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Applications of GIS and Remote Sensing in Highway Project: a Review

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Abstract

The highway contributes significantly to human existence by providing safe, dependable, and cost-effective services that are environmentally friendly and promote economic progress. Highway projects need extensive planning to prevent work revisions, save time and cost, and increase job efficiency. Without a doubt, Highway transportation system must be constantly updated to keep up with technology breakthroughs, environmental change, and rising client needs. Incorporating Remote Sensing (RS) and Geographic Information Systems (GISs) has the potential to go beyond the limitations of RS, which typically collects information about the earth and its peripheries from space, and does not alter, analyze, calculate, query or display geographic engineering maps. Over the last few decades, the fusion of RS and GIS has shown promise, and the researchers are employing it in different stages of the Highway Planning and Development Process (HPDP) such as optimal route analysis, geometric design, operation and management, traffic modeling, accident analysis, and environmental impact analysis (noise pollutions, air pollutions). This paper gives an overall review of the use of RS and GIS on HPDP at various stages of their lifecycles.

1. Introduction

Highways are necessary for efficient travel between locations, which makes traveling simpler and less stressful for individuals. The highway promotes economic growth [1] while providing services that are dependable [2], cost-effective, and environmentally sustainable [3], all of which are essential to the human survival. Highways serve as the foundation of the transportation system throughout the majority of the world's inhabitants. There are still anomalies such as sizable, well-established cities where many people commute by rail and metro. Rail also has a sizable market share in the intercity passenger market for lengthy excursions in addition to long-distance freight operations, notably to and from ports in trainload volumes. However, roads are the common user transportation infrastructure and the basis of all efforts [1]. The highway project will require extensive planning to minimize work adjustments, save money and time, and enhance job effectiveness. The development of artificial intelligence and computer technology in human life necessarily has an impact on the highway construction industry as well [4].

The use of RS and GIS in highway planning and development projects is always a fascinating study subject because of its potential benefits in a range of applications at various phases including planning, design, building, operation, and maintenance, wherever and whenever it is, e.g. estimation of daily traffic [5], [6], population estimating [7], [8] road network evaluating [9], selection of a route [10]–[25], examination of various geometric design requirements [26]–[35], finding out about land acquisition before construction by looking at land usage and land cover [17], [36], [37], construction site surveillance[38]–[41], analysis of road operation and maintenance [42]–[45], traffic control and management [46], [47] road safety evaluation [35],

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[48]–[52] etc. The application of RS and GIS in HPDP at several phases including planning, project development (preliminary design), final design, pre-construction, construction, and operation and maintenance are discussed in this paper.

Numerous researchers have used RS and GIS to research the highway project, and the results have delivered several promising results. A comprehensive examination of the published works is required to provide a research overview, examine the difficulties, and identify emerging patterns because many research work results have been given. In assessments of the use of RS and GIS in highway planning and development process throughout the development phase, no review papers published yet have been found. Several review papers focus on the use of RS and GIS for highway applications such as accident analysis during operation and maintenance[51], optimal route selection during project development [10]–[25], noise[53], air[54]–[58], and environmental impact analysis during operation[59], [60]. Most of them only concentrate on one specific event's investigation. The use of RS and GIS in highway projects today is significant. RS and GIS applications in highway projects while the researcher concentrated on one occurrence, there was no picturing of the entire life cycle.

Therefore, through this review article, the readers may have a better grasp of how to utilize RS and GIS in any highway project at various stages of its life cycle as well as the difficulties and anticipated study patterns. This review has been written for this reason.

2. Remote Sensing (RS)

RS is the practice of the art and science of observing a planet's surface without directly contacting it [61]. This is accomplished by sensing, observing, processing, and using reflected or emitted energy to generate conclusions [62]. Nowadays, many remotely sensed images of the earth's surface that are commercially available might be used as a source of data for environmental capital and infrastructure capital in databases for infrastructure management and transportation planning [61].

Extensive research indicates that the use of road information acquisition from remotely sensed data is now common in highway development projects due to its potential benefits in a variety of applications [63] including autonomous driving [64], road network planning [64], [65], traffic control and management [65]–[67], map navigation [63], [68], and the development of smart cities [69]. Today's innovations and promises from remotely sensed data include, among other things, data fusion, context information learning, and the generation of data sets [63]. Transportation engineers can manage the paperwork for road inspections, the gathering, processing, and analysis of data, as well as the efficient visualization of survey results using RS and GIS. Financial officials can schedule maintenance and repair programs and further assess the financial effects of road degradation [70].

Thus during all stages of the project's development, the RS model will be used as a data repository. The credibility of RS will increase by combining the RS and GIS platforms, which provide high levels of information from RS data storage systems and GIS will manipulate, change, analyze, compute, and query detailed information in HPDP. To increase productivity, RS will also promote collaboration among team members, offer high levels of knowledge acquisition efficiency, and continuously analyze work over time. The numerous applications of RS and GIS in HPDP at various stages of its life cycle are shown in Figure 1.

Figure 1. Application of RS and GIS in highways at various stages of the life cycle.

3. Geographic Information System (GIS)

Geography is the study of the physical characteristics of the earth and how they change through place and time in space [61]. To overcome several spatially specific issues in daily life regarding surroundings, resources that are accessible, potential threats, and planned urban routes, agricultural productivity and income, non-point source pollution from agricultural regions, large quantities of multi-dimensional geographic (spatial) data on weather, soils, topography, land use, water resources, population, and socioeconomic status are required to provide answers to these concerns. Such geographical information may be represented and integrated quite efficiently using GIS [61].

Computers and the first concepts of assessable and computational geography emerged in the 1960s, which sparked the growth of the field of geographic information systems (GIS) [71], [72]. GIS collects, organizes, processes, and maps various kinds of data. GIS connects attribute data to a map and combines all kinds of descriptive data with location data (where objects are) (and what things are like there). The basis for mapping and analysis is utilized in research and virtually every sector is provided by this. GIS aids the users in comprehending trends, connections, and spatial context, resulting in a better management and decision-making, as well as enhanced communication and efficiency [73].

Geographic Information Systems (GISs) are increasingly useful tools for transportation analysis and planning as computer technology advances [74]. Geographic information systems and traffic models are nowadays frequently used in the research of transportation networks. We also note that the GIS data enables modeling integration for planning and operations [74].

The field of information technology known as geographic information systems is vast and has many uses. Companies like ESRI, Here Maps, and Leidos group are creating models for national security systems [75]–[77], cutting-edge automotive technology, and even natural resource models [78]–[80]. GIS programs may be used by individuals and organizations to analyze fine-grained spatial data and conduct geological research.

For a variety of reasons, ongoing work has been done throughout the years to integrate remote sensing (RS) and geographic information systems (GIS) since doing so might provide a project with a comprehensive picture and incredibly precise information from those sources. Figure 2 displays the volume of publications published between 1996 and 2022 on the use of RS and GIS in the HPDP life cycle.

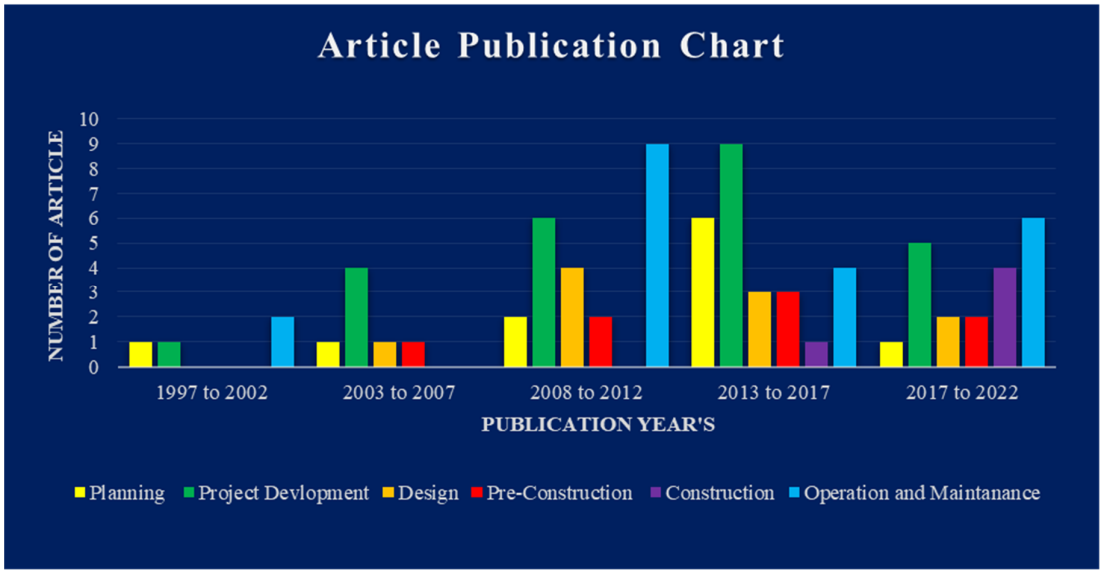

Figure 2. Number of articles that discuss the use of RS and GIS in highways at various phases of their life cycles.

In this article, the RS methodology for the entire HPDP project is explained by using a flowchart from several papers that have been looked at and in which the RS approach is defined for the various HPDP stages.

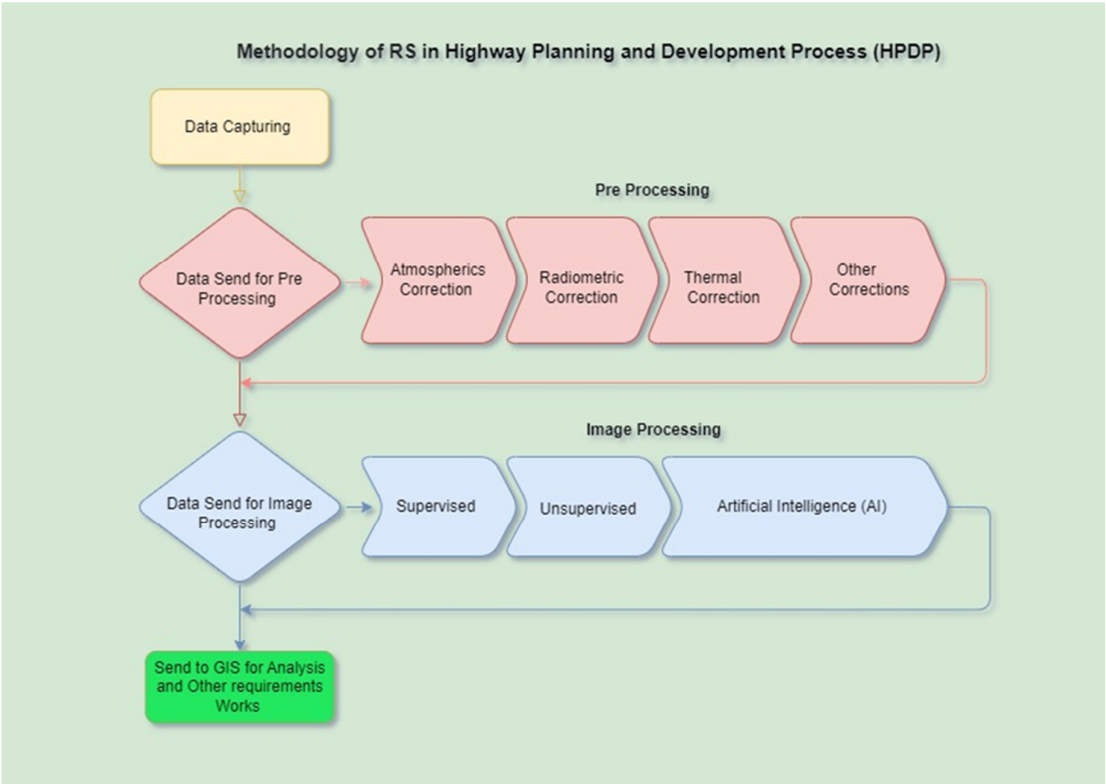

Figure 3. Flowchart of the methodology of Remote Sensing (RS) in Highway Planning and Development Process (HPDP).

4. Application of RS and GIS in HPDP

To develop a highway, several steps must be finished. The act of finishing these steps is referred to as the highway planning and development process. The basic stages in the establishment of a highway are planning, project development (preliminary design), final design, right-of-way, construction, and operation maintenance. The facility will remain in use when construction is complete, as will ongoing maintenance and operations [81].

4.1. Planning

Figure 4 shows the chronological overview of the most relevant application of RS and GIS in HPDP at the planning stage. The review work on the use of RS and GIS in HPDP in the planning stage will be discussed, as per the chronological outline. RS and GIS are now focusing on GIS-T and ArcGIS urban technologies. Land-use and zoning plans may be easily generated, modified, and maintained using ArcGIS urban's interactive 3D environment, which was created with planners in mind [82], where GIS-T supports travel demand modeling through input data processing and validation including network and local area data, as well as output data processing and visualization [74].

Under this review, RS and GIS applications in HPDP at the planning stage are separated into three different categories: RS and GIS applications at the planning stage in HPDP for economic studies, RS and GIS applications at the planning stage in HPDP for economic studies road use studies, RS and GIS applications at the planning stage in HPDP in engineering studies.

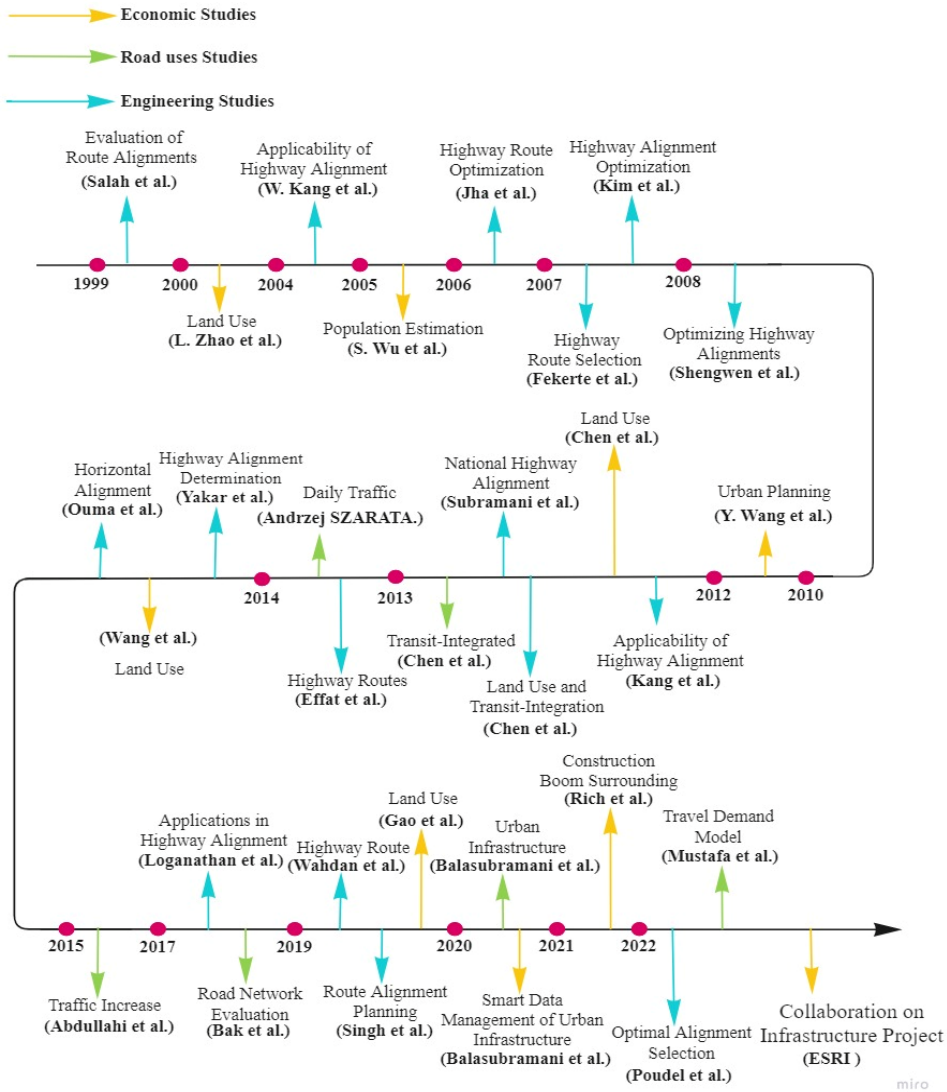

Figure 4. Chronological overview of the application of RS and GIS in HPDP at the planning stage.

4.1.1. Economic studies

The production of agricultural and industrial products [17], [83], exploration and mining studies [78]–[80], [84], population growth trends [82], future development trends in these industries, land use/Land cover [17], [36], [83], the infrastructure of communication [85]–[87] and education must all be collected for economic studies. Additionally, information about the current infrastructure and its use [86], [87], the distribution of the local population [65], estimation of the population [7] and per capita income must be accumulated.

4.1.2. Road use studies

Road use studies must contain traffic-related studies that cover data on the existing road infrastructure [17], [86], daily vehicle traffic volume [5], [6], traffic flow patterns [9], classifications of traffic including passenger vehicles, buses, and trucks, loads transported, average speeds, and projected future trends of traffic increase [6], [88].

4.1.3. Engineering studies

The geography, soil, road life, slopes, faults, and any unique issues with geography and drainage are all covered in this research work, and RS and GIS have already demonstrated that they are quite promising in this field of study [10]–[17], [20]–[26], [89].

4.2. Project development (preliminary design)

The project development phase begins once a highway project has been planned and scheduled for execution. The process of picking a route, examining the influences of the environment, doing several surveys, conducting preliminary design, alternative design, and studying various traffic modes intensifies at this phase of HPDP [81]. Several research projects are already justified highway route selection [10]–[25], [89], environmental impact analysis [60], [90], preliminary survey and design of the highway [91], and transportation mode selection and analysis [66]–[68], [74], [92], [93] are some of the application areas targeted by Integrated RS and GIS. Table (1) highlights the uses of RS and GIS throughout this stage of the HPDP lifecycle.

Table 1. Use of RS and GIS at the project development (preliminary design) stage of the HPDP lifecycle.

Authors	Applications of RS and GIS
El-Gafy *et al*. (2011)	Environmental impact analysis
Mishra *et al*. (2014)	
Salah *et al.* (1999)	Highway route selection
Jha *et al*. (2004)	
Jha *et al.* (2006)	
Fekerte *et al*. (2007)	
Shengwen *et al.* (2008)	
Subramani *et al.* (2012)	
Kang *et al*. (2012)	
Chen *et al*. (2012)	
Xu *et al*. (2012)	
Sanabria *et al.* (2013)	
Effat *et al*. (2013)	
Yakar *et al*. (2014)	
Loganathan *et al.* (2017)	
Wahdan *et al*. (2019)	
M. Singh *et al*. (2019)	
Poudel *et al.* (2022)	
Kim *et al*. (2007)	Transportation mode selection and analysis
Miller *et al*. (2015)	
S. Singh *et al.* (2017)	
D. Chen *et al*. (2021)	
Y. Chen *et al*. (2021)	
Guo *et al*. (2022)	
Park *et al*. (2014)	Preliminary survey and design of the highway

4.3. Detailed Design

The final design phase of a project can begin once a preferred possibility has been figured out and the environmental document's project description has been accepted. This phase results in a comprehensive set of plans, specifications, and estimates (PS&Es) of the necessary material quantities, ready for the request for construction bids and subsequent construction. The length of the final design process might vary depending on the size and complexity of the project [81].

The design phase in the HPDP life cycle is mainly broken down into two sections, which include developing a concept, considering the scale, and detailing it on design appropriately [81] so that discussion of the application of RS and GIS is done appropriately.

4.3.1. Developing a concept

Due to developing a concept, the project becomes more focused and is thus driven on a specific path. The number and size of travel lanes, the kind and size of the median, the shoulders, traffic barriers, overpasses, and bridges, the horizontal and vertical alignment, and the surrounding scenery are just a few of the many elements that make up a highway.

Each component necessitates a variety of separate but connected design choices. To fulfill a single purpose or thought, the designer might make design decisions by combining all these elements. Extensive research has previously been done on the use of RS and GIS in geometric design aspects such use of RS and GIS to figure out Sight distance [27], horizontal curvature [30], vertical curvature, the bypass [26], geography, to calculate seismic hazard analysis [29], etc.

4.3.2. Considering scale

A car's perspective on the world is very different from that of a person strolling along the street. The general planning of our cities has changed due to this significant disparity between the design size for an automobile and the design scale for humans. Since both pedestrians and non-motorized traffic are road users, planners must constantly take their safety as well as that of automobiles into account. In numerous road designs, the needs of motorized vehicles were frequently given priority over those of pedestrians, which mostly results in hazardous walking conditions but may also fundamentally alter how a traffic corridor is used [81].

Designers should do extensive studies on the traffic patterns of road users to address these challenges. The combination of RS and GIS is a highly promising tool for that, even though there is a unique GIS used in transportation called GIS-T that was created exclusively for the study of Traffic modes of road users [74], [93]

4.4. Pre-construction

After the completion of the final designs and the acquisition of the necessary right-of-way, project bid files are distributed, and a contractor is chosen. Minor design modifications may be required during the right-of-way acquisition process; as a result, the design team should be continuously involved throughout these stages [81]. By utilizing RS and GIS, the process of acquiring right-of-way property has become quite simple and systematic.

The Utah Department of Transportation (UDOT) has already begun tackling the project, which entails maintaining over 16,000 miles of state highway and represents an investment of many billions of dollars in roads, bridges, and other assets with the help of ROW GIS software [94].

4.5. Construction

Once the necessary right-of-way has been acquired, construction bid packages have been made available, and a contractor has been chosen, construction of highway work may begin [81]. Construction work planning [95]–[97], quality control management [38], unit price estimation [40], and construction site inspection [37]–[39] are just a few of the numerous simultaneous operations that take place during this period. These tasks will be relatively simple to complete with the aid of RS and GIS.

4.6. Operation and maintenance

The amount of traffic on the highways will rise every day once construction is complete and the facility is ready to resume normal operations. It has also been demonstrated that according to induced demand, today's road construction does not relieve traffic congestion [98]. Therefore, it is crucial to research traffic planning throughout the operational phase so that it might perhaps aid in lessening traffic congestion. We investigate user behaviors, traffic congestion, and traffic accident trends to address these problems and ensure user safety [47]. We also evaluate the environmental impact of noise pollution, carbon emission, and other factors throughout the operating phase to address environmental effects problems in the subsequent project or when upgrading highway projects. The use of RS and GIS in the HPDP operating phase has long held considerable

promise. Some of the RS- and GIS-based activities that are gaining popularity among researchers include highway safety assessment [42], [48]–[50], evaluation [52], analysis of traffic accident black spots [42], [51], monitoring and forewarning of traffic safety [47], evaluation of noise [53], [99], [100] and carbon emissions [54]–[58] by vehicles in highways, as well as the environmental impact assessment [59], [60].

When we release the highway to the public, it will require regular maintenance since portions of the road may be damaged or destroyed in collisions [81]. If the road is not maintained on time, it will be physically damaged, necessitating a larger expenditure to restore it to workable condition. As a result, frequent repair work on existing roadways is required [101]. Yet after development is done, poor maintenance can change the nature of a road [81]. Good roadway maintenance necessitates major investments in terms of time, human resources, and money [43]. The roads are degrading at a rate that makes upkeep difficult for the Department of Transportation due to growing traffic. As a result, DOT must prioritize road maintenance depending on available annual maintenance funding. It is vital to maintain roads in an outlay manner by optimizing the entire cost for the country's complete road network [101]. Including RS and GIS will improve highway maintenance operations planning, which has already been suggested by several scholars. Among these are road maintenance management [45], [101], visualization of integrated highway maintenance and construction planning [43], and a cost prediction tool for road upgrading and maintenance to help the road asset management system [44].

Every year, a major amount of money is spent on clearing landslide debris and maintaining roadways that have been impacted by landslides. Landslides in the modern age are the most harmful and disruptive to the social and natural environment and even highways are no escape from it. Landslides can be caused by a variety of factors including earthquakes, erosion, deforestation, unstable slopes, deep excavations, vegetation clearing, rock falls, and mining. But most of the landslides on the highway are brought on by the monsoon rains [102], [103]. In slopes and steep terrain, landslides are more likely to happen. Every monsoon, a confusing array of landslide threats threaten the highways in the Northeastern region of Nepal as well as in India in the range of the Himalayas. These landslides cause billions of dollars in economic damage [102], [103].

As a reason, while discussing HPDP, it is important to bring up landslide mapping. It falls to the HPDP Life cycle's division of the operation and maintenance phase. There are various methods to map the landslide among that landslide susceptibility zonation (LSZ) and landslide Hazard Zonation (LHZ) mapping with Multi-Criteria Decision Making (MCDM) techniques are very crucial. In MCDM, Fussy logic (FL) and Analytical Hierarchy Process (AHP) are very trending but some other methods are also there for mapping LSZ like the Frequency Ratio (FR) method, Information Value (IV) method, Weight of Evidence (WOE) method, Artificial Neural Network (ANN) model, Logistic Regression (LR) method, Support Vector Machine (SVM) model [102], [103].

5. Discussion

Highway projects are most important and require cooperation for safety, dependability, capacity, cost-effectiveness, quality, and productivity, according to the literature assessment. For instance, enhancing cooperation can result in time and money savings, cost savings, improved quality, lower carbon emissions, increased productivity, and information availability throughout the project lifespan. Integration of RS with GIS, on which multiple kinds of research have been undertaken concentrating on various facets of this subject, might enhance collaboration. A platform for cooperation for enhanced decision-making may be provided via RS and GIS. As a result, there aren't many methods for promoting and overseeing collaboration. This might be because successful teamwork requires several elements.

6. Conclusions and Future Recommendations

The planning studies, project development, detailed design, construction, and operation management of highways phase consume a lot of time and hence affect the duration and cost of the project. Engineers are looking for a possible solution for bringing new technologies to reduce both the duration and cost of highway projects. The current research work was an attempt to provide possible solutions to both factors by connecting RS and GIS in overall highway projects to bridge the gap between global scale and detailed spatial data. There is great potential for RS and GIS in highway applications from its planning stage to detailed construction and even in the operation and maintenance of roads.

The study may be further carried out by combining RS and GIS along with Artificial Intelligence (AI) techniques to evaluate various features of highway projects. Further study may include the applications of RS and GIS along with Vehicular Ad Hoc Network (VANET) for the safety of road users.

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کاربردهای GIS و سنجش از دور در پروژه بزرگراه: مروری

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چکیده:

این بزرگراه با ارائه خدمات ایمن، قابل اعتماد و مقرون به صرفه که سازگار با محیط زیست هستند و پیشرفت اقتصادی را ارتقا می‌دهند، کمک قابل توجهی به وجود انسان می‌کند. پروژه‌های بزرگراهی برای جلوگیری از تجدید نظر در کار، صرفه جویی در زمان و هزینه و افزایش بهره وری شغلی نیاز به برنامه ریزی گسترده دارند. بدون شک، سیستم حمل و نقل بزرگراهی باید دائماً به روز شود تا با پیشرفت‌های فناوری، تغییرات محیطی و نیازهای روزافزون مشتریان همگام شود. ترکیب سنجش از دور (RS) و سیستم‌های اطلاعات جغرافیایی (GIS) این پتانسیل را دارد که از محدودیت‌های RS فراتر رود، که معمولاً اطلاعات مربوط به زمین و پیرامون آن را از فضا جمع‌آوری می‌کند و تغییر، تجزیه و تحلیل، محاسبه، جستجو یا نمایش جغرافیایی نمی‌دهد. نقشه های مهندسی در چند دهه اخیر، ادغام RS و GIS نویدبخش بوده است و محققان از آن در مراحل مختلف فرآیند برنامه ریزی و توسعه بزرگراه (HPDP) مانند تحلیل مسیر بهینه، طراحی هندسی، بهره برداری و مدیریت، مدل سازی ترافیک استفاده می‌کنند. تجزیه و تحلیل حوادث، و تجزیه و تحلیل اثرات زیست محیطی (آلودگی های صوتی، آلودگی هوا). این مقاله مروری کلی از استفاده از RS و GIS در HPDP در مراحل مختلف چرخه حیات آنها ارائه می‌کند.

کلمات کلیدی: فرآیند برنامه ریزی و توسعه بزرگراه، سنجش از دور، سیستم اطلاعات جغرافیایی، مقرون به صرفه بودن، انتشار کربن.