Simple Empirical Guide to Pavement Design of Low-Volume Roads in Indiana

Karim A. Abdel Warith, Panagiotis C. Anastasopoulos, Joseph C. Seidel, and John E. Haddock

Low-volume roads constitute 86% of the developing world’s road network (1). In the United States, approximately 70% of federal-aid road miles are considered low volume, with low-volume road maintenance and rehabilitation accounting for $82 billion per year, or about 54% of the annual road-related investment (2). Of these low-volume roads, more than 2.6 million miles are under the control of local government agencies (3). Although low-volume roads carry only 15% of the traffic in the United States, their corresponding accident rates are considerably higher than those of higher-volume roads. An example of this disparity shows an average of 2.41 accidents per million vehicle miles traveled on low-volume roads versus an average of 1.56 for higher-volume roads (4). More information on low-volume roads and their impacts is available elsewhere (5).

Low-volume roads are an important part of the nation’s transportation infrastructure. To that end, the need to use engineering principles when designing low-volume roads, so as to ensure economy and avoid premature road failures, is exigent. The objective of the work outlined in this paper is to develop an empirical design guide for low-volume roads that requires local agencies to gather only limited, readily available information and that is simple for agencies to use but customizable to account for specific weather and subgrade conditions.

Low-volume roads constitute the vast majority of the U.S. road network. From an economic standpoint, preservation of low-volume roads costs more than $80 billion per year, or more than half the annual investment in roads. Although low-volume roads carry a small percentage of the overall traffic, their associated crash rates are considerably higher than those for higher-volume roads. Because low-volume roads are an important part of the nation’s transportation infrastructure, engineering principles should be used when these roads are designed to ensure economy and to avoid premature road failure. Many agencies have proposed design methods for low-volume roads, yet most of these roads require input that may not be available to local agencies. This paper presents an empirical design guide for low-volume roads that requires local agencies to gather only limited, readily available information and that is simple for agencies to use but customizable to account for specific weather and subgrade conditions.

Low-volume roads are an important part of the nation’s transportation infrastructure. To that end, the need to use engineering principles when designing low-volume roads, so as to ensure economy and avoid premature road failures, is exigent. The objective of the work outlined in this paper is to develop an empirical design guide for low-volume roads that requires local agencies to gather only limited, readily available information and that is simple to use but customizable to account for specific weather and subgrade conditions.

REVIEW OF PAST WORK

FHWA classifies low-volume roads as roads servicing an average daily traffic (ADT) of less than 500 vehicles per day (vpd) (3, 5). Apart from FHWA’s generic definition, which uses traffic volume as the main categorization criterion, low-volume roads have been defined differently by various organizations. A typical alternative criterion is the relative damage to the pavement structure caused by various axle loads that use the equivalent single-axle load (ESAL). This mixed traffic causes various magnitudes and repetitions of wheel loads and can be readily converted to an equivalent standardized loads number, with the most common being the 18,000-lb (80-kN) ESAL. Two standard U.S. ESAL equations are derived from the AASHTO road test; both are dependent on pavement type (rigid or flexible) and on pavement structure (slab thickness for rigid pavements and structural number for flexible pavements). ESAL takes into account mixed traffic loads. This feature allows for heavier and lighter vehicles and their associated loads to be properly considered, along with the number of lanes, traffic growth, traffic distribution, and design period. Therefore, ESAL requires more effort to obtain but has the potential to provide more accurate road function classifications. Hall and Bettis summarize that (a) the 1993 AASHTO Guide for Design of Pavement Structures considers a road to be low volume when 50,000 < ESAL < 1,000,000 (3); (b) the Asphalt Institute considers a road to be low volume when ESAL < 10,000 (6); and (c) the Washington State Department of Transportation considers a road to be low volume when ESAL < 100,000. The AASHTO Guidelines for Geometric Design of Very Low-Volume Local Roads (ADT ≤ 400) classifies low-volume roads as those with ADT < 400 vehicles; however, these guidelines are primarily relevant to roadway geometrics and do not fall within the scope of this investigation (7).

Low-volume design methods have been widely developed and successfully used by federal and state agencies across the United States (8–23). In Indiana, possibly the first such guide was developed in 1974 (24). While these design methods are well adjusted for the particular agency’s needs and capabilities, most of them require input that is typically not available to local agencies. For example, AASHTO has developed a procedure broadly used by 37 of the 48 contiguous United States (2). Interestingly, the design procedure for low-volume roads is a simplified version of that for high-volume roads (similar design charts and input requirements are used). Specifically, the
required inputs involve the subgrade resilient modulus \((M_r)\), design reliability (set to 50%), traffic (ESAL), and material properties for each layer [i.e., the structural layer coefficients \((a_i)\)]. However, the number of variables and relative complexity of this procedure can make it cumbersome for designs for low-volume roads given the limited resources available to local agency engineers. The problem is further compounded by lack of information and time and budget constraints.

The U.S. Army Corps of Engineers (USACE) also developed a design procedure for low-volume roads that is widely used; it is a simplified version of USACE’s design method for airport pavements. The relatively simple procedure has two major design input components: traffic load (ESAL) and soil strength [California bearing ratio (CBR)]. Even though the overall procedure is simple, complex equations are needed to estimate the structural thickness required for a material to be placed over another material of a given CBR strength, provided that the CBR of the added material is greater than the CBR of the underlying material.

The National Crushed Stone Association (NCSA) adapted parts of the USACE method, added several elements, and applied it to bituminous surfaces overlaying a crushed-stone base \((25, 26)\). The expected soil support determined from CBR values is separated into four categories: excellent, good, fair, and poor. A design index (DI) is assigned on the basis of expected traffic conditions, and a total thickness of crushed-stone or bituminous surface is selected from design tables. This design thickness is modified if severe conditions are applicable, such as frost damage or drainage issues.

Relatively recently, several states (California, Illinois, Kentucky, Minnesota, Mississippi, New York, Pennsylvania, Texas, Vermont, and Virginia) developed their own non-AASHTO design protocols for low-volume roads, each with varying levels of complexity and incorporating environmental, soil, and traffic factors specific for their region. A representative example is Minnesota, which has two design procedures: the gravel equivalency (GE) method found in the state aid manual and the \(R\)-value method \((i.e., a measure of the response of a compacted sample of soil or aggregate to a vertically applied pressure under specific conditions) (3, 27)\). The GE method is more commonly implemented throughout the state because of its simplicity and less conservative values. Nonetheless, both procedures are more conservative than the AASHTO method. The GE method has two input variables: traffic load (ADT) and soil strength. The classification of soil, a soil factor, and an assumed \(R\)-value are obtained for the soil strength. Through these inputs, a minimum bituminous GE and a total GE for design are obtained; or, in other words, the amount of bituminous base and surface in inches are acquired (from a chart). The \(R\)-value procedure uses two additional input components: load and strength. However, for this method, load is related to a sigma N-18 value (a standard 18-kip single-axle load serving to identify the cumulative deterioration effect of heavy vehicles for the design life of flexible pavements), and strength is the \(R\)-value determined from a stabilometer \((28)\). The important part in this detail-oriented design procedure is computing the \(R\)-value, as pavement structure requirements are influenced by small changes in this value.

Another example is Virginia’s design procedure for low-volume roads, which appears to be applicable to any U.S. state as long as certain assumptions for local conditions are made. This procedure basically uses traffic and soil inputs. The design ADT is calculated by multiplying the current ADT by a growth factor, and a soil support value (SSV) is used to represent soil strength. Mississippi similarly uses an SSV for soil strength; it is estimated by using a design CBR

### Table 1: Summary of Traffic Input Criteria by Design Procedure for Low-Volume Roads

<table>
<thead>
<tr>
<th>Procedure</th>
<th>ESAL</th>
<th>ADT</th>
<th>Index</th>
<th>Design Period</th>
<th>GF</th>
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<td>AASHTO</td>
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Note: GF = growth factor; blank cells = no input required.

### Table 2: Summary of Subgrade Strength Criteria by Design Procedure for Low-Volume Roads

<table>
<thead>
<tr>
<th>Procedure</th>
<th>(M_r)</th>
<th>CBR</th>
<th>Soil Type</th>
<th>(R)-Value</th>
<th>Frost</th>
<th>Drainage</th>
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Note: Blank cells = no input required.
Pumping, infiltration, and the intensity of frost action are all affected as they approach saturated conditions. The water table elevation, erosion, and the intensity of frost action are all affected by rainfall. Moisture within the pavement affects the contraction and expansion of the material constituents.

**GENERAL CONSIDERATIONS IN PAVEMENT DESIGN**

Three main factors should be considered in pavement design: materials (subgrade, subbase, base, surface), physical loading of the pavement represented by traffic (ESAL, ADT, percentage of heavy commercial vehicles), and the environment (temperature, precipitation, frost) \(^{29}\). The subgrade is the in situ (natural) soil prepared to be the foundation of the pavement structure. Treatments should be applied to the soil if the bearing capacity is insufficient. Desirable properties include high compressive and shear strengths, ease and permanency of compaction, drainage ability, and low susceptibility to volume changes attributable to moisture and freezing. Overlying pavement layers should increase in quality as the surface layer is approached. A compacted subbase may not be needed if the subgrade is of sufficient quality. The subbase can be either a treated or untreated granular layer or a treated layer of soil. The base course, generally consisting of good-quality aggregate, lies directly below the surface course and provides structural support.

Environmental conditions also play an important role in pavement design. Sudden temperature changes accompanied with moisture changes can cause cracking and raveling of asphalt layers. Soil shrinkage results from low temperatures, especially for cohesive soils, and leads to cracking. Temperature changes in the soil cause soil moisture to migrate from warmer to colder zones. Freezing conditions can lead to frost heave as ice lenses form in the subgrade. The depth of frozen soil can be estimated by using the freezing index \[\text{cumulative days below } 32\,^\circ\text{F} (0\,^\circ\text{C})\]. High losses of pavement strength occur in the spring as the soils thaw. Therefore, establishment of a load restriction is important if freezing is an issue. Precipitation also occurs in the spring as the soils thaw. Therefore, establishment of a load restriction is important if freezing is an issue. Freezing can lead to frost heave as ice lenses form in the subgrade. The water table elevation, erosion, pumping, infiltration, and the intensity of frost action are all affected by rainfall. Moisture within the pavement affects the contraction and expansion of the material constituents.

**DESIGN OF LOW-VOLUME ROADS**

The objective of this paper is to demonstrate an empirical design procedure for low-volume roads that requires local agencies to gather only limited, readily available information and is simple for them to use. The design should also be customizable to different weather and subgrade conditions. To that end, the design basis is first determined, and then the design guide is developed.

Of the procedures reviewed earlier, some provide design procedures for low-volume roads by simplifying general design guidelines, whereas others are specifically intended for design of low-volume roads. On the basis of the most promising of these design procedures, key features are identified and used in the development of a design guide for low-volume roads. The proposed design guide is intended to be customizable for low-volume roads, and Indiana is selected as a case state. In particular, the design guide allows for two design options that are cost-effective: aggregate roads and asphalt pavements. Other options include portland concrete cement pavement and roller-compacted concrete pavement, which require a bigger financial commitment from local agencies, as those pavements can frequently be more costly (even though the roller-compacted option may be an economically feasible alternative because of fluctuations in material costs over time). Specifics on portland cement concrete are available elsewhere \((30–32)\), as are those on roller-compacted concrete \((33)\). However, these approaches do not simultaneously satisfy the criteria of simplicity, input availability, and cost-effectiveness.

**Design Basis of Low-Volume Roads**

The USACE and the NCSA pavement design guides were earlier determined to be compatible with the objectives of this study, and the proposed design guide is therefore based on them.

The USACE design method is a simplified design guide based on the USACE procedure developed for airport pavements. It accounts for three main pavement categories: unsurfaced roads (the in-place...
natural soil used as the road surface), aggregate-surfaced roads, and bituminous pavements. It provides a pavement design by using six main surface types (3): (a) earth road, (b) treated surface (earth roads may be treated with bituminous materials to control dust and to waterproof the surface), (c) stabilized soil, (d) gravel roads, (e) processed materials (prepared by crushing and screening rock, gravel, or slag), and (f) spray applications and surface treatments (sprayed treatments and sprayed bitumen with an aggregate surface). The design procedure involves three basic steps. First, a class designation is assigned to the road on the basis of daily traffic. Second, a design category is assigned to the traffic on the basis of the composition of the traffic, which is classified into groups (34, 35). Third, a DI, determined from the design category and road class, is used to determine the thickness of the aggregate surface or flexible pavement system required above a soil with a given CBR strength (charts are used to obtain the values). The procedure is relatively simple to use but has a few limitations. Because the procedure has only two input factors, varying environmental effects and other uncertainties may not be adequately addressed. This procedure is based on equations that give required thicknesses for material that is to be placed over underlying material of a given strength (in CBR), provided that the placed material has greater CBR strength than the underlying material.

The NCSA method requires the CBR value and the DI to be known or estimated. CBR (determined either by field testing, laboratory testing, or estimating from the soil classification) is used to evaluate the subgrade soil, and traffic counts on secondary roads should be made separately for each of the three vehicle types used. The DI is based on the traffic parameter, which in turn is based on ranges of the average equivalent 18,000-lb single-axle loads per lane per day over a life expectancy of 20 years. Once the CBR and the traffic DI have been determined, the total design thickness is obtained by using a design chart.

Design Guide

The proposed design guide is presented as a flow chart and is based on the NCSA design guide and the USACE recommendations for pavement design. The proposed guide requires three basic inputs: traffic count and truck percentage, subgrade strength, and affiliation of the road’s being in a frost zone or not.

To produce the design guide, a number of assumptions were made:

- Different agencies have different traffic ranges that correspond to low-volume traffic, with the assumed range for low-volume traffic of less than 1,000 vpd being widely accepted.
- The lifetime expectancy of low-volume roads ranges from 15 to 20 years, with regular maintenance needed to ensure such service life.
- To simplify the input process for users, all trucks considered in the analysis are assumed to have three or more axles (all axles are expected to be tandem axles, except the steering axle), with pickup trucks and light-duty vehicles not considered trucks (they are considered part of the general traffic).
- Freeze depth in various locations in Indiana (the case state) was approximated by using the USACE frost zone map (29), with Indiana being divided into four frost zones, as illustrated in Figure 1 (Zone A has no frost depth; Zones B, C, and D have frost depths of 5, 10, and 20 in., respectively).
- Soil subgrade strength is listed in both CBR and dynamic cone penetrometer (DCP) values, with the relationship used to convert DCP to CBR being adopted from ASTM D6951, Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications. The equations used for DCP, in inches per blow or millimeters per mill of force, are as follows (36, 37):

\[
CBR = \frac{292}{(DCP \times 25.4)^{1.12}}
\]  

For CL soils with CBR < 10:

\[
CBR = \frac{1}{(0.432283 \times DCP)^2}
\]

For CH soils:

\[
CBR = \frac{1}{(0.072923 \times DCP)}
\]

The inputs needed consist of three components: traffic, geographic location (used to estimate frost depth), and subgrade strength.

Even though the design guide addresses low-volume roads, the traffic range of such roads remains broad for handling by using a single category. For this reason, the traffic is subdivided into three categories: low (less than 70 vpd), medium (70 to 200 vpd), and heavy (201 to 1,000 vpd). While being less broad than one category of up to 1,000 vpd, these traffic categories remain large enough to allow local agencies that do not have readily available traffic data to use an educated estimate to produce a reasonable design. This approach is quite different from the approaches employed by AASHTO, the Asphalt Institute, and the Mechanistic–Empirical Pavement Design Guide (MEPDG) (38), which require an extensive amount of information on the number of vehicles and their axle configurations.

The second traffic component needed for the design is an approximation of the percentage of trucks in the traffic stream, not an exact truck percentage. The only required information is whether the truck percentage is less than 1%, between 1% and 10%, or greater than 10%.

In relation to the component of geographic location, weather conditions differ from one place to another based on differences in latitude and elevation. Because pavements are continually subjected to varying weather conditions, weather must be considered when a pavement is designed. Design methods in the MEPDG involve rigorous analysis of a number of weather elements, such as temperature, precipitation, cloud cover, and wind speed. Although this information may be available, collecting and extracting it requires significant time and effort, and a high level of expertise and experience in the field is needed to process and use it. Simplified design methods proposed by the USACE design guide and NCSA require only knowledge of the frost depth in the area where the roadway is to be located. Because of its simplicity, limited time requirements, and robustness, the second, simplified approach has been adopted here. The case state, Indiana, is a moderately sized state without a homogenous climate, and it was therefore divided into four frost zones, as illustrated in Figure 1 (28). The four zones should not be treated as having fixed boundaries (a conservative estimate should be used in the vicinity of the boundaries); for example, if a road is to
Zone A
(0 frost depth)

Zone B
(5-in. frost depth)

Zone C
(10-in. frost depth)

Zone D
(20-in. frost depth)

FIGURE 1  Frost zone map for Indiana (29).
be built near the boundaries between Zones A and B, the frost depth could have a value of 2.5 in. (i.e., the average of the frost depth of the two zones, 0 and 5 in.).

The subgrade soil type and strength component are directly related to the location and the frost zone. For example, roads built in Zone A (no frost) are required by the design guide to detail subgrade strength in relation to DCP or CBR. Roads built in Zone B, C, or D (frost zones) require only the soil type. Soil types behave differently in freezing conditions, providing the background for the differentiation. Although some adjustments are needed to account for moisture content, soil strength gives an adequate description of the soil in nonfreezing conditions. Soil strength could be misleading when observed under freezing conditions. The subgrade soil type is needed if the road is to be built in a frost zone. The soil type can be classified in four categories, shown in Figure 2. The subgrade strength is required if the road is to be built in a nonfrost zone and is also divided into four categories (Figure 2). Producing a reliable design does not require definite CBR or DCP values, as a rough approximation of the soil strength will suffice. In addition, if knowledge of the soil strength is uncertain (e.g., weak versus medium soil), the proposed guide allows for the timely design of each case so that an informed decision about the cost-effectiveness of the extra thickness can be made.

**Design Process**

The design process involves the following steps: (a) acquiring the DI, (b) determining the frost zone where the road is located, (c) selecting the proper subgrade strength–quality category, and (d) choosing the desired design from the available design options.

The pavement DI is based on the traffic volume and related truck percentage of the road, and it is assigned a value from 1 to 4, as shown in Table 5, which summarizes the combinations of traffic volumes and truck percentages that correspond to each DI and illustrates that higher traffic and higher truck percentages correspond to higher design indices.

The second step in the design process is to identify the location of the road and in turn the corresponding frost zone for the selected road by using the map in Figure 1. Third, the proper subgrade strength–quality category (i.e., weak, medium, or strong) of the soil needs to be identified, in regard to CBR, DCP, or soil type (Figure 2).

The proposed design guide offers two pavement designs for any given set of inputs: an aggregate-road option and a flexible-pavement option. The complete design process is depicted in Figures 3 through 7.

![Figure 2](image-url)
Select Traffic Volume

- <70 vpd
  - Truck percentage: Any
    - DI 1 (go to Figure 4)

- 70–200 vpd
  - Truck percentage: <1%
    - DI 1 (go to Figure 4)
  - Truck percentage: 1%–10%
    - DI 2 (go to Figure 5)
  - Truck percentage: >10%
    - DI 3 (go to Figure 6)

- 201–10,000 vpd
  - Truck percentage: <1%
    - DI 2 (go to Figure 5)
  - Truck percentage: 1%–10%
    - DI 3 (go to Figure 6)
  - Truck percentage: >10%
    - DI 4 (go to Figure 7)

**FIGURE 3** General specifications for pavement designs.

![Diagram showing pavement designs](image)

**FIGURE 4** Proposed sections for pavements with DI 1 (* = use of crushed stone).
FIGURE 5  Proposed sections for pavements with DI 2 (* = use of crushed stone).

FIGURE 6  Proposed sections for pavements with DI 3 (* = use of crushed stone).
Figure 3 provides the general specifications that result in a specific DI (given traffic and truck characteristics, a DI is obtained; in turn, the DI points to an appropriate chart), and Figures 4 through 7 present the proposed sections for aggregate and flexible pavements with corresponding DIs 1 through 4, respectively. In some cases, surface treatments such as double chip seals can be used as an alternative to a 1-in. asphalt surface, though this depends on local circumstances, available funding, and future plans. However, for steep grades (6% or greater), the asphalt concrete surface layer is recommended.

The designer must understand that aggregates used for surface courses and base courses can vary significantly, as the two courses serve different purposes in the pavement. Aggregate gradation, plasticity, and permeability requirements for the two are different. For example, aggregate materials used for a surface course are typically more finely graded and contain higher amounts of fines (material passing the Number 200 (0.075-mm) sieve) than base course aggregates. In addition, when the decision between aggregate and flexible pavements is being made, the costs of maintaining both should be properly taken into account over the life of the pavement. For example, an aggregate road will need additional aggregate placed over time, and in some localities, the application of dust palliatives may be needed on a consistent basis. For flexible pavements, periodic crack sealing may be needed. Information on cases in which conditions in an area support the use of clay or silt can be found in Dell’Acqua et al. (39).

Design examples are presented in Figure 8.

If the frost depth is equal to zero (Zone A), the aggregate road design is a three-layer pavement design. From top to bottom, these layers are (a) aggregate surface course (the top layer of the aggregate design), (b) subbase layer (the second layer in the aggregate design, typically with a coarser gradation than the top layer), and (c) compacted-soil layer (optional layer used in the case of weak soils). Figure 8a shows a typical aggregate layer pavement in a nonfrost zone.

In the case of a frost zone (i.e., frost depth greater than zero), the aggregate road is a four-layer pavement design. From top to bottom, these layers are (a) aggregate surface course (using crushed stone), (b) subbase layer (second layer, typically with a coarser gradation than the top layer), (c) clean soil filter (typically sand), and (d) compacted soil (optional layer used in the case of weak soils or higher levels of traffic). Figure 8b shows a typical aggregate layer pavement in a frost zone.

For the flexible-design option and the case of frost depth equal to zero (Zone A), the flexible road design is a three-layer pavement design: from top to bottom, (a) asphalt surface course (hot- or warm-mix asphalt), (b) aggregate base layer (second layer in the flexible design, typically with a coarser gradation than the surface course), and (c) crushed stone (optional layer used in the case of weak soils). Figure 8c shows a typical flexible pavement in a nonfrost zone.

In the case of a frost zone (i.e., frost depth is greater than zero), the flexible road is a three-layer pavement design: from top to bottom, (a) asphalt surface course (hot- or warm-mix asphalt), (b) aggregate base layer (second layer in the aggregate design, typically with a coarser gradation than the surface), and (c) stabilized soil (typically
cement stabilized, with the depth of this layer equal to the frost depth in the design location). Figure 8d shows a typical flexible pavement in a frost zone.

SUMMARY AND CONCLUSION

This paper developed an empirical design guide for low-volume roads on the basis of USACE and the NCSA pavement design methods. From a comparison among various low-volume road design approaches applied by several U.S. states, these two design guides were found to be the least complex and to require easily attainable input.

The proposed guide was developed on the same principles; that is, it requires minimal input that is readily available to local agencies and is simple to use. As inputs, approximations of the daily traffic and truck percentage are used, along with the subgrade soil type and strength. Given these factors and the location of the road (by identifying weather characteristics affecting the pavement structure), specific aggregate and flexible road design options are given.

The state of Indiana is presented as a case study, and the specified design options for low-volume roads are presented. The flexibility of the proposed guide allows its use by most local agencies and provides for the design of low-volume roads in a timely fashion.

Future direction for work in design of low-volume roads should involve the development of a similar guide for tropical climates or cold regions, as the presented guide is anticipated to be well suited for regions characterized by moderate climate.

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REFERENCES


