Jordan Journal of Civil Engineering, Volume **17**, No. **1**, **2023**
DOI: https://doi.org/10.14525/JJCE.v17i1.13

Integrating a Multi-criteria Route Optimization with ArcGIS for Gravel Road Data Collection

Omar Albatayneh [1)*], Dima A Husein Malkawi [2)], Er Yue [3)], Benjamin Fosu-Saah [4)] and Khaled Ksaibati [5)]

[1)] Assistant Professor, German Jordanian University, Jordan. * Corresponding Author.
E-Mail: omar.albatayneh@gju.edu.jo
[2)] Assistant Professor, German Jordanian University, Jordan.
[3)] Post-doctoral Research Fellow, University of Wyoming, United States of America.
[4)] Graduate Research Assistant, University of Wyoming, United States of America.
[5)] Professor of Civil Engineering, University of Wyoming, United States of America.

ABSTRACT

The ability to identify and collect low-volume roads' data, especially gravel roads, is critical in transportation planning. Developing an effective method for gravel-road data collection allows both decision-makers and local agencies to efficiently obtain information regarding road conditions. In this study, a geographical information system (GIS)-based decision- support system was applied to assist local agencies in determining reliable access routes to all gravel roads in Wyoming. The routing criteria were developed using the Network Analyst tool of ArcGIS software based on the restrictions on average daily traffic (ADT) volume values, speed limits, driving distances and driving hours per day. Results indicated that the routing maps created by ArcGIS software were an easy-to-use method to plan and schedule data collection on gravel roads. The routing analysis provided a reliable means to minimize driving time and distance. The methodology developed in this study may be employed by local transportation agencies for road-maintenance purposes in rural areas.

KEYWORDS: Low-volume roads, Gravel roads, Route optimization, ArcGIS, Data collection.

INTRODUCTION

In the past decade, there has been a growing interest in gravel-road management systems (GRMSs), in order to address the environmental, safety and health concerns of the public (Albatayneh et al., 2020). Special focus, particularly in industrialized low-volume roads (LVRs), is directed at the performance and conditions of gravel roads. Traditionally, for low-volume roads, especially gravel roads, route scheduling for maintenance and data-collection purposes is carried out by the local agencies' engineers without a systematic strategy (Albatayneh et al., 2020; Albatayneh et al., 2019). In such a process, plans and route scheduling can be affected by an individual's personal tendency toward specific goals, criteria and objectives. Better routing models on low-volume roads will allow more information to be collected with minimal travel time. The models would allow for more cost-effective management of both county and other state roads. Comprehensive low-volume road-management strategies will aid decision-makers and planners in scheduling their route-maintenance activities (Apronti et al., 2015). Two recent motivating factors for increased low-volume road-traffic counting and estimating efforts relate to their roles in air quality and in safety mitigation. It is widely recognized that traffic fatality rates on rural roads are higher than on other roads. With better estimates of traffic on low-volume county and other state roads, effective safety improvement efforts can be made. In broader terms, better estimates of traffic volumes and transportation-management strategies of low-volume roads will allow for more effective maintenance.

Generally speaking, the optimization of route-data collection conserves time and resources. Route optimization has the ability to identify the most cost-effective segments of roads and prioritize them based on

Received on 10/5/2022.
Accepted for Publication on 1/9/2022.

certain criteria. Since fuel prices are incessantly rising, managing fuel consumption is considered one of the major benefits of route optimization. Therefore, this method is a basic means intended to cut expenses. Also, by using this automated routing protocol, especially when the complexities of route needs increase, the time spent on trip planning will significantly decrease. The advantages of route optimization are vast. However, increasing the number of gravel-road miles tested per day is considered one of the main benefits of this study. In addition to the routing-optimization algorithms, geographic-information system (GIS) applications are rapidly becoming a key element of planning, coordinating and managing transportation assets. In GIS, Vector and Raster are the most two common data types used in geographic analysis. These types are very different in terms of functionality and usage. Vector data is generally made up of three main types (points, lines and polygons). Points can be connected to form lines and then joined up to create polygons. As a result, objects will have more accurate coordinates. Therefore, combining these two methods together would enhance the planning and scheduling process, especially in rural areas where limited resources are available. As a result, realistic scenarios and models of the network conditions can be established. In this study, a routing protocol that has the ability to optimize relationships between the data's variables is introduced, implemented and discussed for the selection of optimal routes in the case of gravel roads' data collection. The proposed protocol is based on a database that contains a network of geographic coordinates (geo-referenced spatial data) in which the GIS software can support.

The State of Wyoming frequently faces oil- and tourism- industry development in rural areas. A transportation-management plan is needed to accommodate the rural roads with higher traffic volumes. There are three objectives of this study. The first is to identify and locate all gravel roads in Wyoming. The second is to estimate traffic volumes on the gravel roads and group the roads based on their traffic-volume ranges. Finally, a routing analysis is carried out to determine the routes used by local-transportation agencies for maintenance activities. The routing maps generated in this study will support a wide variety of design, planning and management functions on both the state and county road networks.

Background

Research on using route-optimization techniques in GRMSs is still lacking. However, several routing techniques have been developed and briefly discussed in many other engineering fields to select an optimized path or route.

To date, different techniques have been developed to find optimal routes at the network level. These techniques include optimization algorithms, such as Simulated Annealing (Kirkpatrick et al., 1983), Tabu Search (Glover and Laguna, 1997), Genetic Algorithm (Holland, 1975), Ant Colony Optimization (ACO) (Dorigo et al., 1999) and ArcGIS Network Analyst (ArcGIS NA) (Dijkstra, 1959). Many routing algorithms use a heuristic algorithm to determine near-optimal solutions (Parker, 2007). Though there are conceptual similarities in some instances, they differ in applications.

The use of routing-optimization techniques predates the development of advanced GIS applications. However, ArcGIS NA undergoes the concept of the shortest path using the Dijkstra algorithm (Karadimas et al., 2007). The ArcGIS Network Analyst (ArcGIS NA) is a user-friendly extension of ESRI ArcGIS (ESRI). It is a simple and forthright application that can solve routing problems efficiently. Dijkstra's algorithm is the simplest pathfinding algorithm. It strikes a balance between finding an optimum path and computational management (Olivera, 2002). The algorithm was developed by Edgar Dijkstra (Karadimas et al., 2007). Besides, it uses less power and computational time to compute the optimum path.

Moreover, ArcGIS NA provides a valuable platform for spatial analysis of transportation-network planning and can produce maps showing the directions to the shortest route considering the associated constraints (ESRI). The ArcGIS NA tool can construct a network system by connecting nodes (points of link intersection) and arcs (links) (Akay and Sakar, 2009). Interestingly, this tool allows dynamic constraints, like road incidents, street directions and no U-turns to be defined. Other constraints, like time, vehicle capacity and maximum travel time can be also defined. ArcGIS NA can perform analysis including, but not limited to, network analysis (ESRI).

Even though there are many alternative paths between origin and destination, ArcGIS NA determines a better route based on the order and the node to visit first. It calculates the shortest path based on distance and time criteria (Lakshumi et al., 2006). The distance criteria consider the length of the trips while time criteria take road length, vehicle speed and traffic volume into account (Al-Mumaiz, 2012). The use of algorithms gives a better optimal route than the empirical approach. Consequently, finding the best route to minimize time, distance, cost, fuel consumption, noise and air pollution is strategic, complex and relevant due to the collection and analysis of data (Al-Mumaiz, 2012). Transportation data is an important reference data in GIS and is central to essential applications, like emergency response, routing, urban and regional planning, public transport and service delivery in the municipality (Rodrigue).

The ArcGIS NA tool has been used to solve many routing problems in waste-collection management and other transportation-related issues. For instance, the ArcGIS NA tool was used to optimize routes for municipal-waste collection in Athens. In the case of municipal-waste collection of large items, ArcGIS NA proposed an optimized route of 4.592 km. Meanwhile, the truck traveled 5.7km when the route was decided empirically on a particular day. Results from the network optimization showed significant savings in time and cost compared to the current *status quo*. Optimization of 20% success was made compared with the empirical approach (Karadimas et al., 2007). It is important to note that an efficient route can reduce gas usage, vehicle maintenance, driver overtime and more service areas (ESRI). Moreover, the study has shown that applying the ArcGIS NA in solving municipal-waste collection significantly minimized the route length and cost.

The ArcGIS NA tool is used by the Mustafakemalpaşa Forest Enterprise Directorate (FED) located in the city of Bursa, Turkey in the planning of forest transportation. The complex transportation of forest products requires evaluating many alternative routes (Akay and Süslü, 2017). It costs about 40% of the total cost of producing timber. Therefore, finding the optimum route to transport forest products will minimize the overall cost of production in Turkey (Acar and Gumus, 1998). The transportation cost was affected by average truck speed, logging trucks and load capacity. In addition, road features that affect transportation cost include road length, road type, road slope and road condition. Therefore, minimizing travel time was critical to reduce the cost of production. Traditionally, the experience of forest managers is used to plan the route. Obviously, finding the optimum path with this approach is impractical. Consequently, the network-analysis method was employed to find the optimum route for the transportation of forest products safely and cost-effectively. Besides, routes that traversed landslide-risk zones were excluded from the network analysis. Constraints, such as road length and truck speed (affected by road type and condition), were included in the attribute table. The ArcGIS NA was used to find the optimum route with minimum cost. The study concluded that the network analyst reduced the transportation cost by finding the optimum path.

Data Preparation

The Wyoming Technology Transfer Center (WYT2) provided highly accurate attribute data for approximately 9,000 miles of gravel roads in Wyoming, as well as reasonably precise average daily traffic counts, all of which are considered essential components for conducting a route-optimization analysis for this study. Table 1 presents all datasets and data sources for this study. As mentioned earlier, this study utilized the vector type of data in the analysis. For example, buildings such as the engineering building at the University of Wyoming were coded as point data in order to connect them with other infrastructures to form a line. Besides, the gravel roads as well as the highways used in this study were taken from the WYDOT GIS directory.

Table 1. Types and sources of data

Data	Type	Source
Gravel roads	Shapefile	WYT2
Highways shapefile	Shapefile	TIGER
ADT	Attribute	WYT2
Engineering building (University of Wyoming)	Point	Geo-coded coordinates

Road-network Data

The estimation of traffic volume requires an accurate representation of the road network serving the region. All transportation models that include highways/local roads, transit elements, and/or mode choices must include road networks (Mondal et al., 2021). The road-network data used in this study was obtained from TIGER and WYT2. TIGER products are a public-census digital database containing data for roads, railroads, census statistical boundaries, … etc. for the entire United States.

The road-network database lists the physical characteristics of each road segment, including the number of lanes, posted speed limit, road capacity and direction (one-way or two-way facility). Figure 1 shows the road network used in this study. Figure 2 presents the detailed procedure of preparing road-network data.

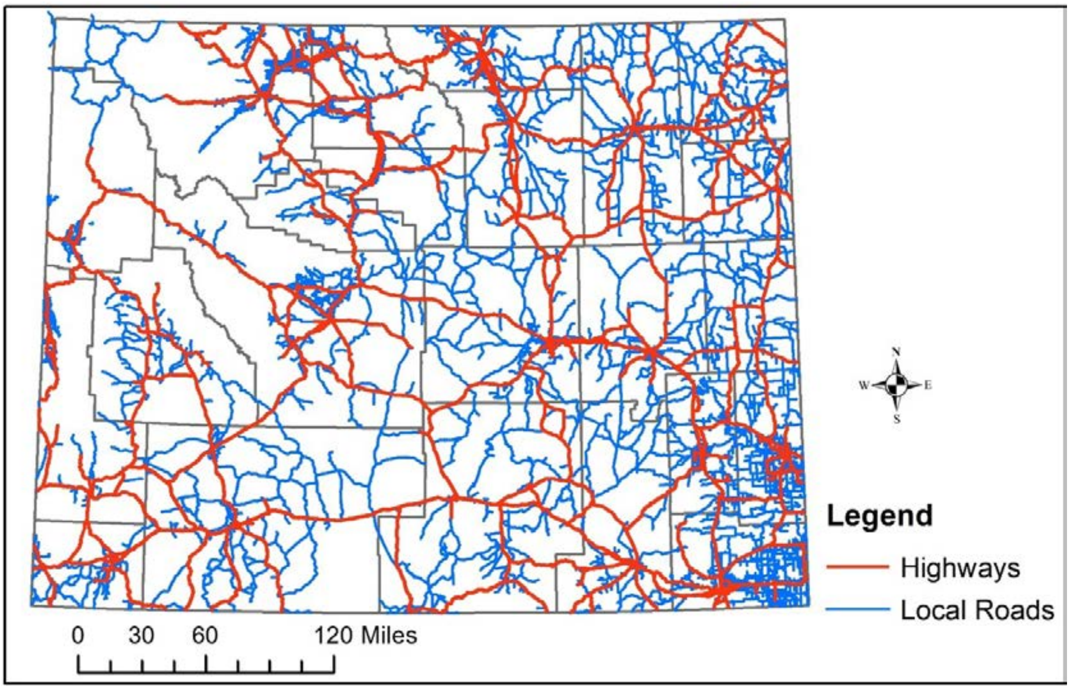


Figure (1): Wyoming road network

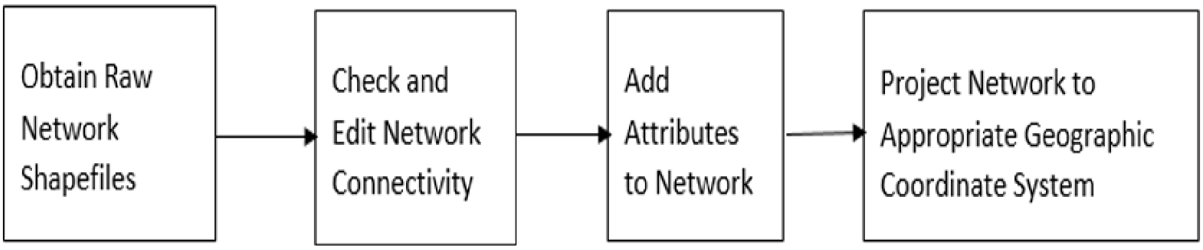


Figure (2): Road-network data-preparation procedure

Methodology

The primary objective of this study is to combine spatial data of paved and unpaved roads, for the purpose of creating an optimized data-collection process regarding gravel routes based on multiple criteria. In this research, the road-network data, both paved and unpaved, was obtained from the Wyoming Technology Transfer Center (WYT2). Each road segment contains the name, city and county it belongs to, length, speed limit and average daily traffic (ADT) value. For paved roads, shapefile data was used only as a link between gravel roads in order to provide a complete road network for routing. Therefore, this study employs ArcGIS software in order to establish, weigh and combine multi-criteria factors.

Network Analyst

The network analysis is conducted with the aid of GIS to select the shortest routes. Routing and designing efficient road networks are powerful means to reduce the negative impacts of the transportation system (Zhang et al., 2000). In this research, the Network Analyst tool in ArcGIS software was used for identifying routes that cover all unpaved roads for Wyoming. ArcGIS Network

Analyst is a widely used tool in transportation research and applications that provides quantitative analysis on routing, travel directions, closest facility and service area. It allows users to model various network conditions based on their needs (Bhambulkar, 2011). The routing analysis in ArcGIS Network Analyst can find the best way to get from one location to another or to stop by several locations.

In this study, the optimized route is generated based on the locations of unpaved roads. The route was specified by placing stops at the starting and ending points of each gravel-road segment. The Network Analyst created the routes between two stops using either the fastest travel time or the shortest distance based on the Dijkstra algorithm (Lakshumi et al., 2006). For the distance criterion, the optimized routes are generated based on the location of the starting and ending points. On the other hand, for the travel-time criterion, the overall travel time for each road-segment was computed as the total running time of the testing vehicle, which is calculated for each road segment based on the testing vehicle's speed and the road-segment length. Additionally, the traffic volume for each segment was considered for this criterion. As a result, this study applied the criterion of the fastest travel time, since the most efficient driving route was required and the speed limit of each road was known. To the extent possible, the gravel roads in this study were ranked based on their ADTs, where higher levels of importance were given to roads with higher ADTs. The overall process to create optimized gravel-road routes is shown in Figure 3.

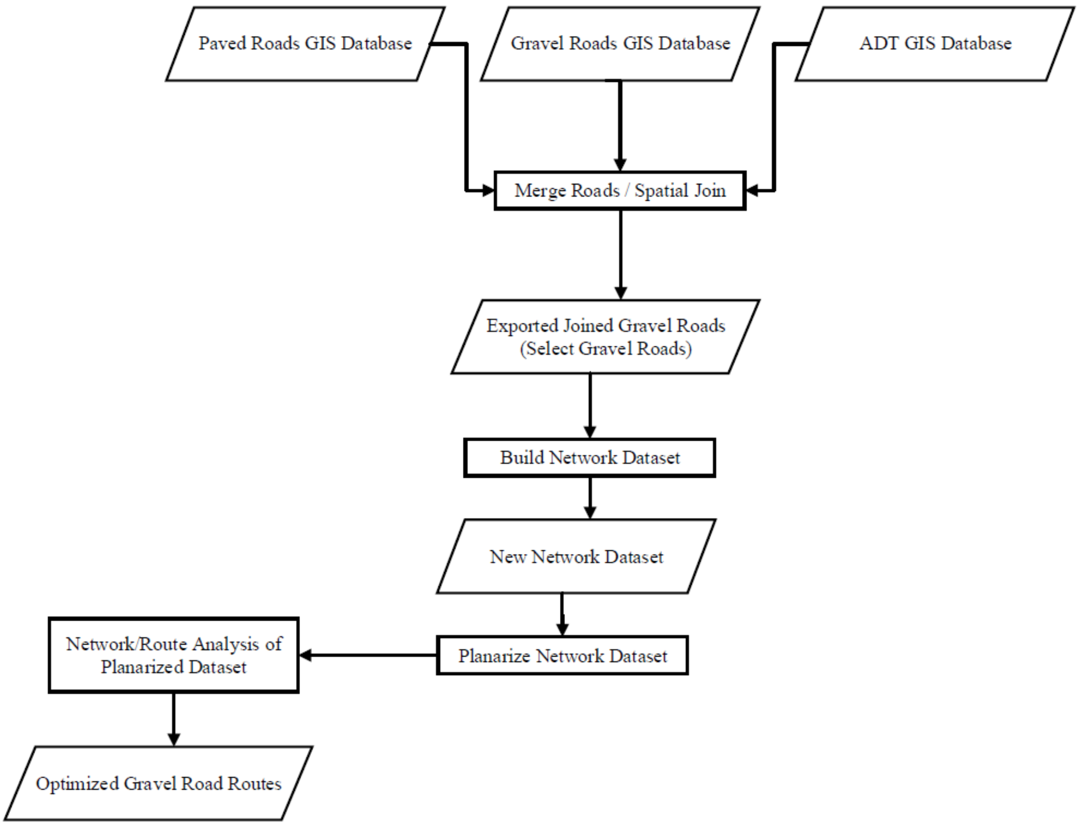


Figure (3): The model overflow of the NA optimization

Optimization Functions

The vast majority of the optimization functions in transportation planning, especially for network level, are considered as segment-linked (Morcous and Lounis, 2005; Ferreira et al., 2002), which means a number of segments in the road's network that are identified and selected for data-collection and maintenance activities every year (Mitchell, 2012; Eastman, 1999; Albatayneh et al., 2021). Therefore, the optimization function used for optimizing the gravel-road routes in Wyoming and its constraints are described as follows.

The primary strategy is to maximize the number of gravel roads included in the analysis. Equation 1 shows the optimization function to maximize the total number of gravel-road miles in the network. N_1 is the total number of gravel roads considered in the analysis, C_i is the distance between two gravel roads. Furthermore, the multi-criteria factors in this study were used as the main constraints to formulate the optimization function (Equations 2 and 3), where U_i is the number of working hours per day. In this study, the routing criteria were developed based on several restrictions recommended by WYDOT staff and engineers on average daily-traffic (ADT) volume values, speed limits, driving distances and driving hours per day. However, several studies developed methodologies that are only based on one factor (economic, environmental or social metrics) (Martinkus et al., 2019).

$$Maximize \sum_{i=1}^{N_1} C_i x_i$$

$$x_i = \begin{cases} 1 & the\ path\ from\ two\ gravel\ roads \\ 0 & otherwise \end{cases} \quad (1)$$

Constraints (subjected to):

1- Working (driving) hours ≤ 8 hrs/day (2)

$$\sum_{i=1}^{N_1} C_i U_i x_i \leq 8\,\frac{hrs}{day}$$

$$U_i = \frac{miles}{Speed\ limit}$$

2- Speed ≤ 55 mph (gravel roads) (3)
Speed ≤ 75 mph (highways)

Case Study- Demonstration

The State of Wyoming is home to approximately 14,000 miles of gravel roads. Many of these roads were constructed decades ago. Therefore, Wyoming's gravel-road network lays out several unique maintenance challenges for county engineers. These gravel roads boast very low volumes of usage and they are assigned with limited local budgets and resources to complete maintenance projects. In this study, Wyoming was chosen to implement the developed protocol based on the availability of data. Wyoming lies in a mountainous region along the Rockies "Rocky Mountains". However, like other western states, Wyoming has a relatively large area of flat plains where unpaved roads shape most of the roads in the network. The existing dataset contains geo-referenced layers for the locations and the ADT counts regarding both paved and unpaved roads. The examined area (as shown in Figure 4) is approximately 97,818 mi^2 with 9,000 miles of gravel roads. Figure 4 shows the paved and unpaved roads included in this study. Figure 5 shows the process flow diagram for monitoring gravel roads in Wyoming.

In Wyoming, ADT-volume data of gravel roads is used to prioritize road inspections, surface condition inventories and other appurtenances for maintenance activities. Roads with the highest ADTs are ranked and selected first for data collection and maintenance. In this study, gravel roads were classified into four groups based on the ADT percentiles; (100-75%), (75-50%), (50-25%) and (25-0%). However, two different scenarios were used. The first scenario is the gravel roads with the highest 25% of ADT, which is the group of 100-75%. The second scenario is the gravel roads with the highest 50% of ADT, which is the group of 100-50%. Figure 5 shows the process that was used for this case study.

Generally, the automation of data-collection scheduling yields higher throughput, improved data quality and labor cost savings. Besides, the application of routing technology in data collection yields systematic systems beyond human manual capabilities. Using the ArcGIS NA tool, two scenarios were evaluated. The first scenario, which is the highest 25% of gravel roads in terms of ADT, resulted in 9 days with a total of 2,254 miles of gravel-road routes for data collection. On the other hand, for the second scenario, where gravel roads with the highest 50% are included, 14 days of data collection with a total of 4,454 miles resulted as optimized routes. Generally, when comparing the results of the optimized routes with the manual-routing protocol, the ArcGIS NA provided a fewer number of days. A demonstration of the optimized data-collection routes is shown in Figures 6 and 7. Tables 2 and 3 detail each optimized route for each day for the selected scenarios.

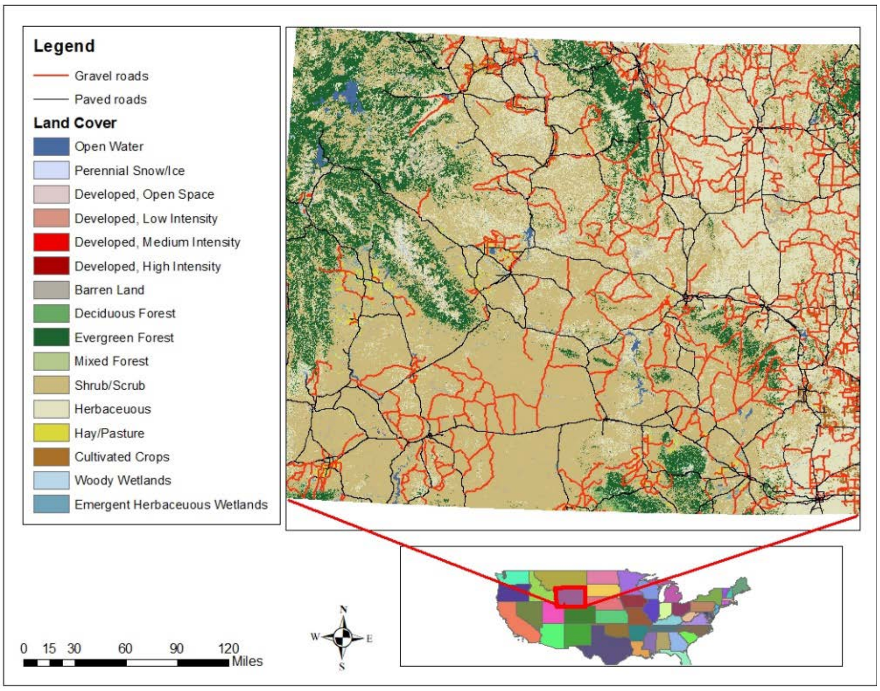


Figure (4): The examined road network in Wyoming

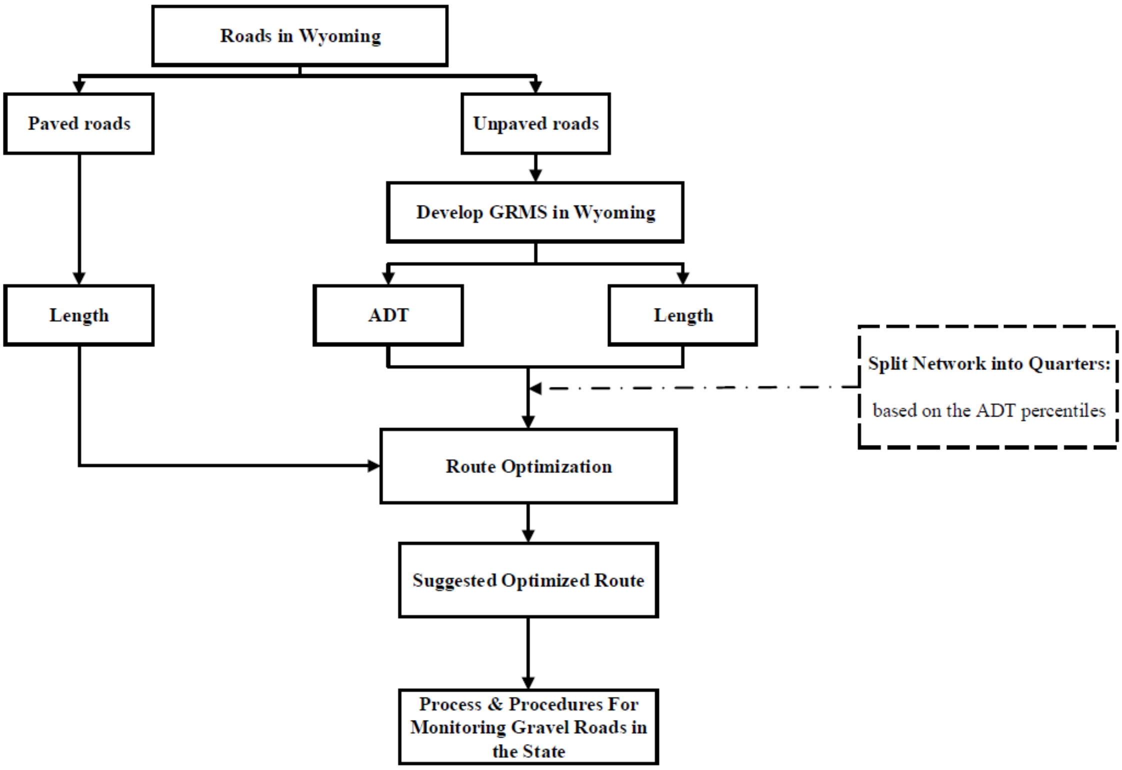
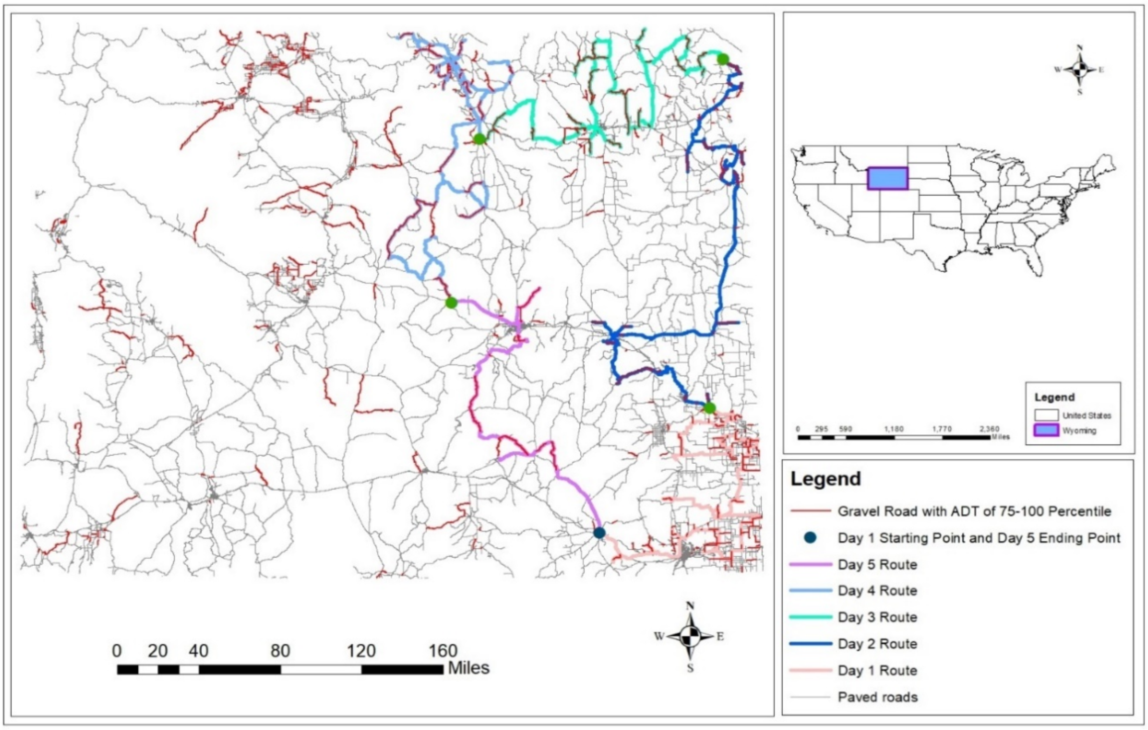
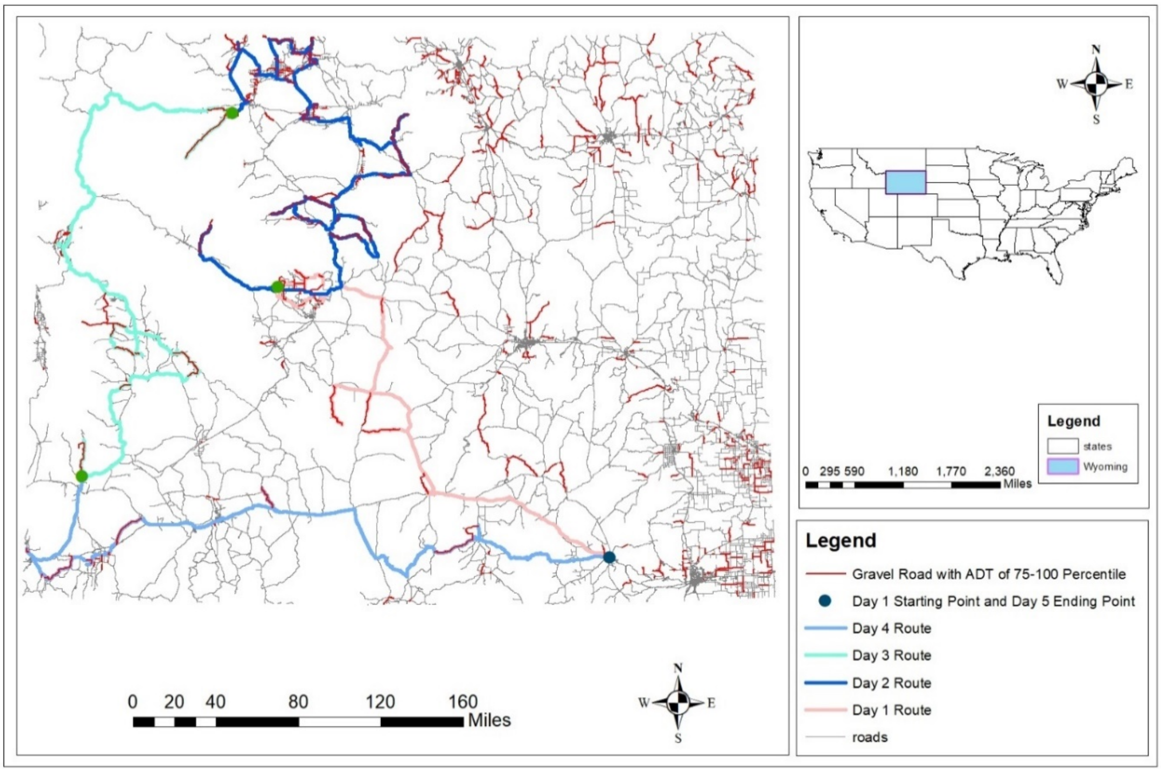


Figure (5): Process flow diagram for monitoring gravel roads in Wyoming



(a) 5 days of optimized routes for the first scenario

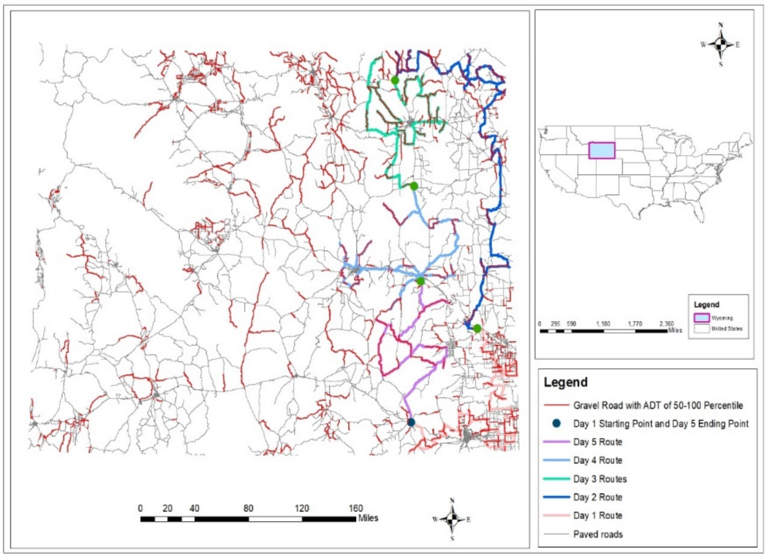


(b) 4 days of optimized routes for the first scenario

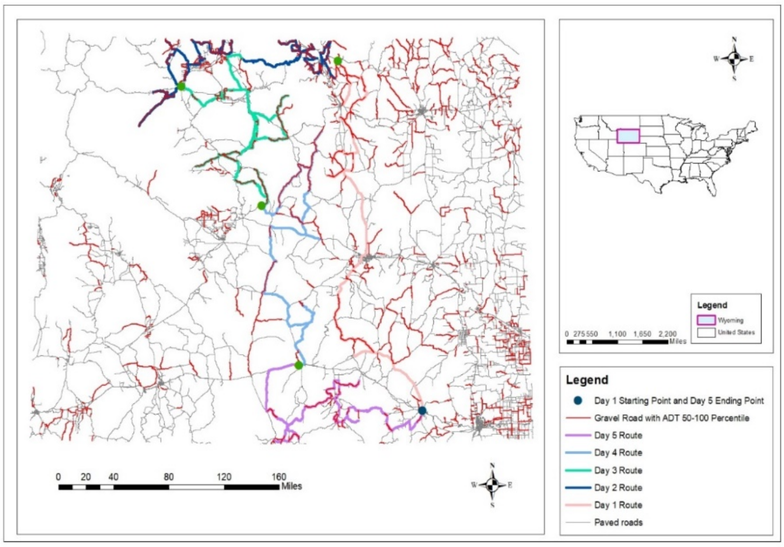
Figure (6): Optimized gravel-road routes for scenario 1

Table 2. Optimized routes for scenario 1

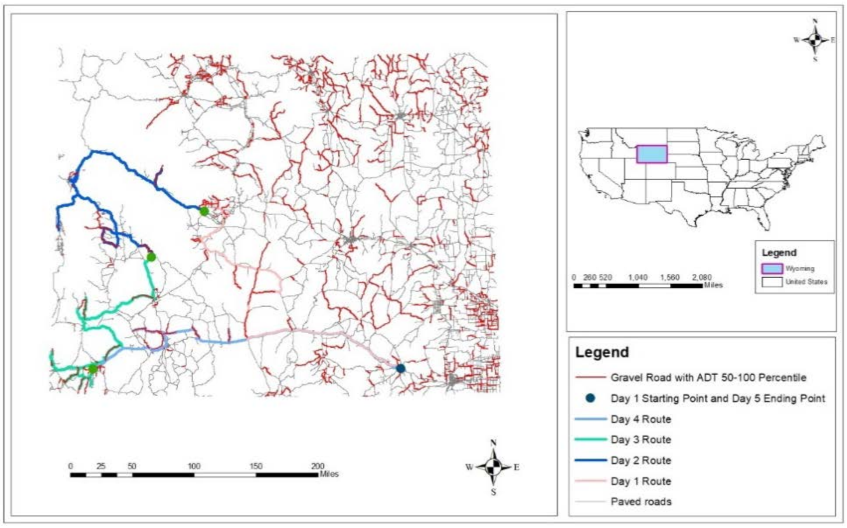
Route	Total Length (Miles)	Total Unpaved Road Length (Miles)
Day 1	528.4	310.2
Day 2	569.3	178.8
Day 3	550.7	294.5
Day 4	556.7	272.6
Day 5	353.6	145.5
Day 6	518.7	256.8
Day 7	579.2	315.3
Day 8	577.5	278.5
Day 9	506.5	201.8



(a) 5 days of optimized routes for the second scenario



(b) 5 days of optimized routes for the second scenario



(c) 4 days of optimized routes for the second scenario

Figure (7): Optimized gravel-road routes for scenario 2

Table 3. Optimized gravel-road routes for scenario 2

Route	Total Length (Miles)	Total Unpaved Road Length (Miles)
Day 1	543.9	390.5
Day 2	579.6	398.3
Day 3	562.4	397.5
Day 4	586.6	379.3
Day 5	425.0	345.5
Day 6	563.8	394.9
Day 7	579.2	390.9
Day 8	563.9	389.6
Day 9	477.7	239.6
Day 10	457.2	227.3
Day 11	565.0	230.8
Day 12	476.6	239.5
Day 13	444.6	275.7
Day 14	390.7	153.9

Economic Evaluation

Developing a comprehensive gravel-road conditions' database is a critical component of any road-management system (Pierce et al., 2013). In Wyoming, gravel-road condition data is collected periodically to assess the current status of the gravel-road network. The collected-road condition data is considered mainly to support the decision-making process. Monitoring gravel-road networks and collecting high-quality and accurate information require substantial resources and time. To make this process more efficient, a transition from manual-based systems to smartphone-based data collection is required. This paper describes a method in which the routes for data-collection and maintenance practices of gravel roads in Wyoming can be effectively scheduled using the developed route optimization tool that employs the most current and high-level IT developments. Therefore, implementing this technology can lessen the time-consuming procedures in any data-collection process.

The cost of the traditional data-collection methods without using advanced technologies is prohibitive.

Transportation agencies nationwide are facing budget cuts and limited resources. Optimizing routes for data collection will not just save travel time; it will also save the cost of travel as well as labor cost. As a result, using the developed automated protocol for optimizing the data-collection routes would have many advances over manual methods. For instance, the automated protocol is free of most of the biases that may occur through other traditional manual-scheduling methods, since it has a systematic method in planning gravel-road routes. Table 4 lists some of the major differences between the two protocols. As can be seen, time and cost related to the manual protocol are one of the major challenges facing local agencies, especially with limited budgets. With this technological change, the local agencies would have the same amount of collected data with fewer budget and personnel resources, or even more data can be collected with the same limited resources available. For the case in point, Laramie county in Wyoming was selected to perform a pilot study in 2017. This study required collecting gravel-road condition data over the entire county. More than 1,000 miles were included in this study. A team of two qualified engineers collected condition data. Also, road segmentation was performed during the data-collection process in order to obtain a homogeneous and uniform process. For this purpose, the trained team spent two months collecting gravel-road condition data. However, using the developed route-optimization tool would save the time spent in data collection, as this tool provides optimized routes. As a result, the adoption of advanced technologies at the local agencies' level would lower the number of days spent on data collection. Therefore, this automation results in an enhanced output per unit labor.

Furthermore, the number of gravel-road miles that can be tested per day is also considered as a limitation of using the manual protocol. These challenges associated with the manual method can be avoided by using the newly developed ArcGIS tool introduced in this study. Eventually, the developed automated routing method will be successfully adopted as a standard practice in the future for counties.

Table 4. Major differences between the two gravel-road routing protocols

Scheduling Process	Number of Planners	Scheduling Time	Tested Miles/ Day
Automated Protocol	1	20 min.	More than 140 miles
Manual Protocol	At least 2	More than 2 hrs.	Less than 100 miles

CONCLUSIONS

Due to the lack of cost-effective management tools for gravel roads, there is a need to integrate innovative techniques to plan and collect condition data and make informed decisions of maintenance, especially with limited resources. This study utilized an intelligent-based technique for decision-makers to be followed as a standard practice among local agencies. An optimization process is proposed to select gravel-road segments for data collection, so that future maintenance activities can be identified. The main objective of this study was to provide local agencies with an easy-to-use method to plan and schedule data-collection and maintenance activities for route optimization. The comprehensive and extensive coverage of high-quality spatial data allowed us to conduct geo-spatial analyses for Wyoming. This study proposed an automated protocol to minimize distance, time and effort effectively. For this study, Wyoming State with a total of 9,000 miles of gravel roads was taken as a case study to implement and demonstrate this protocol.

The current method of selecting routes for collecting data and maintenance is laborious. Based on human judgment and without any engineering and management concerns, the manual protocol can seem counterintuitive, while the automated ArcGIS tool generates optimized routes, since its advantages outweigh the traditional manual method. Therefore, the resulting routes are considered the most optimal paths for the considered criteria in a timely manner in such a way that minimizes the total operating costs and improves public satisfaction.

Automation of data-collection planning and process through technological advancement is changing the way tasks are performed lately. While it reduces the number of personnel and labor that traditionally perform manual tasks, it reduces the number of working hours. This study systematically contributes to the gravel-road data collection process literature. Using the developed ArcGIS tool, the cost and the amount of time spent on data collection can be minimized. This automated protocol will help engineers expand the number of gravel-road segments (miles) to be tested and maintained. Then, the collected data can be used to establish a gravel-road management system. Such management systems will provide local agencies with cost-effective solutions associated with gravel-road maintenance and rehabilitation. At the present stage, tool elaboration is needed to master some of the advanced engineering and environmental criteria to be rolled out to the national level.

In conclusion, previous efforts made to automate the data-collection process for gravel roads are still impractical for application and require an analysis level that may supersede the capabilities of small local agencies. This study established a baseline methodology to automatically optimize gravel-road routes for data-collection and maintenance activities. The performance goals of this automated tool should fulfill the objectives of this study stated earlier. It is anticipated that this proposed study will result in changing the currently conventional practices for managing gravel roads in Wyoming. The innovative techniques and the emerging technologies will provide lawmakers in the state with the appropriate reports to approve funding for maintaining gravel roads in the state. Also, the developed routing protocol will emphasize the delivery of maintenance projects to meet the expectations in terms of timeliness, quality and cost.

Recommendations

The creation of the automated protocol for optimizing the selection of gravel-road routes for data-collection and maintenance activities has established several opportunities for improving the GRMS operations. At this point, the developed automated protocol views gravel roads merely on the basis of distance and ADT. In future studies, it might be possible to take into account other engineering and environmental criteria, such as road features, land use, industrial activities, urbanization, working or maintenance zones, vertical profile of roads, % upgrade, … etc.

Acknowledgement

The authors gratefully acknowledge the generous financial support from the Mountain-Plains Consortium (MPC) for this study. All opinions, findings and results are solely those of the authors.

Data-availability Statement

Some or all data, models or codes that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Acar, H.H., and Gumus, S. (1998). "Determination of forest-road art construction requirements using geographical information systems". In: ESRI and ERDAS Meetings (Vol. 8).

Akay, A.E., and Sakar, D. (2009, November). "Using GIS-based decision-supporting system in determining optimum path that provides the transportation to fire zone at the shortest time". The Chamber of Turkish Engineers and Architectures: The Congress of Geographic Information Systems, 02-06. (Accessed on October 7, 2019).

Akay, A.E., and Süslü, H.E. (2017). "Developing GIS-based decision-support system for planning transportation of forest products". Journal of Innovative Science and Engineering (JISE), 1 (1), 6-16.

Albatayneh, O., Aleadelat, W., and Ksaibati, K. (2021). "Dynamic programming of 0/1 knapsack problem for network-level pavement asset-management system". Canadian Journal of Civil Engineering, 48 (4), 356-365.

Albatayneh, O., Forslöf, L., and Ksaibati, K. (2019). "Developing and validating an image-processing algorithm for evaluating gravel-road dust". International Journal of Pavement Research and Technology, 12 (3), 288-296.

Albatayneh, O., Forslöf, L., and Ksaibati, K. (2020). "Image retraining using TensorFlow implementation of the pre-trained inception-v3 model for evaluating gravel-road dust". Journal of Infrastructure Systems, 26 (2), 04020014.

Albatayneh, O., Moomen, M., Farid, A., and Ksaibati, K. (2020). "Complementary modeling of gravel-road traffic-generated dust levels using Bayesian regularization feedforward neural networks and binary probit regression". International Journal of Pavement Research and Technology, 13 (3), 255-262.

Al-Mumaiz, M.O. (2012). "Paths planning for Al-Ramdi intercity road using GIS tool". Engineering and Technology Journal, 30 (2), 265-281.

Apronti, D.T., Hepner, J.J., and Ksaibati, K. (2015). "Wyoming low-volume roads' traffic-volume estimation". Federal Highway Administration. Final Report, FHWA-WY-16/04F.

Bhambulkar, A.V. (2011). "Municipal solid-waste collection routes optimized with arc GIS network analyst". International Journal of Advanced Engineering Sciences and Technologies, 11 (1), 202-207.

Dijkstra, E.W. (1959). "A note on two problems in connection with graphs". Numerische Mathematik, 1 (1), 269-271.

Dorigo, M., Caro, G.D., and Gambardella, L.M. (1999). "Ant algorithms for discrete optimization". Artificial Life, 5 (2), 137-172.

Eastman, J.R. (1999). "Multi-criteria evaluation and GIS". Geographical Information Systems, 1 (1), 493-502.

ESRI, ArcGIS Network Analytics. https://www.esri.com/en-us/store/extensions/arcgis-network-analyst (Accessed on October 17, 2019).

Ferreira, A., Picado-Santos, L., and Antunes, A. (2002). "A segment-linked optimization model for deterministic pavement-management systems". International Journal of Pavement Engineering, 3 (2), 95-105.

Glover, F., and Laguna, M. (1997). "General-purpose heuristics for integer programming—Part I". Journal of Heuristics, 2(4), 343-358.

Holland, J.H. (1975). "Adaptation in natural and artificial systems". University of Michigan Press.

Karadimas, N.V., Kolokathi, M., Defteraiou, G., and Loumos, V. (2007, December). "Ant-colony system *vs.* ArcGIS network analyst: The case of municipal solid-waste collection". In: 5th WSEAS International Conference On Environment, Ecosystems and Development, 128-134.

Kirkpatrick, S., Gelatt, C.D., and Vecchi, M.P. (1983). "Optimization by simulated annealing". Science, 220 (4598), 671-680.

Lakshumi, A., Ramiya, A., and Ssthya, R. (2006). "Optimal-route analysis for solid-waste disposal using GIS". In: Proceedings, International Conference of Land Registration and Cadastre-MAP India, New Delhi, India.

Martinkus, N., Latta, G., Rijkhoff, S.A., Mueller, D., Hoard, S., Sasatani, D., ..., and Wolcott, M. (2019). "A multi-criteria decision-support tool for bio-refinery siting: Using economic, environmental and social metrics for a refined siting analysis". Biomass and Bioenergy, 128, 105330.

Mitchell, A. (2012). "The ESRI guide to GIS analysis: Modeling suitability, movement and interaction". (Vol. 3). ESRI Press.

Mondal, M.S., Garg, R.D., Pandey, V., and Kappas, M. (2021). "Route-alignment planning for a new highway between two cities using geo-informatics techniques". The Egyptian Journal of Remote Sensing and Space Science, 24 (3), 595-607.

Morcous, G., and Lounis, Z. (2005). "Maintenance optimization of infrastructure networks using genetic algorithms". Automation in Construction, 14 (1), 129-142.

Olivera, F. (2002). "Map analysis with networks". http://ceprofs.tamu.edu/folivera/GISCE/Spring2002/Presentations/NetworksIntro.ppt

Parker, M. (2007). "Planning land information technology research project: Efficient recycling-collection routing in Pictou county".

Pierce, L.M., McGovern, G., and Zimmerman, K.A. (2013). "Practical guide for quality management of pavement-condition data collection". U.S. Department of Transportation. Federal Highway Administration, Washington, D.C.

Rodrigue, J.P. "Network data models". In: Transport Geography on the Web. https://people. hofstra.edu/ geotrans/eng/ch2en/meth2en/ch2m3en.html, (Accessed on September 15, 2019).

Zhang, J., Hodgson, J., and Erkut, E. (2000). "Using GIS to assess the risks of hazardous materials' transport in networks". European Journal of Operational Research, 121 (2), 316-329.