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Benefit Cost Analysis of Aggregate Options for a Granular Roadway

Sajjad Satvati

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Benefit Cost Analysis of Aggregate Options for a Granular Roadway

by

Sajjad Satvati

A Creative Component submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering [Geotechnical Engineering]

Program of Study Committee:
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Iowa State University
Ames, Iowa
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>CHAPTER 1. GENERAL INTRODUCTION</td>
<td>4</td>
</tr>
<tr>
<td>CHAPTER 2. PERFORMANCE-BASED ECONOMIC ANALYSIS TO FIND THE SUSTAINABLE AGGREGATE OPTION FOR A GRANULAR ROADWAY</td>
<td>9</td>
</tr>
<tr>
<td>Abstract</td>
<td>9</td>
</tr>
<tr>
<td>Introduction</td>
<td>10</td>
</tr>
<tr>
<td>Site description</td>
<td>13</td>
</tr>
<tr>
<td>Methods</td>
<td>17</td>
</tr>
<tr>
<td>LWD</td>
<td>18</td>
</tr>
<tr>
<td>Dustometer</td>
<td>19</td>
</tr>
<tr>
<td>IRI</td>
<td>20</td>
</tr>
<tr>
<td>Performance-based economic analysis approach</td>
<td>21</td>
</tr>
<tr>
<td>Results</td>
<td>24</td>
</tr>
<tr>
<td>LWD</td>
<td>24</td>
</tr>
<tr>
<td>Dustometer</td>
<td>25</td>
</tr>
<tr>
<td>IRI</td>
<td>29</td>
</tr>
<tr>
<td>Cost/benefit estimation</td>
<td>31</td>
</tr>
<tr>
<td>Construction and Maintenance</td>
<td>32</td>
</tr>
<tr>
<td>Value of Users’ Time</td>
<td>33</td>
</tr>
<tr>
<td>Discount Rate and Service Life</td>
<td>36</td>
</tr>
<tr>
<td>Appropriate Distribution Selection</td>
<td>36</td>
</tr>
<tr>
<td>Economic Analysis Results</td>
<td>37</td>
</tr>
<tr>
<td>Conclusions</td>
<td>41</td>
</tr>
<tr>
<td>Author contribution statement</td>
<td>42</td>
</tr>
<tr>
<td>Declaration of Competing Interest</td>
<td>42</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>42</td>
</tr>
<tr>
<td>References</td>
<td>43</td>
</tr>
<tr>
<td>CHAPTER 3. GENERAL CONCLUSION</td>
<td>50</td>
</tr>
<tr>
<td>References</td>
<td>51</td>
</tr>
</tbody>
</table>
ABSTRACT

Material costs and hauling costs are considerable portions of construction costs for granular roadways. It is more desirable for county engineers to use granular materials from nearby sources to reduce the hauling costs. However, the quality of the granular materials differ from source to source and directly relates to the serviceability and sustainability of granular roadways. Heavy traffic loads and freeze-thaw weathering deteriorates surface aggregates and leads to several distresses such as material loss, rutting, and potholes and results to require more frequent maintenance. However, the use of more durable aggregates from a source with higher hauling time rather than low-quality materials from a nearby source could reduce the maintenance costs. Therefore, a process for evaluating the performance of the granular roadways based on cost-effectiveness would be desirable for local road engineers in reducing the overall costs during the service life of a roadway.

In this study, laboratory and field tests were conducted to examine the link between the quality and the performance of granular aggregate materials used in granular road applications, and materials were tested and observed from various quarries in Iowa on field test sections. The field performance (modulus, dust production, and surface roughness) and, a comprehensive cost-performance analysis was conducted to evaluate the cost-effectiveness of the various materials to determine whether it was economically advantageous to transport more durable aggregate materials from distant sources rather than using locally available materials of lower quality.
CHAPTER 1. GENERAL INTRODUCTION

Aggregate deterioration is described as a progressive weakening process of aggregate conditions and it depends on the physicochemical properties and geological formation of the aggregates and other effects such as environmental conditions. (Alzubaidi and Magnusson 2002; Paterson 1987; Provencher 1995; Strombom 1987). The performance of a granular road is highly dependent on gradation characteristics, plasticity index (PI), abrasion resistance, morphology, and mineral composition of aggregates. Besides, traffic loads, moisture content (e.g., from precipitation) of the aggregates, and degree of compaction during construction are other important factors that could impact the material loss and deterioration of aggregates used in granular roads (Fathi et al. 2019; Hardin 1985; Lade, Yamamuro, and Bopp 1996; Lees and Kennedy 1975; Marsal 1967; Nurmikolu 2005; Paterson 1991; White, Vennapusa, and Jahren 2004; Zeghal 2009).

It is well-known that the abrasion and freeze-thaw resistances of granular roads are highly dependent on the aggregate characteristics (Alzubaidi and Magnusson 2002; Satvati et al. 2019). Traffic loads also cause deterioration of aggregates by breaking them. The breakage potential and breakage ratio caused by traffic loading depend on the traffic volume, speed, and load magnitudes (Cetin et al. 2019; Dobson and Postill 1983; Isemo and Johansson 1976; Jalali et al. 2019). Under heavy traffic loads (especially during spring seasons), aggregate particles are either scattered or broken into finer size particles, which results in a general loss of stability on the granular roadways. Moreover, aggregates with low abrasion resistances tend to have higher breakage potential, which yields increases in fines contents of the original gradation of the aggregate mixture. As a result, a noticeable decrease in the overall performance of granular roadways has been observed, and more frequent maintenance is required.
Freeze-thaw durability of surface aggregate materials is another factor that could influence the performance of granular roads (Li et al. 2016; Vallejo et al. 2006; White & Vennapusa 2013 and 2014). The freezing and thawing processes result in an increase in moisture content due to capillary water trapped in the surface courses and the underlying subgrades of granular roads. Consequently, the presence of moisture within the aggregate mixtures leads to losses of strength and stiffness in road layers. Blading the surface aggregates and dumping virgin aggregates are typical practices that are used for repairing freeze-thaw damage of granular roadways rather than improving the frost susceptibility of the surfacing aggregates (White 2013; White and Vennapusa 2014b).

Layer stiffness is an important factor in mechanistic design and evaluation of the performance of the roadway systems, and it is affected by a variety of factors such as moisture content of the road layers, temperature, and gradation of the aggregate and soil materials in the surface and subgrade layers (Alimohammadi and Abu-Farsakh 2019; Fathi et al. 2019; Vennapusa and White 2009). Falling weight deflectometer (FWD) and light weight deflectometer (LWD) tests are two common test methods to determine the stiffness of road layers. However, LWD provides a faster way to calculate the elastic modulus by rapidly capturing the elastic modulus by inferring the deflection beneath the loading plate.

The roughness of the road surface affects ride quality, with lower International Roughness Index (IRI) values reflecting higher ride quality, lower fuel consumption, and longer service lives (Jia et al. 2018). In the current study, road roughness measurements representative of road conditions were performed using a smartphone application named Roadroid. The application used a typical smartphone accelerometer to evaluate the roughness index of various surfaces rapidly and cost-effectively (Akinmade et al. 2018).
The dustometer test is another road-performance measure used in this study to compare the performance of various alternative options with regard to fugitive dust emissions. To evaluate the dust production of the various aggregates in each test section, dustometer tests were performed several times throughout the project.

Benefit-cost analysis (BCA) estimates the net present value of the benefits minus the costs of projects to guide decision makers regarding the worthwhileness of a project and is an important process to determine the efficiency of the project in utilizing the resources, due to the need to facilitate social and economic activities (Alimohammadi 2020; Carlsson et al. 2015; Dharmadhikari et al. 2016; Habibzadeh-Bigdarvish et al. 2019; Mishan and Quah 1976; Prest and Turvey 1965). Deterministic BCA is considered as a traditional decision-making approach in pavement management (Nahvi et al. 2018; Walls III and Smith 1998). Prest and Turvey (1965) presented four main criteria prior to performing any benefit-cost analysis: (1) enumeration of costs and benefits; (2) valuation of costs and benefits; (3) choice of interest rate; and (4) relevant constrains (Prest and Turvey 1965). Dharmadhikari et al. (2016) presented four main steps to perform a lifecycle benefit-cost analysis: (1) determining the project base case and alternatives, (2) defining the benefits, (3) calculating the costs and benefits, and (4) determining the current value of costs and benefits (Dharmadhikari et al. 2016). The base-case is defined as the condition that no alternatives are implemented, whereas the alternatives are the other options to be considered in attempt to make the project more beneficial. Therefore, the granular road test section with the minimum construction costs was considered as the base case in the present study. The selection of the base case and determination of the benefits should be performed with extreme care to obtain a solid and trustworthy cost analysis. Moreover, the agencies should avoid adopting the BCA framework directly from one project to another due to the differences in the various
consideration and assumptions made for each project (Gibson and Wallace 2016). The values of the annual costs and benefits and the project’s present value with consideration of proper discount rates are included in the overall approaches to BCA (Layard 1994). Jones et al. (2014) identified the development of the traffic forecast, cost estimation, discount rate, 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 (Jones et al. 2014). The main factor in deterministic BCA is the benefit cost ratio (BCR), which is the ratio of the net present value (NPV) of the benefits divided by the NPV of the costs of a project (Walls III and Smith 1998).

Hauling and placing aggregates are the most costly processes for construction and maintenance of granular roadways. Therefore, it is important to evaluate whether constructing granular roads using more durable materials is cost beneficial and can sustain their performance for longer durations with less maintenance. However, there is a lack of high quality aggregate sources in certain regions of Iowa while in other parts of Iowa such as the north-east have durable aggregates, possibly cutting in half the amount of aggregate required to maintain a roadway to a certain level of construction and maintenance performance. This project presents a case study of the use of benefit-cost analysis (BCA) of granular road. The findings could help the Iowa Department of Transportation (Iowa DOT) and Iowa County Engineers to determine the most beneficial combination of material and hauling alternatives that lower the combined costs of hauling, material, labor, and equipment for both construction and maintenance of granular roadways.
CHAPTER 2. PERFORMANCE-BASED ECONOMIC ANALYSIS TO FIND THE SUSTAINABLE AGGREGATE OPTION FOR A GRANULAR ROADWAY

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Abstract

Approximately 110,000 km of granular roadways exists in the 183,500 km 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, high performance, and environmentally sustainable 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. The long-term performance and mechanistic behaviors of the different surface materials, including stiffness, surface roughness and dust production were evaluated for a period of two years. Using the resulting data, a mechanistic-based life cycle benefit-cost analysis approach was developed to evaluate the use of coarse aggregate materials on granular roadways. The stochastic benefit-cost analysis (BCA) results for different aggregate materials are presented in the form of probability density functions. Two different scenarios are presented and the benefits are evaluated in terms of dust
production and surface ride quality.

**Keywords:** Granular roadways; Benefit cost analysis; Dust; Elastic modulus; IRI; Stochastic life cycle cost analysis; Monte Carlo simulation.

**Introduction**

Nowadays, the construction of the sustainable roadways is in daily interest for all the governmental and private sectors [1]. 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 [2]. Moreover, the aforementioned deteriorations following by using low-quality aggregates can cause severe problems such as increase in dust production and surface roughness of the granular roadways, where the dust production cannot be underestimated as a main concern for the residents of rural areas [3]. Therefore, finding a cost-effective sustainable 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 [4]. In addition, low-quality aggregates could result in greater vehicle operating costs (e.g. reduced fuel consumption, increased wear and damage) and dust production. 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 [5,6].
Approximately 50% of the total road network in the US 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 US [6]. 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 [8–11].

Stiffness of the granular surface layers, dust production, and ride quality are important performance measures for granular roadways. Non-destructive tests such as falling weight deflectometer (FWD), multichannel analysis of surface waves (MASW), and light weight deflectometer (LWD) have been commonly used to determine the stiffness of the granular road surface layers due to their fast and easy procedures compared to destructive tests such as dynamic cone penetrometer (DCP) [12,13]. However, LWD is a relatively rapid test and measures a non-linear (stress and strain dependent) elastic modulus of unbound granular materials [14–16]. Dust emission from granular roads are one of the main problems for the residents of the rural areas [17]. A portable dust measurement device called dustometer has been successfully used to measure the dust emission from granular roads for almost twenty years [3,18–20]. Performance of the granular roads is a function of serviceability [21]. Roughness of the road surface as a representative of ride quality is an important factor to evaluate the granular roadway serviceability, and lower roughness reflect higher ride quality, lower fuel consumption, and longer service life [22]. International roughness index (IRI) as a predictor of the road surface condition is commonly measured by the use of a smart phone based application, called Roadroid, which is cost-effective and efficient
roughness measure compared to the traditional techniques [23–25].

Benefit Cost Analysis (BCA) is an assessment of decisions based on the consequences (benefits and drawbacks) in accordance with them [26]. 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 [27–29]. 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 [18,30–36], and some have studied the economic performance of these roads [7,11], 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 [37]. In this study, seven different surface aggregate materials were collected from four different Iowa quarries and various performance measures were tested over a two-year period. Using the performance measure tests, 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 lightweight deflectometer (LWD), dustometer, and international roughness index (IRI). The second main objective is to investigate the economic performance of granular roads constructed with the different surface materials.

**Site description**

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) (Fig. 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.

![Locations of the aggregate quarries in Iowa.](image)

**Fig. 1.** Locations of the aggregate quarries in Iowa.

Seven field test sections were built in Decatur County, IA. The first three sections consisted of Class A materials: LCF Class A, OFD Class A, and BFL Class A, while the local BFL
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 [35]. 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. Fig. 2 shows the grain size distribution of all seven surface aggregate materials.

![Grain size distribution curves](image)

**Fig. 2.** Particle size distribution curves for the surface aggregate materials used in this study.

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 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. OFD Class A exhibited non-plastic 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.

**Table 1.** Particle-size analysis, Atterberg limits and soil classification results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LCF Class A</th>
<th>OFD Class A</th>
<th>BFL Class A</th>
<th>80% BFL Class A + 20% CL</th>
<th>70% BFL Class A + 30% OFD</th>
<th>70% BFL Class A + 30% LCF</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle-size analysis results (ASTM D422-03)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel Content (%) (&gt;4.75 mm)</td>
<td>46</td>
<td>54</td>
<td>61</td>
<td>79</td>
<td>72</td>
<td>65</td>
<td>71</td>
</tr>
<tr>
<td>Sand Content (%) (4.75-75μm)</td>
<td>45</td>
<td>37</td>
<td>24</td>
<td>13</td>
<td>18</td>
<td>23</td>
<td>19</td>
</tr>
<tr>
<td>Fines Content (%) (&gt;75μm)</td>
<td>9</td>
<td>9</td>
<td>15</td>
<td>8</td>
<td>10</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>D₁₀ (mm)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.6</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>D₃₀ (mm)</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>5</td>
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<tr>
<td>D₆₀ (mm)</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>15</td>
<td>12</td>
<td>11</td>
<td>11</td>
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<tr>
<td>Coefficient of Uniformity, Cᵥ</td>
<td>48</td>
<td>91</td>
<td>185</td>
<td>25</td>
<td>111</td>
<td>154</td>
<td>103</td>
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<tr>
<td>Coefficient of Curvature, Cᵥ</td>
<td>7</td>
<td>2</td>
<td>17</td>
<td>5</td>
<td>19</td>
<td>17</td>
<td>19</td>
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<tr>
<td>Atterberg limits test results (ASTM D4318-10e1)</td>
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<td></td>
<td></td>
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<td>Liquid limit (%)</td>
<td>15</td>
<td>NA</td>
<td>20</td>
<td>20</td>
<td>19</td>
<td>17</td>
<td>19</td>
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<tr>
<td>Plasticity Index</td>
<td>1</td>
<td>NA</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>5</td>
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<tr>
<td>AASHTO and USCS soil classification (ASTM D2487-11 &amp; D3282-09)</td>
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<tr>
<td>USCS group symbol</td>
<td>GW</td>
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<td>GW</td>
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<td>GW</td>
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</table>
Fig. 3 indicates that the thicknesses and widths of all sections were 10 cm and 9.1 m, respectively. The length of each test section was 152.4 m, except for Section 2 - OFD Class A, where due to the lack of sufficient material, the length was reduced to 91.4 m.

Test sections were subjected to major maintenance only once. Before the major maintenance operations, the change in the thickness for each section was measured and the required materials to recover the thickness to the initial thickness (10 cm) for each test section was calculated. In this regard, the required aggregate materials according to the proposed mixing ratio and based on Fuller’s model was calculated as described by [35]. Fig. 4 show the change of the thickness for each section and it demonstrates that Section 5 - 70% BFL Class A + 30% OFD Clean and Section 2 - OFD Class A had the highest and lowest changes in the gradation, respectively.
Fig. 4. Thickness loss for each of the sections before maintenance.

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).

Methods

In this study, several non-destructive field tests including light weight deflectometer
(LWD), dustometer, and international roughness index (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. To monitor changes in the stiffness, ride quality, and dust production of the road surfaces, the performance of each section was tested several times over the course of 2 years.

**LWD**

Light weight deflectometer 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\textsubscript{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 [38], density of the road layers, water content, and temperature [39]. 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\textsubscript{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 hammer with a drop height of 0.5 m, and a base plate diameter of 30 cm. The in-situ elastic modulus then was calculated based on the average vertical deflection as it is shown in Equation 1.

\[
\text{LWD} - E_{\text{Comp}} = (1 - v^2)\sigma_0Af/d_0
\]

where \(E_{LWD}\) is composite elastic modulus of surface and subgrade, as the result of LWD test, \(\sigma_0\)
is vertical stress applied on top of the plate, \( v \) is Poisson’s ratio (assumed as 0.4), \( d_0 \) is applied stress, \( A \) is plate radius, and \( f \) is shape factor (assumed 2 for a uniform stress distribution [14]).

**Dustometer**

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. Fig. 5 shows the setup of the dustometer device, attached to the bumper of a one-ton truck by a steel bracket. It has a 30.5×30.5 cm steel mesh with a 200 \( \mu \)m mesh size sieve to prevent large particles from damaging the tightly-held filter paper. A 1/3-horsepower suction pump is connected to the mounted Dustometer with a 5 cm diameter flexible hose to collect dust behind the rear wheel while driving at a speed of 72 km/hr. 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.
Fig. 5. Dustometer test setup: (a) a dusty road; (b) dustometer setup; (c) dust production measurement filter paper.

IRI

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 [22]. 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. In this method, the smart phone was mounted on the windshield of a one-ton truck and, after adjustments, the calculated International Roughness Index (cIRI) values were measured and stored in the phone while driving between 64 to 80 km/hr.

Performance-based economic analysis approach

Dharmadhikari et al. (2016) presented four main steps for performing a lifecycle benefit-cost analysis (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 [40]. 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 [40].

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 [41]. 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 [42].

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 benefit cost ratio.

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 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 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. Fig. 6 summarizes the methodology suggested in this study.
Deterministic BCA involves utilizing point estimates (discrete values), resulting in a single output value [8,43]. 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 [10,11,26–28,30,44], 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.

Results

LWD

LWD test was performed seven times from October 2016 to May 2018 to evaluate the stiffness of road layers (surface and subgrade). In addition, the temperature and water content of the surface materials were collected as the same time LWD was performed due to their effects on the stiffness values. Fig. 7 shows that the LWD-E_{Comp} results had a major increase in December 2016 because of the severe cold weather which made the surface frozen and the results of stiffness for all of the sections were over-estimated. However, LWD-E_{Comp} results did not change significantly from the first time, when the temperature was higher than 0°C and the moisture content of the surface materials had not a significant change. Moreover, LWD-E_{Comp} results did not change after the maintenance on May 2017, which it represents that adding new materials to recover the surface after severe freeze and thaw cycles did not have a major impact on the stiffness values. Therefore, E_{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.
Fig. 7. Average LWD Composite elastic modulus results for each section over time.

Dustometer

Fig. 8 shows the results of dust production per kilometer during two years of the project for all seven test sections. To focus on the important factors effective in the dust production, the temperature and moisture content data are presented in Fig. 8. It was proved that in a constant temperature, lower moisture content of the surface aggregate materials caused higher dust
production. However, dust production for 70% BFL Class A + 30% CRG Clean was the highest after construction in October 2016 despite the fact that this section had higher moisture content. Field observations showed that the coarser surface aggregates for this section were less angular and could not bind with the finer aggregates after the construction. Therefore, the lack of binding in the aggregate matrix caused loose coarse aggregates flow over the surface and result in higher dust production. On the other hand, LCF Class A and BFL Class A had lower dust production due to the high plasticity of their materials. The values of dust production along with ambient temperature and moisture content values for all of the sections almost did not change from October 2016 to November 2016, except for 70% BFL Class A + 30% CRG Clean which the water content was decreased and dust production was increased. The dust production and water content of surface materials in December 2016 for all sections was in a very close range (0.33 to 0.75 gr/km) due to the frozen ground condition (-16 °C).
Fig. 8. Dustometer results for each section over time.

With increase in the ambient temperature, surface aggregates tended to get drier caused higher dust production for February and April 2017 compared to the dust production for December 2016 where the ground was frozen. However, the dust production for February and April 2017 were lower than the dust production for the earlier stages in October and November 2016 after the construction because to the compaction of the surface aggregates over time by traffic load. Maintenance including adding fresh aggregate materials and blading them with the existing
aggregates was performed on all of the section in May 2017. This procedure detached the surface aggregates that were compacted over time by traffic loads and caused the dust production readings for June 2017 to be higher than April 2017. 70% BFL Class A + 30% CRG Clean had the highest and LCF Class A and BFL Class A had the lowest dust productions due to the previously mentioned reasons. Dustometer test was performed for the last time one year after the maintenance in May 2018 while the moisture content values did not change significantly from June 2017. The dust production values also did not change except for 70% BFL Class A + 30% CRG Clean which the traffic loads helped to compact the loose aggregate materials of this section.

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 Fig. 9. It can be concluded that 70% BFL Class A + 30% CRG Clean had the maximum dust production value (2.48 gr/km), and LCF Class A had the lowest dust production value, about (0.48 gr/km). Sections are categorized by color codes in Fig. 9. Summarizing the above discussion, demonstration sections were divided into three categories (Fig. 9). The first group with the highest dust production (1.7 to 2.5 gr/km) included 70% BFL Class A + 30% CRG Clean, 70% BFL Class A + 30% OFD Clean, and 70% BFL Class A + 30% LCF Clean, the second group with moderate dust production (1 to 1.7 gr/km) included OFD Class A and 80% BFL Class A + 20% BFL Clean and the third group with the lowest dust production (<1 gr/km) included BFL Class A and LCF Class A.
As mentioned in the test section descriptions, we know that the required maintenance time for the road built with conventional materials (80% BFL Class A + 20% BFL Clean – base case) would vary between one to three years depending on traffic volume, temperature, freeze-thaw cycles, etc., so for a stochastic benefit cost analysis 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.

**IRI**

In this project, IRI was measured by “Roadroid”, an android-based application. Although
Roadroid provides both estimated IRI (eIRI) and calculated IRI (cIRI) values, it has been reported that cIRI values provide higher accuracy than eIRI values [24]. The cIRI values are shown in Fig. 10 during the two years of the project. Surface roughness depends on various factors related to weather and surface road conditions. Therefore, the average values of the surface roughness over two years of project are shown in Fig. 10. Surface roughness values are categorized in three different groups where cIRI values less than 4, between 4 and 6, and above 6 are, respectively, representative of “Good”, “Fair”, and “Poor” conditions. Accordingly, Fig. 10 shows that all of the sections possessed “Fair” surface roughness condition except 70% BFL Class A + 30% OFD Clean and 70% BFL Class A + 30% CRG Clean which had “Poor” surface roughness condition.

![Bar graph showing surface roughness results for each section over time.](image)

**Fig.10.** Roads roughness results for each section over time.
Table 2 presents the best, most likely, and the worth cases for the possible maintenance scenarios based on dust and cIRI measurements for all sections. Base on Dustometer results, the base, most likely, and the best cases of the required maintenance times were considered to be, respectively, 3, 4, and 5 years for LCF Class A and BFL Class A; 2, 3, and 4 years for OFD Class A and 80% BFL Class A + 20% BFL Clean, and 1, 2, and 3 years for 70% BFL Class A + 30% OFD Clean, 30% BFL Class A + 30% LCF Clean, and 70% BFL Class A + 30% CRG Clean. On the other hand, based on the IRI results, test sections were categorized into two different groups (fair performance or poor performance) (Table 2). 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.

Table 2. Maintenance frequency scenarios developed based on the IRI and dustometer results.

<table>
<thead>
<tr>
<th>Section</th>
<th>IRI</th>
<th>Dustometer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Best Case</td>
<td>Most Likely Case</td>
</tr>
<tr>
<td>LCF Class A</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>OFD Class A</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>BFL Class A</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>80% BFL Class A + 20% BFL Clean</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>70% BFL Class A + 30% OFD Clean</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>70% BFL Class A + 30% LCF Clean</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>70% BFL Class A + 30% CRG Clean</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

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 4 - 80% BFL Class A + 20% BFL Clean), 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**

Fig. 11 (a) and (b) 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 (Fig. 11 (b)). 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 \(D_m\) is the difference in monetary value between the cost of maintaining conventional roads with new ones, \(N_f\) is the new maintenance frequency, \(N_c\) is the new gravel road maintenance cost (per mile), \(C_f\) is the conventional road maintenance frequency, and \(C_c\) is the conventional granular road maintenance cost.
Fig. 11. (a) Construction costs per mile; (b) Maintenance costs per mile.

Value of Users’ Time

Delay time is the extra travel time required either to pass through a work zone or to detour around it [45]. 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 [46]. According to FHWA guideline [45], the following
formula can be used to estimate travel delay cost:

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

(3)

where, \( T_t \) is truck traffic percentage (based on discussions with Iowa county engineers \( T_t \) assumed to be 25%), \( P \) is a personal travel, \( V_p \) is a value (US$/hr) of personal travel time, and \( V_t \) is a value (US$/hr) of truck travel time. Values of personal and truck travel time, obtained from the Bureau of Labor Statistics (BLS) data base [47], are 25 US$/hr and 54 US$/hr, respectively. Iowa granular roadway traffic data was obtained from the Iowa DOT traffic count data base (Fig. 12) [48]. 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).
Fig. 12. Traffic volume distribution in the state of Iowa.

Fig. 13 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 [49], since driving time for a one mile road would be two minutes, assuming a 48 km/hr speed, as shown in Fig. 13, assuming six minutes (three times more than regular route) for driving through a detour would be reasonable.
Fig.13. Actual route vs. detour.

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 [50,51]. 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 [10], an analysis period of 20 years was used for all the road sections [52].

Discount rate data for the previous twenty years were obtained from a Federal Reserve [53] data base 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” [54]. In this paper, inputs associated with
availability of sufficient historical data (i.e. discount rate and ADT) 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 [55], which is often used in business decision making [56–58], was used [55]. 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 [43,59–61].

**Economic Analysis Results**

To perform stochastic benefit cost analysis, 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 s to 75 s. Fig. 14 shows the results of simulation for performance-based economic analysis based on dust production measurements.
Fig. 14. Monte Carlo simulation results (scenarios developed based on dust production measurements).
Fig. 15 presents simulation results in probability density functions (PDF) format, that shows relative likelihood of benefit cost ratio (BCR) for each granular road test section. In addition, standard deviation values, “indicators of the amount of dispersions” of BCR [55], 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” [62].

As shown in Fig. 15, among all the alternatives, BFL Class A yields the highest median benefit cost ratio. In addition, this section is the only granular road option that met 100% reliability, a probability that BCR stays above one, 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 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 BFL Class A, the chance of yielding more benefits using LCF Class A would be lower than for BFL Class A.

70% BFL Class A + 30% LCF Clean and 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, 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. Fig. 15 shows the outcome of simulations for performance-based benefit cost analysis developed for IRI results. There were 10,000 iterations, with simulation times ranging from 37s to 73s.
Fig. 15. Monte Carlo simulation results (scenarios developed based on IRI results). The outcomes of stochastic economic analysis based on IRI measurements were close to the previous analysis based on dust production. Note that for BFL Class A, 80% BFL Class A
+ 20% BFL Clean, 70% BFL Class A + 30% OFD Clean, and 70% BFL Class A + 30% CRG Clean the results were identical, because for all these aggregate products identical maintenance frequency scenarios were developed (see Table 2).

As shown in Fig. 15, as in the previous analysis based on dust production, among all of the alternatives BFL Class A exhibits the highest median benefit-cost ratio 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 LCF Class A and 70% BFL Class A + 30% LCF Clean exhibited the best economic performance among other alternatives (comparing with the base case aggregate option - 80% BFL Class A + 20% BFL Clean).

Conclusions

This paper presents a stochastic performance-based Life Cycle Benefit-Cost Analysis (LCBCA) method for comparing economic performance of granular roads. Seven different surface aggregate materials were collected from four different quarries in Iowa and different performance measure tests were conducted over two years. Using LWD, IRI, and dustometer test results, maintenance 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 proper performance measures for estimating maintenance frequency. In addition, among alternatives, BFL Class A, compared to the base case aggregate option (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 and consequently will help to develop sustainable granular roads. Recommendations that may result from this research project would be founded in fundamental economic analysis theory and can provide various transportation agencies with an added level of confidence in predicting economic impact associated with granular road material alternatives of interest.

**Author contribution statement**

The authors confirm contribution to the paper as follows: study conception and design: Jahren, C, Satvati, S., Nahvi, A.; data collection: Satvati, S., Nahvi, A.; analysis and interpretation of results: Satvati, S., Nahvi, A.; draft manuscript preparation: Satvati, S., Nahvi, A. All authors reviewed the results and approved the final version of the manuscript.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHAPTER 3. GENERAL CONCLUSIONS

In order to evaluate the performance of several different surface aggregate materials, the changes in layer stiffness, dust production, and ride quality of seven granular road test sections in Decatur County, Iowa were monitored on several occasions throughout the duration of the study. The aforementioned performance measures were considered in a benefit cost analysis model to select the most dependent variable and to estimate maintenance frequencies for the test sections. The following conclusions were drawn:

- LWD test results showed that LCF Class A had the maximum and 70% BFL Class A + 30% CRG Clean had the minimum composite (surface and subgrade) elastic modulus values. Composite elastic modulus values for all sections were generally consistent through different seasons, except in December 2016 when tests were performed on frozen ground.
- Dustometer test results showed that the 70% BFL Class A + 30% CRG Clean section had the maximum dust production and LCF Class A had the lowest dust production.
- The average values of IRI (ride quality) for all sections corresponded to a fair quality of smoothness except for the following sections: 70% BFL Class A + 30% OFD Clean and 70% BFL Class A + 30% CRG Clean, which had poor smoothness quality. The average values of the IRI values over time showed that LCF Class A and BFL Class A had the best smoothness relative to all other sections.
- The local BFL Class A materials exhibited the best economic performance due to the proximity of the source of this material. Moreover, LCF Class A and 70% BFL Class A + 30% LCF Clean had the best economic performance among other alternatives, with the base case aggregate option selected as 80% BFL Class A + 20% BFL Clean.
• 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.

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