Revolutionizing Highway Construction Projects: A Big Data-Driven Approach to Transformative Innovation Management

Nisha Meena
Research Scholar
Kalinga University,Raipur (C.G.)
nishameena199695@gmail.com

Abstract

This study delves into the forefront of innovation management in highway construction projects, employing a paradigm shift facilitated by big data technology. Recognizing construction technology as the cornerstone of highway engineering, the research emphasizes the need for targeted focus on key processes to elevate the technical prowess of construction. Utilizing big data technology, particularly in drawing and simulation, the study advocates for a transition from manual drawing to computer-generated engineering drawings, ushering in a new era of technological innovation management.

The implementation of a construction period control system takes center stage in optimizing project timelines and economic outcomes. Through a database-driven approach, the system strategically manages construction periods by setting the standard completion time as the primary objective. This innovative application of big data in project management involves the scientific analysis and preparation of construction period network diagrams.

Safety management in construction emerges as a critical aspect, emphasizing the importance of safety awareness among personnel. Leveraging network courses based on big data, the study proposes a systematic approach to enhancing safety awareness, thereby improving overall staff quality. Furthermore, big data's predictive capabilities are harnessed to establish a safety accident prediction system, allowing enterprises to anticipate incidents and formulate tailored emergency plans. The integration of full-time safety officers at construction sites, coupled with dynamic tracking through GPS systems, adds an additional layer of safety measures.

A robust quality management system is deemed essential for guiding the smooth progress of construction projects. Rooted in big data, this system encompasses data collection, computer-based data arrangement and analysis, information review, and the formulation of control indices based on a comprehensive database. As the construction industry enters a new era of innovation, this study advocates for the widespread adoption of big data technology to revolutionize highway construction projects, ensuring efficiency, safety, and quality in the modern construction landscape.

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1 Introduction

It is crucial to emphasize that the objective of highway construction technology is to ensure that the construction meets the technical quality standards set by construction units. To fulfill the evolving demands of highway traffic, it is imperative not only to witness technological advancements in highway engineering but also to revolutionize the project management methodologies applied in highway construction. Furthermore, in recent years, as modernization and

economic globalization continue to prevail, the escalating number of vehicles in India underscores the increasingly pivotal role played by highway engineering in the overall process of modernization. This development has garnered significant attention from both concerned individuals and government authorities.

The advent of computer big data has propelled our society into the information age. As previously mentioned, the imperative lies in undertaking technological and project management innovations in highway engineering. Leveraging the capabilities of big data information technology can significantly enhance the management tasks associated with highway engineering projects. In comparison to traditional approaches to highway engineering project management, the computational power of computer big data is considerably more robust. Its computational prowess opens up new avenues for efficient and innovative project management within the realm of highway engineering.

The continuous proliferation of modernization and economic globalization has led to a surge in the number of vehicles in India, elevating the significance of highway engineering in the process of modernization. This heightened importance has not gone unnoticed, drawing considerable attention from both concerned individuals and government authorities.

The advent of computer big data has ushered in the information age, providing an unprecedented opportunity to revolutionize highway engineering project management. The formidable computing power of computer big data, surpassing that of traditional approaches, offers a robust platform for innovative and efficient project management in the realm of highway engineering.

2 Challenges Persist in Contemporary Highway Engineering Management

Numerous challenges persist in contemporary highway engineering management, posing obstacles to the efficient execution and success of projects. Here are some prevalent issues:

2.1 Unjustifiable Cost Management

The financial aspects of highway engineering are intricately tied to the capital mobilization of enterprises. While cost management constitutes a crucial facet of the construction project management process, an unwarranted emphasis on achieving the lowest possible costs can lead to counterproductive outcomes. The utilization of low-cost materials may compromise the overall quality of the project. Hence, enterprises must adopt a balanced approach by implementing rational and well-thought-out cost management strategies.

Effective cost management plays a pivotal role in curbing financial waste and preventing the creation of substandard projects. It is my perspective that embracing scientific and standardized cost management practices is imperative for ensuring the seamless progression of the construction project. This approach not only safeguards against the misallocation of funds but also prevents the emergence of poorly executed projects, commonly referred to as "bean curd residue projects." In essence, a judicious and systematic approach to cost management is indispensable for achieving optimal project outcomes.

2.2 Financing Challenges in Road Infrastructure Development

Roads play a pivotal role in fostering economic development on both national and local fronts, serving as vital conduits for growth. Major road links and motorways not only propel economic development but also play a crucial role in ensuring social well-being by providing access to essential services, education, and healthcare in remote regions. However, financing road construction projects, particularly those with minimal economic returns, poses a significant challenge, especially in developing countries.

While toll motorways traditionally present profitable investments, economic downturns can create funding scarcities even in prosperous nations. The financing conundrum is particularly acute in weaker economies, where sourcing funds for road construction projects becomes a formidable obstacle. Addressing this financial gap is imperative as roads are integral drivers of economic development.

3 Insufficient Preparations in the Initial Construction Phase

In the execution of highway engineering projects, a recurring challenge manifests as a shortage of construction materials, impeding the seamless progress of the construction endeavors. The dearth of materials often results in project delays, underscoring

the fundamental issue of inadequate preparation in the early stages of construction. This deficiency may extend to the realm of construction machinery organization, where the stringent mechanical requirements of road construction demand meticulous planning. In cases where mechanical work efficiency is compromised due to inadequate preparation, the overall project timeline becomes susceptible to disruptions. Additionally, the absence of robust emergency plans exacerbates the impact of unexpected issues, making resolution more challenging.

4 Deficiency in Project Monitoring and Management

Effective supervision of construction quality extends beyond mere preliminary assessments; it necessitates comprehensive testing throughout the entire project lifecycle. However, in the expansive domain of highway engineering construction, characterized by intricate processes and prolonged durations, maintaining rigorous quality oversight becomes a formidable task. The sheer scale and complexity may lead to complacency, with stakeholders potentially becoming lax in their commitment to meticulous project monitoring. This laxity poses a significant risk to the overall quality and safety of the project, as details may go unchecked, compromising the integrity of the construction endeavor.

4.1 Energy Consumption Challenges in Transportation

Transportation's heavy reliance on oil-derived fuels, constituting approximately 94% of final energy demand, underscores a critical challenge. Road transport, responsible for three-quarters of total transport energy consumption, witnesses a continual rise in energy demand. In Europe, the dominance of diesel fuel in road transport has increased significantly, posing sustainability issues that demand urgent alternative solutions.

Moreover, the energy consumption of highway infrastructure itself, encompassing lighting, signage, and various digital information systems, further exacerbates the energy challenge. Finding sustainable alternatives to the current fossil fuel-intensive road operations becomes imperative for long-term environmental viability.

4.2 Road Serviceability and Maintenance Challenges

Road serviceability, encompassing pavement quality, safety levels, information provision, and service stations, represents a multifaceted challenge. Meeting the expectations of drivers and travelers for high standards of road performance necessitates significant human and capital resources. This includes on-site operations, anticipation of maintenance needs, and the planning of effective engineering interventions.

Congestion and maintenance emerge as the most pressing issues according to a Eurobarometer survey, highlighting external costs borne by drivers. Mitigating congestion involves a comprehensive approach, from road widening to promoting public transport. Maintenance planning is equally crucial, affecting both industrialized and developing countries, where the growing motorway networks demand careful consideration of serviceability over national and regional scales.

4.3 Climate Change Impacts on Road Infrastructure

The vulnerability of the road sector to climate change is a pressing concern. Extreme weather events, such as tsunami waves, wildfires, floods, and hurricanes, pose significant risks to the safety, reliability, and sustainability of road transportation systems. These events not only jeopardize passengers, vehicles, and goods but also threaten the integrity of transport infrastructure.

Despite scientific advancements in risk assessment methods and engineering measures, efficient confrontation and reduction of climate threats remain elusive. National road authorities and motorway operators worldwide face the imperative to adapt infrastructure to climate change and enhance road transport resilience to extreme weather. Urgent attention, alternative measures, and adequate financial resources are essential to tackle this growing challenge effectively.

4.4 Environmental Impacts of Road Transport

The surge in demand for road transport, coupled with evolving travel preferences and advancements in transport infrastructure, has given rise to significant environmental consequences. These include air pollution, noise exposure, alterations in land use, habitat fragmentation, and adverse effects on

biodiversity and wildlife. The scientific community, particularly those monitoring climate change, is increasingly concerned about reducing greenhouse gas (GHG) emissions from the transport sector.

In Europe, transport emissions have seen an upward trend, constituting approximately one-quarter of the EU's total GHG emissions. Notably, the road transport sector has emerged as a major and rapidly expanding contributor to GHG emissions, accounting for nearly 73% of all GHG transport emissions in 2013. This concerning trajectory has prompted the implementation of alternative strategies to mitigate emissions on regional and local levels in various Western European countries.

4.5 Safety Challenges on Roads and Highways

The World Health Organization estimates that road crashes claim the lives of 1.25 million people annually, equating to almost 2,400 road fatalities per day, with up to 50 million injuries. These accidents stand as a leading cause of death among individuals aged 15–29. In response, the United Nations has adopted resolutions on road safety, including the Decade of Action for Road Safety 2011–2020, aiming for a 50% reduction in road traffic deaths and injuries by 2020.

While significant progress has been made in reducing fatalities in OECD/high-income countries over the past decade, the situation remains challenging in low-income countries. Pile-up accidents on motorways remain inadequately addressed, and projections indicate a significant global increase in road fatalities. Consequently, the challenge of road safety persists, necessitating continued efforts to enhance global safety standards.

4.6 Economic Considerations and Cost-Effectiveness in Road Transport

Road transport holds a pivotal role in short- and medium-distance travel operations, but concerns arise regarding its cost-effectiveness. The unit cost of transportation per ton × km in road transport remains comparatively high and becomes increasingly cost-ineffective as travel distance extends. The overall cost structure includes direct costs such as fuel, capital depreciation, maintenance, tolls, ferry fares, and wages, as well as external costs encompassing noise, congestion, infrastructure damages, and health and environmental issues.

Despite being an attractive option for various reasons, travel by car is often deemed expensive. Congestions, delays, and road closures can significantly escalate both direct and indirect costs. To address these challenges, road operators are leveraging innovative technologies to reduce the overall cost of travel. This not only benefits road users but also aligns with the goals of transportation agencies and contributes to environmental sustainability.

5 Highway Engineering Construction Element Management through Big Data Innovation

Effective management is pivotal to the success of highway engineering projects, and the integration of big data technology offers groundbreaking opportunities for innovation across various facets of construction. Here, we delve into three key areas of management innovation in the realm of highway engineering, leveraging the power of big data.

5.1 Innovative Management of Construction Personnel:

Construction personnel constitute the backbone of any project, with their attitudes and enthusiasm directly influencing the quality of engineering construction. Drawing on insights from engineering psychology, the management of construction personnel can be redefined through big data technology. By establishing a comprehensive information system using databases, project managers gain real-time access to the details of every individual involved in the construction process. This data-driven approach enhances innovation in personnel management, fostering a more efficient and engaged workforce.

5.2 Innovative Management of Construction Materials:

The sheer diversity and volume of construction materials in highway engineering projects present a significant management challenge. Traditional methods relying on manual warehouse management are often inefficient and prone to inaccuracies. Big data technology comes to the forefront by creating information databases for warehouse materials. This digital solution allows warehouse management personnel to intuitively monitor material surplus and usage through computer interfaces, ensuring a more streamlined and accurate approach to material management.

5.3 Innovative Management of Construction Equipment:

Efficient management of construction equipment is indispensable to the overall success, efficiency, and quality of highway engineering projects. Leveraging the capabilities of big data, a sophisticated leasing system for construction equipment can be established. This system goes beyond conventional approaches by assigning specialists to oversee the maintenance and usage of mechanical equipment. Through real-time monitoring and supervision, this innovative management approach ensures optimal utilization of construction machinery, contributing to enhanced project outcomes.

In essence, the infusion of big data technology into the management of construction personnel, materials, and equipment marks a transformative shift in highway engineering. These innovations not only improve operational efficiency but also contribute to the overall success and sustainability of modern construction projects. As technology continues to advance, the highway engineering landscape stands to benefit from continued exploration and integration of cutting-edge solutions.

6 Innovation strategy of Highway Construction Projects through Big Data

6.1 Transformative Oversight of Construction Technology

Construction technology serves as the cornerstone of highway engineering projects. To enhance the innovative management of construction technology, a targeted focus on key processes is essential. Big data technology encompasses various aspects of highway construction, including drawing and simulation technologies. By leveraging computer-based big data, we can replace manual drawing processes with more efficient engineering drawings, fostering technological innovation management.

6.2 Implementation of a Construction Period Control System

The construction period is a critical factor influencing the economic outcomes of a project. Establishing a database-driven construction period control system allows for effective management. By making the standard completion time of the construction unit the primary objective, a scientific analysis and preparation of the construction period network diagram can be achieved. This represents an innovative application of big data in project management.

6.3 Innovative Safety Management in Construction

Emphasizing safety awareness is paramount in construction projects. Leveraging network courses based on big data facilitates the management of employee safety awareness, enhancing the overall quality of staff. Additionally, big data can be employed to establish a predictive system for safety accidents. This system, based on different parameters, aids enterprises in anticipating safety incidents, enabling the formulation of tailored emergency plans. Integrating full-time safety officers at construction sites, utilizing GPS systems for dynamic tracking and inspection, further enhances safety measures.

6.4 Establishment of a Robust Quality Management System

Developing a comprehensive quality index control system is pivotal for guiding the seamless progress of construction. In the modern era of highway engineering, the significance of the index control system in the development process is increasingly apparent. The construction process of the index control system, rooted in big data, involves data collection, computer-based data arrangement and analysis, information review, and the formulation of control indices based on a comprehensive database.

7 Other Responses and remedies

7.1 Strategies for Managing Unsolicited Project Proposals and Value Engineering

During periods of limited public resources, public authorities often seek project proposals through the Public-Private Partnership (PPP) modality. Proposals submitted in response to official invitations are termed solicited proposals. However, private entities may also proactively submit proposals without prior requests from public authorities, referred to as unsolicited project proposals. While some countries have successfully implemented unsolicited PPP projects, others refrain due to ethical concerns, particularly regarding risks related to competition and transparency (United Nations Economic and Social Commission for Asia and the Pacific (ESCAP), 2008).

These unsolicited proposals often bring forward innovative project ideas. The challenge lies in striking the right balance between encouraging private companies to present groundbreaking ideas and

maintaining the transparency and efficiency inherent in a competitive tender process. Recognizing the potential merits of unsolicited proposals, some governments have developed systems to transform them into competitively tendered projects, with proponents receiving bonus points in the bidding process (ESCAP, 2008).

Value engineering emerges as another innovative concept for tendering authorities to consider. This approach aims to maximize the performance-to-cost ratio of a project or asset by either enhancing performance or reducing costs (Marinelli et al., 2018). While resembling a cost-benefit analysis, value engineering goes beyond by actively seeking non-obvious, alternative, and cost-effective solutions to fully exploit the asset's value.

In the context of urban or peri-urban road infrastructure, the challenge of increasing road capacity due to high traffic volume is a common concern. Given the location between an urbanized area and a forestry zone, traditional widening is practically impossible. The initial proposal was to construct a costly 2×2 motorway in a new alignment and tunnel section. However, through an innovative approach, a cross-cantilever bridge (Figure 2) emerged as an equally operational solution at only 25% of the cost of the tunnel option, with a shorter construction time. This "think different" strategy showcases the potential of value engineering in delivering cost-effective and efficient solutions to complex infrastructure challenges.

7.2 Promoting Energy-Efficient Transportation: The Energy-Harvesting Road

Energy-efficient transportation requires a multifaceted approach targeting system efficiency, travel efficiency, and vehicle efficiency. Strategies to enhance energy efficiency in transport encompass avoiding increased transport activities, shifting demand to more efficient transport modes, and improving vehicles and fuels (Boehler-Baedeker and Hueging, 2012).

Highways and associated infrastructure, traditionally seen as consumers of energy, also present an untapped potential for energy production. The area directly linked to highways, within their ownership, holds promise for energy generation. Technologies such as thermal collection, photovoltaic collection, wind microgeneration, and LED lighting solutions are explored to harness energy from the highway context, as outlined in the PIARC Report 2014 (World Road Association, 2014). However, it's noteworthy that these technologies are still in the experimental stage.

At Aristotle University of Thessaloniki, ongoing research focuses on triboelectric energy generation. Laboratory tests involving asphalt surfaces and electrical conductors demonstrate the potential for low-intensity electric current production through the interaction of rolling wheels on asphalt (Barkas et al., 2019). The objective is to design an assembly for installation on urban road network pavements, creating energy and charging nearby street lighting.

7.3 Integrating Recycled Materials in Pavement Construction

The integration of recycled materials in pavement construction emerges as a sustainable practice with environmental, engineering, and economic implications. Recognizing the need to boost the

highway industry's use of recycled materials, the Federal Highway Administration (FHWA) emphasizes factors such as cost savings, life-cycle cost, and engineering performance, reduction in landfill, and environmental stewardship (FHWA, 2002).

Various recycled materials, including fly ash, steel slag, glass, rubber tires, and demolition waste, are employed in pavement construction. While exhibiting satisfactory performance, challenges such as pre-processing requirements and transport costs persist. Ongoing research at Aristotle University explores the reutilization of industrial by-products like fly ash, steel slag, and bauxite residue, showcasing promising results in pilot and real construction projects (Mouratidis and Pernientaki, 2018). These materials find application in semi-rigid pavements and anti-skid asphalt layers, contributing to sustainable road construction practices.

7.4 Climate-Change Adaptation Strategies for Road Infrastructure

Adapting road infrastructure to climate change remains a persistent challenge, with various measures implemented to protect against extreme weather events. Despite progress, severe wildfires, floods, and heavy snowfall continue to pose threats, highlighting the need for continued research and commitment (World Road Association, 2016b).

Figure – 3 Delhi Mumbai expressway wildlife crossings.

A distinctive approach developed at Aristotle University proposes alternative engineering actions, emphasizing the restoration of the initial balance on a broader contextual scale of road links. This includes realistic solutions, value engineering measures, emergency service preparedness, and the use of new technologies for forecasting and anticipating risks. Despite occasional challenges, this approach aims to provide powerful and effective weapons against climate threats.

7.5 A Low-Carbon and Sustainable Road Infrastructure: The Green Highway

Understanding the relationships between the physical environment and road activities is essential for sustainable road transport planning. Aristotle University's research introduces a holistic "Smart Highway" model, applicable to 2-lane roads and motorways, aiming to reduce energy needs, road accidents, and interventions using low-cost techniques. The model focuses on energy consumption, road safety, serviceability, geotechnics, and environmental aspects, incorporating features such as auto-fluorescent markings, auto-dimming lighting, solar islands, rumble strips, asphalt anti-icing additives, and perpetual asphalt pavements.

7.6 Real-Time Safety Management System

Innovative applications of digital technology, such as real-time safety condition assessment and warning systems, play a crucial role in enhancing road safety. These systems receive and process real-time images of traffic conditions to evaluate accident risk, providing timely warnings to drivers through variable message signs or in-vehicle displays (connected vehicles) (Oh, 2007).

The Laboratory of Highway Engineering at AUTH has identified ten major criteria of accident risk to be introduced into a safety management software. These criteria include factors such as excessive speed, headway vs. speed/tailgating, critical merging conditions, deceleration ahead, border or off-lane

driving, inconsiderate driving, ghost vehicles, adverse weather conditions, low visibility, and extreme weather events. The application of these systems proves beneficial in congested motorways and areas prone to accidents.

7.7 Transition to Infrastructure and Logistics for Electric Vehicles

The growing interest in electric vehicles (EVs) prompts considerations for road transport infrastructure to accommodate this technological shift. The economic impact of EVs, in addition to their environmental benefits, is a critical aspect to evaluate. Operating costs for plug-in electric vehicles (PEVs) are expected to remain lower and less volatile than fuel costs for conventional vehicles, contributing to the economic feasibility of EV adoption.

The transition to EV-friendly road infrastructure hinges on advancements in vehicle autonomy and cost within the automotive industry. The provision of electric power generated by renewable sources and the gradual reduction or abandonment of fossil fuels pose challenges that require ongoing research and commitment.

In conclusion, these strategies and initiatives collectively contribute to a more sustainable and efficient road infrastructure, addressing challenges from energy consumption to climate change adaptation and fostering the integration of innovative technologies.

8 Conclusion

In conclusion, the integration of big data technology into highway construction projects presents a transformative shift in innovation management, addressing critical facets such as construction technology, project timelines, safety, and quality. The emphasis on leveraging big data for drawing and simulation technologies underscores a departure from manual processes, ushering in a new era of efficiency and precision in construction.

The establishment of a construction period control system, driven by a comprehensive database, marks a strategic approach to optimize project timelines, directly impacting economic outcomes. This innovation in project management signifies a departure from traditional methods, allowing for the scientific analysis and preparation of construction period network diagrams.

Safety management emerges as a paramount concern, with big data facilitating safety awareness programs and predicting safety accidents. The proposed systems not only enhance personnel safety awareness but also empower enterprises to anticipate and address safety incidents proactively. The incorporation of full-time safety officers and dynamic tracking through GPS systems further solidifies safety measures.

The study also underscores the importance of a robust quality management system, driven by big data. This comprehensive system, encompassing data collection, analysis, information review, and control index formulation, ensures that construction projects adhere to stringent quality standards, guiding their smooth progression.

As the construction industry navigates the demands of modernization, economic globalization, and increasing vehicular traffic, the adoption of big data technology emerges as a crucial strategy. By embracing innovation in construction technology, project timelines, safety, and quality management, highway construction projects can not only meet current technical quality indicators but also pave the way for sustainable, efficient, and safe infrastructure development. The study advocates for the widespread adoption of big data in the construction landscape, heralding a new era of advancements in highway engineering projects.

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