A Novel Performance-Based Economic Analysis Approach: Case Study of Iowa Low-Volume Roads

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Abstract
Approximately 110,000 km (68,400 mi) of granular roadways exist in the 183,500-km (114,000-mi) road network in the state of Iowa, and operation and maintenance of these roadways costs roughly US$270 million annually. The major maintenance costs of these roads are aggregate cost and hauling costs from the quarry to the site. Accordingly, acquiring a cost-effective and high-performance surface material to be utilized in granular roadways can be a challenge. In this study, three conventional granular roadway materials and four coarser aggregate materials from different quarries were used to construct seven test sections to assess their relative performance and costs. The first three test sections were constructed with conventional materials, and the other four sections used optimum mixtures of the four coarse aggregate materials with the local conventional aggregate. The long-term performance and mechanistic behaviors of the different surface materials, including stiffness, changes in ride roughness, and dust production were evaluated for a period of 2 years. Using the resulting data, a mechanistic life-cycle benefit–cost analysis approach was developed to evaluate the use of coarse aggregate materials on granular roadways. The stochastic benefit–cost analysis results for different aggregate materials are presented in the form of probability density functions. Two different scenarios are presented based on the field test results, and the benefits in terms of dust production and surface ride quality are evaluated for each section.

Disciplines
Civil Engineering | Economics | Structural Materials

Comments

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Aproximately 110,000 km (68,400 mi) of granular roadways exist in the 183,500-km (114,000-mi) road network in the state of Iowa, and operation and maintenance of these roadways costs roughly US$270 million annually. The major maintenance costs of these roads are aggregate cost and hauling costs from the quarry to the site. Accordingly, acquiring a cost-effective and high-performance surface material to be utilized in granular roadways can be a challenge. In this study, three conventional granular roadway materials and four coarser aggregate materials from different quarries were used to construct seven test sections to assess their relative performance and costs. The first three test sections were constructed with conventional materials, and the other four sections used optimum mixtures of the four coarse aggregate materials with the local conventional aggregate. The long-term performance and mechanistic behaviors of the different surface materials, including stiffness, changes in ride roughness, and dust production were evaluated for a period of 2 years. Using the resulting data, a mechanistic life-cycle benefit–cost analysis approach was developed to evaluate the use of coarse aggregate materials on granular roadways. The stochastic benefit–cost analysis results for different aggregate materials are presented in the form of probability density functions. Two different scenarios are presented based on the field test results, and the benefits in terms of dust production and surface ride quality are evaluated for each section.

INTRODUCTION

The quality of granular roadway materials (e.g., abrasion resistance, freeze–thaw durability) is very important since common surface deteriorations such as material loss, gradation change, loss of crown, surface erosion, rutting, and potholes can be directly related to the quality of the materials used in these roadways (1). Granular material sources such as aggregate quarries produce aggregates with different qualities and different prices. Moreover, depending on the location of the quarry the total cost of obtaining a given aggregate could vary significantly due to the hauling costs. Therefore, finding a cost-effective high-quality aggregate source (with a balance between quality and hauling costs) is a common concern and challenge for construction and maintenance of granular roadways.

Since hauling of high-quality aggregate from greater distances increases construction and maintenance costs significantly, it is important to assess the benefits of using these materials for
construction of granular roadways, and determine if they can sustain performance for longer durations and with less maintenance. More frequent maintenance activities on granular roadways may require road closures which would increase maintenance costs (2). In addition, low-quality aggregates could result in greater vehicle operating costs (e.g., reduced fuel consumption, increased wear, and damage). Moreover, low-quality aggregates will generally abrade faster, thus producing more dust which can penetrate into engines and other vehicle components, resulting in greater wear rates and more frequent maintenance (3, 4).

There is a lack of high-quality aggregate sources in United States, particularly in the Great Plains region. For instance, previous studies reported that aggregate sources northeast Iowa have higher-quality aggregates than other regions such as the west and south portions, requiring the use of only half as much aggregate for comparable roadway performance (5–7).

Stiffness, dust, and surface roughness are three main factors in the evaluation of the serviceability of granular roadways and can serve as quality assurance–quality control (QA/QC) parameters. Evaluating the performance of the granular roadway layers by nondestructive tests is inexpensive due to their availability and low operation costs (1–4). There are several nondestructive test methods for stiffness measurements of granular roads. These include multichannel analysis of surface waves, falling weight deflectometer, automated plate load test, and lightweight deflectometer (LWD) tests. Among these tests, LWD is the most commonly used for measuring the stiffness of unbound granular surface layers due to its relatively low cost in terms of equipment and labor required (5, 6). In order to measure the amount of dust produced in the road, a quantitative dust measuring device has been developed that is commonly used as a repeatable and reproducible method (7–9). Moreover, measuring the International Roughness Index (IRI) by smartphone as a simple and low-cost solution to evaluate the surface roughness is growing rapidly while other traditional methods such as profilometers are expensive and labor-intensive (10, 11).

Approximately 50% of the total road network in the United States is composed of granular roads. Although literature on the importance of maintenance for paved roads is vast, this is not the case for granular roads (7). Because granular roadways provide access for rural areas, mostly for transportation of agricultural products, sustainability of these roads is very important to the economy of the United States (4). Since operation and maintenance of these granular roads costs roughly US$270 million annually (7), economic analysis is helpful to determine the cost-effectiveness of transporting materials from high-quality sources to replace low-quality local materials in granular road construction and maintenance (18–21).

Benefit–cost analysis (BCA) is an assessment of decisions based on the consequences (benefits and drawbacks) in accordance with them (22). BCA evaluates the benefits of using different alternatives instead of using a base case, by calculating the benefit–cost ratio (BCR) which is defined as the ratio of the present value of benefits over the service life of the project to the present value of the initial and future costs (23, 24). BCA is closely dependent on many important decision-making factors. Therefore, to define the benefits properly requires a deep oversight of the project and exact knowledge of the costs.

While there have been extensive mechanistic-based performance studies on low-volume roads (5, 25–31), and some have studied the economic performance of these roads (7, 21), to the best knowledge of the authors, performance-based economic studies of granular roads have not yet been investigated in detail. This paper presents a performance-based life-cycle benefit–cost analysis (LCBCA) method for comparing economic performance of granular roads constructed in rural road systems. Monetizing resilience benefits of higher-quality aggregate in a LCBCA
framework provides an assessment of broader benefits from such materials and contributes to building more-resilient and sustainable infrastructure. In this study, a granular road was defined as a two-lane local road with a granular surface, with traffic of less than 400 average daily vehicles and providing access for areas with low population density (32). In this study, seven different surface aggregate materials were collected from four different Iowa quarries and different performance measures were tested over a 2-year period. Using the performance measure tests, different possible scenarios for establishing the maintenance frequency of test sections were developed to use in an economic analysis framework. This paper has two major objectives. The first is to identify benefits associated with different types of gravel materials based on their long-term performance. The performance measurement techniques used in this study to identify such benefits were LWD, dustometer, and IRI. The second main objective is to investigate the economic performance of granular roads constructed with the different materials.

SITE DESCRIPTIONS

Surface aggregate materials for this study were collected from quarries featuring four different Iowa bedrock types: Lime Creek formation (LCF), Oneota formation dolomite (OFD), Bethany Falls limestone (BFL), and crushed river gravel (CRG) (Figure 1). The first three quarries provided both conventional (Class A) and coarse clean aggregate materials, while the CRG provided crushed coarse clean gravel materials. The main difference between the Class A and clean materials was their particle sizes, whereby the Class A materials had higher fines contents and lower percentages of coarse aggregates than the clean materials.

![FIGURE 1 Locations of the aggregate quarries.](image-url)
Seven field test sections were built in Decatur County, Iowa. The first three sections consisted of Class A materials—LCF Class A, OFD Class A, and BFL Class A—while the local BFL Class A material was also mixed with clean aggregate materials collected from all four quarries for the final four sections. Therefore, the local BFL Class A material was the only one mixed with the four clean materials to examine the mechanistic performance of such mixtures. To achieve the best performance and durability for the mixture sections, the optimum target particle size distribution (PSD) curves of the mixtures were determined via the gradation optimization method described in Li et al. (5). According to the optimization analyses, it was determined that the mixing ratios by weight for the last four test sections should be as follows: 80% BFL Class A with 20% BFL clean; 70% BFL Class A with 30% OFD clean; 70% BFL Class A with 30% LCF clean; and 70% BFL Class A with 30% CRG clean aggregate. Figure 2 shows the grain size distribution of all seven surface aggregate materials.

Table 1 also summarizes laboratory results of the soil index properties, including sieve analysis, Atterberg limits, and soil classification. The gravel, sand, silt, and clay contents for the surface aggregate materials ranged from 46% to 79%, 13% to 45%, 7.8% to 13.5%, and 0.1% to
### TABLE 1  Particle Size Analysis, Atterberg Limits, and Soil Classification Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Section 1 (LCF Class A)</th>
<th>Section 2 (OFD Class A)</th>
<th>Section 3 (BFL Class A)</th>
<th>Section 4 (% BFL Class A + 20% BFL Clean)</th>
<th>Section 5 (% BFL Class A + 30% OFD Clean)</th>
<th>Section 6 (% BFL Class A + 30% LCF Clean)</th>
<th>Section 7 (% BFL + % CRG Clean)</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_{10} (mm)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.62</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>D_{30} (mm)</td>
<td>2.2</td>
<td>1.2</td>
<td>2.7</td>
<td>7.17</td>
<td>5.0</td>
<td>3.6</td>
<td>4.8</td>
<td>0.0</td>
</tr>
<tr>
<td>D_{60} (mm)</td>
<td>5.7</td>
<td>8.2</td>
<td>9.2</td>
<td>15.45</td>
<td>11.9</td>
<td>10.8</td>
<td>11.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Coefficient of uniformity (Cu)</td>
<td>47.5</td>
<td>90.5</td>
<td>185</td>
<td>25.12</td>
<td>110.7</td>
<td>154</td>
<td>103.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Coefficient of Curvature (Cc)</td>
<td>6.7</td>
<td>2.1</td>
<td>16.6</td>
<td>5.41</td>
<td>19.4</td>
<td>17.1</td>
<td>19.1</td>
<td>6.6</td>
</tr>
</tbody>
</table>

#### Particle Size Analysis Results (ASTM D422-03)

- **D_{10} (mm)**: 0.1, 0.1, 0.1, 0.62, 0.1, 0.1, 0.1, 0.1
- **D_{30} (mm)**: 2.2, 1.2, 2.7, 7.17, 5.0, 3.6, 4.8, 0.0
- **D_{60} (mm)**: 5.7, 8.2, 9.2, 15.45, 11.9, 10.8, 11.3, 0.0
- **Coefficient of uniformity (Cu)**: 47.5, 90.5, 185, 25.12, 110.7, 154, 103.2, 0.0
- **Coefficient of Curvature (Cc)**: 6.7, 2.1, 16.6, 5.41, 19.4, 17.1, 19.1, 6.6

#### Atterberg Limits Test Results (ASTM D4318-10e1)

- **Liquid limit (%)**: 14.6, NA, 19.5, 20, 19, 17, 19, 31.1
- **Plasticity index**: 1.2, NA, 4.2, 5.2, 3.6, 3, 5.1, 11.7

#### AASHTO and USCS Soil Classification (ASTM D2487-11 and D3282-09)

- **AASHTO**:
  - Section 1: A-1-a
  - Section 2: A-1-a
  - Section 3: A-1-a
  - Section 4: A-1-a
  - Section 5: A-1-a
  - Section 6: A-1-a
  - Section 7: A-6
- **USCS group symbol**:
  - Section 1: GW
  - Section 2: GW
  - Section 3: GW
  - Section 4: GW
  - Section 5: GW
  - Section 6: GW
  - Section 7: GW
  - Subgrade: CL

2%, respectively. All the surface aggregate materials were classified either as USCS well-graded gravel (GW) or AASHTO A-1-a, while the subgrades were sandy lean clay (CL) or A-6. Test Section 2 (OFD Class A) exhibited nonplastic behavior, while the liquid limit and plasticity index values for the other sections ranged from 14.6 to 20 and 1.2 to 5.2, respectively.

Figure 3 indicates that the thicknesses and widths of all sections were 10 cm (4 in.) and 9.1 m (30 ft), respectively. The length of each test section was 152.4 m (500 ft), except for Section 2 (OFD Class A), where due to the lack of sufficient material, the length was reduced to 91.4 m (300 ft).

### FIELD TESTS AND MAINTENANCE OPERATIONS

In this study, several nondestructive field tests including LWD, dustometer, and IRI were performed to monitor the performance and estimate the required maintenance frequencies for the test sections. These tests were selected because they are inexpensive, can be performed relatively quickly, and the equipment required to conduct these tests are generally available for most agencies and private-sector entities.
Test sections were subjected to major maintenance only once. Before the major maintenance operations, the change in thickness of each section was measured and the amount of materials required to recover the material lost for each test section was calculated. The required aggregate materials were then determined according to the proposed mixing ratio based on the optimized Fuller’s model as described by Li et al. (5). Figure 4 shows the change in thickness of each test section and demonstrates that Section 5 (70% BFL Class A + 30% OFD clean) and Section 2 (OFD Class A) experience the largest and smallest changes in their original thickness, respectively.
The major maintenance procedures included the following steps: (1) scraping the granular surfaces down to the subgrade with a motor grader (scarifier blades were required for the second section due to its stronger surface); (2) spreading new Class A and clean aggregates from piles; (3) blading of both existing and new aggregates to achieve the optimum uniform mixture; (4) shaping the crown of the granular surface with motor graders; and (5) compacting the granular surface with the motor grader (12 to 16 passes).

**Lightweight Deflectometer Tests**

LWD tests were conducted to determine the maintenance frequency required for the test sections. The tests were performed on five points within each test section to evaluate the in situ composite elastic modulus ($E_{Comp}$) (stiffness) of the granular surfaces and subgrades, as a measure of road serviceability. This stiffness is a function of several factors, including compaction quality, packing structure of the various particle sizes (33), density of the road layers, water content, and temperature (34). Any changes in these factors can result in severe distresses (e.g., potholes, rutting, etc.), creating a need for road maintenance. Therefore, along with the $E_{Comp}$ data for each test section, the surface layer temperature and water content are presented. The ambient temperature of the surface course was measured using a thermocouple installed in the middle of the first section and the same ambient temperature was assumed for all the sections. The water content values were measured from samples collected during field testing. The LWD device used for testing in this study features a 10 kg (22 lb) hammer with a drop height of 0.5 m (19.69 7 in.), and a base plate diameter of 30 cm (11.81 in.). The in situ elastic modulus then was calculated based on the average vertical deflection as it is shown in Equation 1.

\[
E_{LWD} = \left(1 - \frac{\nu^2}{d_0}\right)\sigma_0 A f
\]

where

- $E_{LWD}$ = elastic modulus, as the result of LWD test;
- $\sigma_0$ = vertical stress applied on top of the plate;
- $\nu$ = Poisson’s ratio (assumed as 0.4);
- $d_0$ = applied stress;
- $A$ = plate radius; and
- $f$ = shape factor (assumed for a uniform stress distribution) (35).

**Dustometer Tests**

The dustometer test is another road performance measure used in this study to estimate the appropriate granular road maintenance frequency. To evaluate the dust production of each test section in relation to the different aggregate sources utilized in the surface layers, dustometer tests were performed several times over the length of the project. Figure 5 shows the setup of the dustometer device, attached to the bumper of a 1-ton truck by a steel bracket. It has a 30.5 × 30.5 cm (12 × 12 in.) steel mesh with a 200 μm (0.0079 in.) mesh size sieve to prevent large particles from damaging the tightly held filter paper. A 1/3-hp suction pump is connected to the mounted dustometer with a 2-in. diameter flexible hose to collect dust behind the rear wheel.
while driving at a speed of 72 km/h (45 mph). A 4,400-watt gasoline-powered generator provides power for the suction pump. The filter paper was removed after performing the test over a section and the mass of the dust on the paper divided by the length of the sections to determine the amount of dust per unit length.

**International Roughness Index Tests**

Roughness of the road surface as representative of ride quality is an important factor to evaluate the granular roadway performance, and lower IRI values reflect higher ride quality, lower fuel consumption, and longer service life (36). In the current study, the collection of road roughness measurements representative of road condition was done using a smart phone application named Roadroid. This software used a built-in smart phone accelerometer to evaluate roughness index of the different surfaces in a rapid and cost-effective manner (37). In this method, the smart phone was mounted on the windshield of a 1-ton truck and, after adjustments, the calculated IRI (cIRI) values were measured and stored in the phone while driving between 64 to 80 km/h (40 and 50 mph).
PERFORMANCE-BASED ECONOMIC ANALYSIS APPROACH

Dharmadhikari et al. presented four main steps for performing a LCBCA: (1) determining the project base case and alternatives; (2) defining the benefits; (3) cost and benefit calculation; and (4) determining the current value of costs and benefits (38). The base case is defined as a condition where no alternatives are suggested, and the alternatives are the other options to be considered for making the project more beneficial (38).

The determination of both the base case and the benefits should be conducted with extreme care to produce a valid and trustworthy cost analysis. Values of annual costs and benefits and the project’s present value considering the proper discount rate should be included in an overall approach to the LCBCA (39). Jones et al. enumerated traffic forecasts, cost estimations, discount rates, value of life, safety, value of time, regional impacts, local impacts, equity, environmental impacts, and residual use as the major challenges in performing BCA for transportation infrastructure (40).

In the present case, Section 4, built with a mixture of local conventional Class A and clean local materials (Section 4 = 80% BFL Class A + 20% BFL clean), with the lowest construction cost among the other aggregate options, was considered to represent the base case scenario. If a granular road incurred a cost lower than the base case scenario (Section 4) it was considered beneficial (cost saving) in the economic analysis platform. For example, if one of the user costs associated with a road alternatives would be lower than the base case user costs, the difference between these monetary values was considered as a cost saving or benefit, while if a pavement’s cost item was larger than the costs associated with the granular road built with local conventional material, the difference between these two costs items would be considered as a cost factor in the BCR.

The data required to estimate benefits (cost savings) and additional costs associated with the alternative granular roadway materials were collected from construction, maintenance, field measurements, and Iowa Department of Transportation (DOT) publicly available data sets. Since one of the most important factors in the economic analysis of granular roads is the frequency of maintenance activities (7), many performance measurements are conducted to compare new alternatives with the base case test section (Section 4). Then, based on similarities and differences among the alternative road sections and base case maintenance frequencies associated with an aggregate, the benefits of the each alternative section were estimated. Then, using maintenance frequencies of granular road material alternatives, benefits–costs associated with them were estimated. The major benefits–costs considered in the LCBCA platform are reduction–increase in road users’ lost time, reduction–increase in maintenance costs through the life cycle, and reduction–increase in car-damage costs. Figure 6 summarizes the methodology suggested in this study.

Deterministic BCA involves utilizing point estimates (discrete values), resulting in a single output value (8, 9). If the ratio of benefits to net costs is larger than one (>1), while general economic arguments would support action to make the associated investment, there are issues associated with deterministic factors such as sensitivity of results to the chosen discount rate and a mismatch between the volatilities of underlying factors (uncertainty associated with initial costs, maintenance frequency, traffic volume, duration of service life, etc.) that can be addressed by building a stochastic economic analysis model. To this end, as in previous studies on pavement decision-making (10–15), a stochastic analysis approach was used to perform the economic analysis. A stochastic benefit–cost model would use Monte Carlo simulation and allow input variables to fluctuate through their probability distributions based on recent historical and regional changes.
FIGURE 6 Research methodology.
FIELD TEST RESULTS LWD

The average results of the LWD composite elastic modulus for each test section, along with temperature and water content data over the past 2 years, are presented in Figure 7.

Immediately after construction on October 2016, the first set of LWD tests were performed on all sections, and the calculated LWD composite elastic modulus ($E_{\text{Comp}}$) for the sections were very close to each other and in the range of 54.8 MPa (7.95 ksi) to 81.8 MPa (11.86 ksi). However, the water content of the sections varied over a wide range (between 3.5% and 10.1%). The second set of LWD field testing was performed on November 2016 and the range of LWD $E_{\text{Comp}}$ was between 54.8 MPa (7.95 ksi) to 80.5 MPa (11.68 ksi), similar to the values measured in October 2016. It is worth mentioning that the $E_{\text{Comp}}$ of Section 3 (BFL Class A) changed insignificantly from that of October 2016 and all the other sections except for from Section 4 (80% BFL Class A + 20% BFL clean) had an increase in their $E_{\text{Comp}}$. The third set of LWD field testing was performed in December 2016, during the freezing season, and all sections exhibited a significant increase in their $E_{\text{Comp}}$ values because of the very low temperatures, that made the ground frozen and the range was between 143.8 MPa (20.86 ksi) to 445.5 MPa (64.62 ksi). Note that since the water content range was smaller (between 2% to 6.3%) then it might be concluded that temperature effects were much greater than the effect of water content during the freezing season. The first LWD field testing in 2017 was performed in February, during the thawing season, and all sections exhibited a significant decrease in their $E_{\text{Comp}}$ range due to thawing between 40.8 MPa (5.92 ksi) to 75.4 MPa (10.94 ksi). The second 2017 LWD field testing was performed in April, after freezing and thawing seasons. All of the sections exhibited a slight increase in their $E_{\text{Comp}}$ values except Section 2 (OFD Class A), which the LWD $E_{\text{Comp}}$ did not change for this section. The range of the LWD $E_{\text{Comp}}$ was between 44 MPa (6.38 ksi) to 99.1 MPa (14.38 ksi). The last set of LWD field testing in 2017 was conducted on June 2017, after the major maintenance to monitor the effects of removing distresses (e.g., potholes, rutting, and wash-boarding) on the soil stiffness. All sections except for Section 2 (OFD Class A) exhibited an unanticipated slight decrease in their $E_{\text{Comp}}$ values compared to those from February 2017. However, the range stayed similar to values from April 2017 between 42.5 MPa (6.16 ksi) to 96.4 MPa (13.98 ksi). The final set of LWD field testing measurements was performed on May 2018, after the second freeze and thaw season. The $E_{\text{Comp}}$ values for Section 1 (LCF Class A) and Section 7 (70% BFL Class A + 30% CRG Clean) were virtually changed, and the $E_{\text{Comp}}$ values increased for all the other sections except for Section 2 (OFD Class A). The highest $E_{\text{Comp}}$ was observed for Section 4 (80% BFL Class A + 20% BFL clean) (13.51 ksi), and the lowest $E_{\text{Comp}}$ was observed for Section 7 (70% BFL Class A + 30% CRG clean) (6.16 ksi).

The reason for the decrease in the $E_{\text{Comp}}$ value for this section may be related to poor binding between the coarse and fine aggregate materials. It was observed that the coarse materials in this section (CRG clean) had moved gradually to the roadsides due to the lack of binding between the coarse and fine aggregates (Figure 8).

As shown in Figure 7 and also explained in detail above, $E_{\text{Comp}}$ value (stiffness measure) cannot be used as a unified standard factor indicator for longevity of granular road serviceability, although some similar trends were observed for some of the sections. Therefore, the LWD results were not considered for the BCA and not used to estimate the appropriate maintenance frequency for the granular road sections.
FIGURE 7 Average LWD composite elastic modulus results for each section over time.
Dustometer

Figure 9 shows the results of dust production per mile during 2 years of the project for all seven test sections. To focus on the important factors effective in dust production, the temperature, water content, and fines content (amount passing #200 sieve) data are presented in Figure 9.

To monitor surface material degradation, samples from the granular surfaces of each section were collected for gradation analyses. The results for fines content for each section were derived from gradation tests.

The first dustometer test was conducted on October 2016 (after construction) and the dust production was in the range of 0.72 g/km (0.0026 lb/mi) to 4.92 g/km (0.018 lb/mi). The ambient temperature was about 35°F, the water content was in a range between 3.5% and 10.1%, and the fines content was in a range between 9.14% and 15.08%. The second set of dustometer test was conducted on November 2016 at about the same ambient temperature with October 2016 (32°F).

Surface aggregate sample collection was not performed because since it was assumed that the materials had not deteriorated significantly at that time. The gradation and fines content of the materials was assumed to be the same as when the samples were collected following construction on October 2016. The moisture content of the surface materials was in a range between 3% and 7.2% and did not change significantly since October 2016. The rate of dust production placed between 0.62 g/km (0.0022 lb/mi) to 4.66 g/km (0.0165 lb/mi). The third
FIGURE 9 Dustometer results for each section over time.

set of dustometer tests was conducted on December 2016, during the freezing season (4°F). The water content range had decreased to a smaller range, between 4% and 6.3%. The dust production rate decreased significantly, and it was confined to a small range for all of the sections, between 0.33 g/km (0.0012 lb/mi) and 0.75 g/km (0.0027 lb/mi). The sample collection was not conducted on December 2016 due to frozen ground. The fourth set of dustometer tests was conducted on February 2017, during the thawing season, where the ambient temperature got close to that at the time of construction (31°F). The water content range decreased to 1.2% to 3.1%. The dust production rate was increased significantly from December 2016, and it was in the range of 0.13 g/km (0.0005 lb/mi) to 1.57 gr/km (0.0056 lb/mi). The overall fines content of the surfaces increased significantly from October 2016, due to deterioration of the surface aggregate during the freezing and thawing season. The fifth set of dustometer tests was
conducted on April 2017, after the thawing season (71°F). While virtually all the sections had had almost the same range of dust production between 0.39 g/km (0.0014 lb/mi) to 1.77 g/km (0.0063 lb/mi) and the same range of water content between 1.7% to 3%, with February 2017. The sixth set of dustometer field tests was conducted on June 2017. A slight increase in the range of dust production, which was between 0.39 g/km (0.0014 lb/mi) to 3.74 g/km (0.013 lb/mi), was observed compared to February and April 2017 due to the higher temperature (106°F) and drier surface (1.1% to 2.6% water content). The final set of dustometer field tests was conducted on May 2018 after the second freeze and thaw season (43°F). The dust production was observed to be in the range of 0.66 g/km (0.0023 lb/mi) to 2.36 g/km (0.0084 lb/mi) with the water content in the range of 1.2% to 3%.

While dust production depends on many different factors such as condition of surface materials (wet or dry), temperature, wind, etc., an overall reading of the dustometer results shows that dust production after construction and maintenance was higher than at other times, depending somewhat on environmental conditions. Nevertheless, all times showed about the same amount of dust production. The average results of dust production for each section for the different times of performing dustometer test are shown in Figure 10. It can be concluded that Section 7 (70% BFL Class A + 30% CRG clean) had the maximum dust production value, 2.48 g/km (0.0088 lb/mi), and Section 1 (LCF Class A) had the lowest dust production value, about 0.48 g/km (0.0017 lb/mi). Sections are categorized by color codes in Figure 10.

![Test sections classification based on dust production.](image.png)
Summarizing the above discussion, demonstration sections were divided into three categories (Figure 10). The first group with the highest dust production included Sections 7, 5, and 6; Sections 2 and 4 were the demonstration sections with moderate dust production; and Section 3 and Section 1 exhibited the lowest dust productions.

As mentioned in the test section descriptions, we know that the required maintenance time for the road built with conventional materials (Section 4, base case) would vary between 1 to 3 years depending on traffic volume, temperature, freeze–thaw cycles, etc., so for a stochastic BCA three possible scenarios were developed to determine maintenance time of conventional road sections (i.e., best case = 3 years; most likely case = 2 years; and worst case = 1 year). Moreover, by considering dust production as a performance measure of the gravel road section, two other scenarios were developed for the second and the third groups. Figure 11 presents the best, most likely, and the worst cases for the possible maintenance scenarios based on dust measurements for all sections. The base, most likely, and the best cases of the required maintenance times were considered to be, respectively, 3, 4, and 5 years for Sections 1 (LCF Class A) and 3 (BFL Class A); 2, 3, and 4 years for Sections 2 (OFD Class A) and 4 (80% BFL Class A + 20% BFL clean); and 1, 2, and 3 years for the last three sections (70% BFL Class A + 30% OFD clean, 30% BFL Class A + 30% LCF clean, and 70% BFL Class A + 30% CRG clean). Although most test sections were in good condition, to monitor the condition of the road the maintenance was conducted after almost 1 year for all test sections. This is mainly due to the limited time associated with the project.

![Figure 11 Maintenance frequency scenarios developed based on the dustometer results.](image-url)
International Roughness Index

In this project, IRI was measured by Roadroid, an Android-based application. In order to remove any additional movement of the phone while performing IRI, a firm mount was used to connect the phone to the windshield. Moreover, the same truck and mounting location were used each time the test was performed. The calculated IRI (cIRI) with a narrower range of speed between 60 to 80 km/h was used, rather than of the estimated IRI (eIRI) which has a broader range of speed between 20 to 100 km/h. Therefore, cIRI values provided higher accuracy than eIRI values (41).

The cIRI values measured during this study are shown in Figure 12. Based on the IRI results, test sections were categorized into two different groups (fair performance or poor performance) (Figure 12). In addition, similar to the dustometer section, but based rather on IRI results, scenarios were developed for estimating required maintenance time of granular road sections for use in stochastic economic analysis (Figure 13).

COST–BENEFIT ESTIMATION

Costs and benefits associated with new granular roadway materials were estimated. As mentioned in the methodology discussion, if a section’s incurred cost was lower than the base case scenario (Section 3, BFL Class A), this was considered to represent a benefit (cost saving). To conduct the economic analysis, reduction–increase in users’ time was monetized along with cost/benefit associated with alternative unpaved road material maintenance operations. In the remainder of this section calculations for these two methods are explained in detail.

Construction and Maintenance

Figure 14a and 14b show the details of the construction and maintenance costs for each test section. Due to the sections having different lengths, while costs associated with the new gravel road material (gravel and hauling costs) were considered on a per-mile basis, it was observed that the equipment and in-site labor costs were virtually the same for all sections, so only the cost of hauling material and aggregate were considered in the economic analysis.

The differences between the costs of maintaining conventional granular roads with the new ones were estimated using maintenance frequency estimated values and actual costs of maintenance conducted on May 2017 (Figure 14). Equation 2 was used to calculate maintenance cost savings–additional costs estimations:

\[
D_m = N_f \times N_c - C_f \times C_c
\]

where

\[
D_m = \text{the difference in monetary value between the cost of maintaining conventional roads with new ones};
\]

\[
N_f = \text{the new maintenance frequency};
\]

\[
N_c = \text{the new gravel road maintenance cost (per mile)};
\]

\[
C_f = \text{the conventional road maintenance frequency}; \text{ and}
\]

\[
C_c = \text{the conventional granular road maintenance cost}.
\]
FIGURE 12  Roads roughness results for each section over time.

FIGURE 13  Maintenance frequency scenarios developed based on the IRI results.
Value of Users’ Time

Delay time is the extra travel time required either to pass through a work zone or to detour around it (42). Since travel time costs are given serious consideration and can become a significant factor when large queues occur, best-practice LCCA calls for consideration of not only agency costs, but also costs to roadway users (43). According to FHWA guideline (42), the following formula can be used to estimate travel delay cost:

\[
\text{Travel delay cost} = (1 - T_t) \times P \times V_p + T_t \times V_t
\]  

(3)

where

\( T_t \) = truck traffic percentage (based on discussions with Iowa county engineers, \( T_t \) assumed to be 25%);
\( P \) = personal travel;
\( V_p = \) value (US$/h) of personal travel time; and
\( V_t = \) value (US$/h) of truck travel time.

Values of personal and truck travel time, obtained from the Bureau of Labor Statistics (BLS) data base (44), are US$25/h and US$54/h, respectively. Iowa granular roadway traffic data was obtained from the Iowa DOT traffic count data base (Figure 15) (45). Traffic volume was considered as one of the stochastic input variables in the economic analysis platform (further details are provided in the appropriate distribution selection section).

Figure 16 shows an actual route and detour for a generic gravel road. Based on site surveying during construction and maintenance, it was observed that since vehicles usually tried to change their routes when they encountered the construction sign, a detour was considered to be an alternative route during maintenance. According to Omni drive time calculator (46), since driving time for a 1-mi road would be 2 min, assuming a 30-mph speed, as shown in Figure 16, assuming 6 min (three times more than regular route) for driving through a detour would be reasonable. Unless otherwise signed, the Code of Iowa sets the speed limit on rural gravel roads at no faster than 55 mph between sunrise and sunset and no more than 50 mph between sunset and sunrise.
Discount Rate and Service Life

Similar to other studies on pavement management, analysis period was taken as the projected number of years until either the final disposal of the road or the removal of the road materials was required (47, 48). In this study, since all the demonstration sections were placed on a local road with the same amount of traffic load and weather conditions, the same amount of service life was assumed have for all the sections. Since a FHWA life-cycle costs analysis bulletin recommends treating common variable among alternatives with the same value deterministically (20), an analysis period of 20 years was used for all the road sections (49).

Discount rate data for the previous 20 years were obtained from a Federal Reserve data base (50) and added to the stochastic economic analysis model.

Appropriate Distribution Selection

“Determining the appropriate probability distribution for each input variable is an important step in stochastic economic analysis” (51). In this paper, inputs associated with availability of sufficient historical data (i.e., discount rate and average daily traffic) were fitted to a distribution using a maximum likelihood method. To determine which distribution had the best fit, a chi-squared goodness-of-fit test (52), which is often used in business decision-making (53–55), was used (52). In addition, for other input variables with insufficient data availability (e.g., maintenance frequency), a triangular distribution was used, conforming to a common method for describing the distribution of such variables (56–59).
ECONOMIC ANALYSIS RESULTS

To perform stochastic BCA, commercial simulation software (@Risk) was used to develop a Monte Carlo simulation-based (MCS) economic analysis model. MCS were run with each simulation iterated 10,000 times, each iteration lasting from 35 to 75 s. Figure 17 shows the results of simulation for performance-based economic analysis based on dust production measurements.

Figure 17 presents simulation results in probability density functions format, which shows relative likelihood of BCR for each granular road test section. In addition, standard deviation values, “indicators of the amount of dispersions” of BCR (52), along with median values, were shown. “The median is a good measure because, regardless of distribution shape, half the values are above the median and half are below the median” (60).

As shown in Figure 17, among all the alternatives, Section 3 (BFL Class A) yields the highest median BCR. In addition, this section is the only granular road option that met 100% reliability, a probability that BCR stays above 1, which means that use of the aforementioned section would be a more favorable economic investment compared to use of a conventional aggregate option under all the conditions assumed in this study. In addition, although using Section 1 (LCF Class A) is also a secure economic investment with 100% chance of getting BCR above one, since this section has a lower median value than Section 3 (BFL Class A), the chance of yielding more benefits using Section 1 (LCF Class A) would be lower than for Section 3 (BFL Class A).

Section 6 (70% BFL Class A + 30% LCF clean) and Section 2 (OFD Class A) also had high reliability percentages (96% and 86%, respectively), making them good aggregate options for graveling low-volume roads in the state of Iowa. Among all the aggregate options, Section 5 (70% BFL Class A + 30% OFD clean) with 1.02 and 54% median BCR value and reliability, respectively, would be the worst economic investment.

Like stochastic economic analysis developed for the dustometer, point estimates in the deterministic BCR model based on IRI results were replaced with probability distributions and the output estimated in a quantity-variation format. Figure 18 shows the outcome of simulations for performance-based BCA developed for IRI results. There were 10,000 iterations, with simulation times ranging from 37 to 73 s.

The outcomes of stochastic economic analysis based on IRI measurements were close to the previous analysis based on dust production. Note that for Section 3 (BFL Class A), Section 4 (80% BFL Class A + 20% BFL clean), Section 5 (70% BFL Class A + 30% OFD clean), and Section 7 (70% BFL Class A + 30% CRG clean) the results were identical, because for all these aggregate products identical maintenance frequency scenarios were developed (Figure 11 and Figure 13).

As shown in Figure 18, as in the previous analysis based on dust production, among all the alternatives Section 3 (BFL Class A) exhibits the highest median BCR and percentage reliability. However, because different aggregate options exhibited less difference in terms of roughness than for dust production, fewer scenarios were developed for IRI based economic analysis (i.e., two scenarios based on IRI and three for dust production). Therefore, median values of BCR based on IRI results were the same or lower than for dust production performance-based analysis. In general, BFL Class A along with Section 1 (LCF Class A) and Section 4 (80% BFL Class A + 20% BFL clean) exhibited the best economic performance among other alternatives [comparing with the base case aggregate option, Section 4 (80% BFL Class A + 20% BFL clean)].
FIGURE 17  MCS results (scenarios developed based on dust production measurements): (a) Section 1, LCF Class A; (b) Section 2, OFD Class A; (c) Section 3, BFL Class A; (d) Section 5, 70% BFL Class A + 30% OFD clean; (e) Section 6, 70% BFL Class A + 30% LCF clean; and (f) Section 7, 70% BFL Class A + 30% CRG clean.
FIGURE 18  MCS results (scenarios developed based on IRI results): (a) Section 1, LCF Class A; (b) Section 2, OFD Class A; (c) Section 3, BFL Class A; (d) Section 5, 70% BFL Class A + 30% OFD clean; (e) Section 6, 70% BFL Class A + 30% LCF clean; (f) Section 7, 70% BFL Class A + 30% CRG clean.
CONCLUSIONS

This paper presents a stochastic performance-based LCBCA method for comparing economic performance of granular roads constructed in a rural road system. Seven different surface aggregate materials were obtained from four different quarries in Iowa and different performance measure tests were conducted over the last 3 years. Using LWD, IRI, and dustometer test results, scenarios were developed for maintenance frequency of test sections to be used in the economic analysis framework. This study used the IRI and dust production results as performance measures for estimating maintenance frequency. In addition, among alternatives, BFL Class A, compared to the base case aggregate option (Section 4, 80% BFL Class A + 20 % BFL clean), exhibited the best economic performance. These findings could help agencies, county engineers, and contractors in estimating the most beneficial material alternatives in terms of lower costs of hauling, material, labor, and equipment for construction and maintenance of granular roads.

The methodology developed in this study provides agencies with the probability that a preferred alternative can produce the lowest life-cycle cost. Recommendations that may result from this research project would be founded in fundamental economic analysis theory and can also provide various transportation agencies with an added level of confidence in predicting economic impact associated with granular road material alternatives of interest.

ACKNOWLEDGMENTS

The authors gratefully acknowledge sponsorship for this research study from the Iowa Highway Research Board (IHRB) and the Iowa DOT. The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the IHRB and Iowa State University. This paper does not constitute a standard, specification, or regulation.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: Study Conception and Design: C. Jahren, S. Satvati, and A. Nahvi; Data Collection: S. Satvati and A. Nahvi; Analysis and Interpretation of Results: S. Satvati and A. Nahvi; Draft Manuscript Preparation: S. Satvati and A. Nahvi. All authors reviewed the results and approved the final version of the manuscript.

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