables described above. The designs represented two roadway functional classifications, three traffic volumes, three growth rates, three truck percentages, three levels of soil stiffness and three levels of HMA stiffness. For each design, several iterations where the HMA thickness was changed were required to obtain a 30 year pavement performance period. For each iteration, 2,500 Monte Carlo cycles were executed automatically by PerRoad to determine the stochastic-based performance period. Designs were developed to the nearest 0.25 in. (6.4 mm). From these simulations, design equations were developed for each functional classification with the following format:

$$\text{HMA} = C_0 + C_1 * \text{AADT} + C_2 * \% \text{Trucks} + C_3 * \% \text{Growth} + C_4 * \text{Soil Stiffness} + C_5 * \text{HMA Stiffness} \quad (3)$$

where:

HMA = required thickness of HMA, in.

AADT = two way average annual daily traffic (500 to 5000)

% Trucks = percentage of trucks in AADT (5% to 20%)

% Growth = growth rate of trucks over 30 year period (0% to 3%)

Soil Stiffness = subgrade soil stiffness, psi (10,000 psi to 30,000 psi)

HMA Stiffness = stiffness of HMA, psi (400,000 psi to 1,000,000 psi)

$C_0, C_1, C_2, C_3, C_4, C_5$ = regression constants

Table 3 lists the statistical parameters for each functional classification. The high R^2 , shown in the table, indicates a very good fit between the regression equations and PerRoad designs. This is further exemplified in Figure 8 where the plotted points fall within a tight band around the unity line. The randomness about the unity line is due to the stochastic nature of the pavement designs using Monte Carlo simulation.

Through statistical testing, it was found that the rural local collector required marginally thicker HMA given the same input parameters. The explanation for this can be seen in Figures 5 and 6 where the Class 9 vehicle is heavier and more prevalent on rural local collectors and therefore increases the HMA design thickness.

A notable concern in Figure 8, with respect to low volume roads, is thicknesses approaching 16 in. (400 mm). These pavement designs correspond to the highest traffic levels and lowest stiffnesses in the design matrix and are not likely to be constructed by local agencies as low-volume roads. Take, for example, 5,000 AADT with 20% trucks and 3% growth. This level of traffic would correspond to approximately 8.6 million trucks over a 30-year period; certainly not low-volume by most agency standards. Therefore, as discussed above, it is recommended that thicknesses exceeding 8 in. (200 mm) be re-evaluated with the full PerRoad or other, more sophisticated, design approaches.

It is also important to encourage designers to consider the available materials in addition to the traffic level in determining if a facility is low-volume. Some combinations of higher quality materials can handle larger traffic volumes with reasonably thin HMA. For example, a rural collector facility with 5,000 AADT, 3% growth and 10% trucks can be designed with an 8 in. (200 mm) HMA layer if the soil and HMA stiffnesses are 30,000 psi and 1,000,000 psi (210 MPa and 6,895 MPa), respectively. This same traffic level, which represents over 4.4 million trucks in 30 years, would require 14 in. (355 mm) HMA if the soil were 10,000 psi (70 MPa) and the HMA were 400,000 psi (2760 MPa). Therefore, it is important to consider both the materials and traffic in developing a low-volume road design.

The primary advantage of the design equation approach is to greatly simplify the design procedure. While it does embody a mechanistic-empirical stochastic pavement analysis, the equations are very easy to use and can facilitate rapid design development.

TABLE 3 Design Equation Regression Constants

Coefficient	Urban Collector	Rural Local Collector
C ₀	10.963	11.963
C ₁	6.661E-4	6.753E-4
C ₂	0.120	0.124
C ₃	0.258	0.234
C ₄	-1.150E-4	-1.276E-4
C ₅	-5.071E-6	-5.486E-6
R ²	0.942	0.938

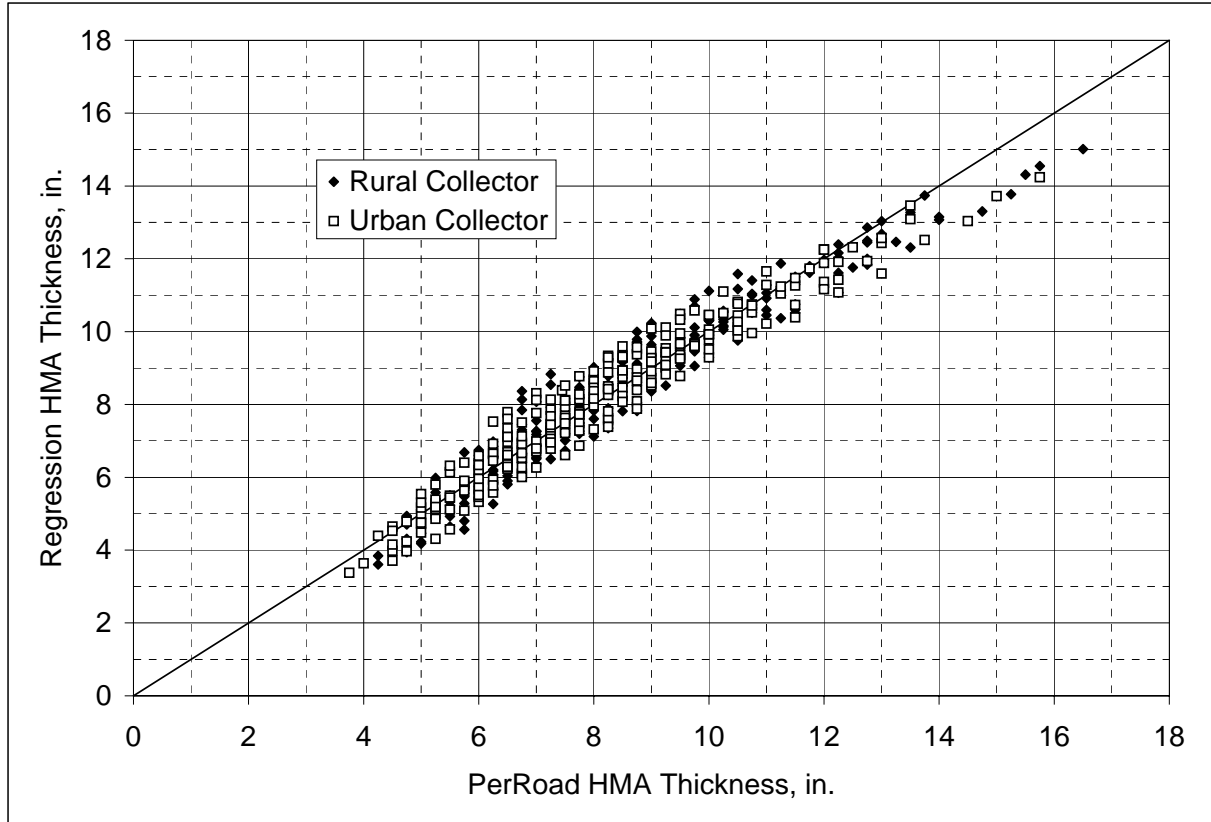


FIGURE 8 Regression Results.

CONCLUSIONS AND RECOMMENDATIONS

While the design of perpetual pavements has historically been devoted to high-volume facilities, recent studies have indicated a need for applying the same concepts to low volume roads. Based upon information presented above, the following conclusions and recommendations are made:

1. Within the range of conditions considered in this study, the linear regression equations for rural and urban collector facilities can be used to for low-volume road design with reasonable accuracy.
2. Designers should not only focus on traffic volume to define a low-volume facility, but also the available materials. Some combinations of higher-quality materials are capable of handling larger traffic volumes with HMA thicknesses less than 8 in. (200 mm).
3. Designs resulting in HMA greater than 8 in. (200 mm) should be further evaluated with the full PerRoad software or other more sophisticated design tool.
4. The simplicity of the design equations should enable local agencies and consultants to develop low-volume road designs with minimal training, software and time requirements.
5. A low volume roads component of PerRoad will be developed and included as a module in the next release of the software.

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