

The Role of Big Data Analytics in Transportation Planning and Infrastructure Development: A Data-Driven Approach to Enhance Urban Mobility and Sustainable Infrastructure Design

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Abstract

Big Data Analytics is transforming how modern transportation systems are conceived, managed, and developed. In the age of rapid urbanization and increasing transportation demand, the integration of data analytics offers a powerful means to optimize planning, reduce congestion, predict travel behavior, and improve infrastructure investment decisions. This paper explores the vital role Big Data Analytics plays in the planning and development of transportation infrastructure. It outlines how data from various sources—such as GPS, mobile applications, traffic sensors, and social media—can be collected, processed, and utilized to support real-time and long-term decision-making. The study also delves into the challenges of data privacy, quality, and integration, while highlighting opportunities for smarter, more sustainable transport ecosystems. The future of transportation lies in data-driven planning, and this paper advocates for its essential adoption by urban planners, policymakers, and engineers alike.

Keywords: *Big Data Analytics, Transportation Planning, Infrastructure Development, Smart Mobility, Urban Transport Systems*

LITERATURE REVIEW

Evolution of Data-Driven Transport Planning

Transportation planning has historically relied on static models and manual data collection methods such as surveys, traffic counts, and the analysis of census data. While these approaches offered valuable insights into general traffic patterns and infrastructure needs, they were often limited by their inability to respond quickly to changes in traffic flow, travel demand, and other dynamic factors. These traditional methods were also constrained by the infrequency of data collection, meaning that transportation planners lacked real-time adaptability and flexibility.

The advent of digital technologies has facilitated a shift towards data-driven transport planning. The increasing availability of real-time data streams, coupled with advanced analytics tools, has allowed planners to move away from one-size-fits-all solutions and embrace dynamic, adaptive models. For instance, real-time traffic monitoring systems can now adjust traffic signal timings based on actual congestion levels, ensuring more efficient traffic flow. Similarly, urban planners can now utilize Big Data to optimize route planning for public transport systems, taking into account fluctuating demand patterns that were previously impossible to forecast using traditional methods.

Moreover, recent literature emphasizes the importance of real-time adaptability in transport planning. For example, systems that leverage predictive analytics can forecast traffic patterns, detect congestion, and even predict infrastructure wear and tear. This forward-thinking approach is key to transforming urban mobility systems from reactive to proactive, enabling cities to address transportation challenges before they escalate.

Key Studies and Applications

The application of Big Data Analytics in transportation has been demonstrated in several key studies and urban settings, showcasing its capacity to revolutionize the way cities manage traffic and transportation infrastructure. For example, in Singapore, the Land Transport Authority uses Big Data analytics to optimize traffic flows. By analyzing data collected from

vehicles, traffic signals, and road sensors, the system dynamically adjusts signal timings to minimize congestion and improve travel efficiency. Similarly, London has integrated Big Data to enhance its public transport system, using live data from buses and trains to adjust routes and schedules based on current passenger demand.

In addition to urban traffic management, Big Data has been applied in several other areas of transportation planning. For instance, data collected from GPS devices is now being used to model commuter behavior with remarkable precision. This allows cities to predict traffic volumes, estimate travel times, and plan for infrastructure needs with greater accuracy. Another critical application is in the optimization of bus routes. By analyzing passenger data from ticketing systems, planners can make data-driven decisions to improve the efficiency and coverage of bus services, especially during peak hours or in underserved areas.

In rail systems, predictive maintenance powered by Big Data analytics has become an essential tool for minimizing downtime and maximizing operational efficiency. Data from sensors embedded in trains and along the tracks allows operators to identify potential issues before they result in costly disruptions. Similarly, Big Data analytics can be used to assess the environmental impacts of transportation systems, from the carbon footprint of road networks to the noise and air pollution levels associated with specific transport modes.

Integration with Smart Cities Initiatives

The integration of Big Data with smart city initiatives has become an important focus of urban development. Smart cities leverage data and technology to improve urban infrastructure and enhance the quality of life for residents. Transportation systems are a central component of smart city planning, with Big Data serving as the backbone for system integration, real-time monitoring, and policy formulation.

Research highlights how Big Data can play a pivotal role in the development of sustainable urban mobility systems. Data-driven insights can be used to promote energy-efficient transportation modes, reduce congestion, and improve air quality by encouraging the use of cleaner modes of transport such as electric vehicles (EVs) and bicycles. Smart transportation systems that integrate data from various sources—such as sensors, GPS, and ticketing systems—create a comprehensive view of urban mobility, enabling more efficient planning,

management, and decision-making. Furthermore, the use of real-time data helps cities respond more rapidly to disruptions or emergencies, improving the resilience of urban transport networks.

This growing synergy between Big Data and smart city initiatives underscores the importance of a holistic, data-driven approach to urban planning. As cities continue to embrace technology, Big Data will remain a cornerstone of the push towards more sustainable, efficient, and people-centric transportation systems.

BIG DATA SOURCES IN TRANSPORTATION

Sensor-Based Data

One of the most valuable sources of Big Data in transportation comes from the growing deployment of sensors embedded in various aspects of the transportation network. These sensors are installed in roads, vehicles, traffic signals, and other infrastructure, capturing a wide range of data about traffic flow, vehicle speed, congestion patterns, and overall system performance.

Traffic sensors, for example, can measure vehicle counts at intersections or along highways, enabling transportation authorities to analyze traffic patterns, identify bottlenecks, and optimize signal timings. These data streams can also inform predictive models that forecast traffic conditions in real time, improving the efficiency of urban mobility systems. Moreover, sensor-based data can provide insights into air quality, noise levels, and other environmental factors, allowing planners to assess the broader impacts of transportation networks on the surrounding environment.

The use of sensors in transportation networks is continually expanding, with advancements such as inductive loop sensors, infrared sensors, and cameras enabling increasingly sophisticated data collection. These sensors help create a granular, real-time picture of the transportation system, allowing authorities to manage and adjust traffic flows instantaneously.

Mobile and GPS Data

Mobile phones and GPS-enabled devices have become integral to the collection of real-time location-based data in transportation systems. Smartphones, equipped with GPS and other

sensors, provide an invaluable data source for tracking travel behavior, commuter preferences, and traffic conditions. For example, ride-hailing apps such as Uber and Lyft collect vast amounts of data on travel times, routes, and passenger demand. This data can be analyzed to identify trends in commuter behavior, peak travel times, and areas with high demand for ride-sharing services.

In addition to private transportation, GPS data is crucial for managing public transit systems. Public transportation agencies can use GPS data to track buses, trains, and other vehicles in real time, enabling passengers to receive accurate information on arrival times, delays, and service disruptions. The real-time nature of this data also allows for the dynamic adjustment of transit routes and schedules to accommodate fluctuations in demand, improving service efficiency and reducing wait times.

Social Media and Crowd sourced Data

Social media platforms such as Twitter, Facebook, and Reddit, along with dedicated apps like Waze, provide real-time crowd sourced data that can help transportation planners understand public sentiment, identify traffic disruptions, and gain insights into users' mobility patterns. For instance, Waze allows users to report accidents, road closures, and other incidents, offering immediate data that can be used to adjust traffic management strategies.

Crowd sourced data from social media can also provide valuable insights into how people are experiencing transportation systems. Planners can analyze social media feeds to identify recurring issues such as traffic congestion, safety concerns, or delays. Public sentiment often reflected in real-time posts and discussions, can help policymakers prioritize improvements that directly address the needs of the community.

Public Transit and Ticketing Systems

Another significant source of Big Data in transportation comes from electronic ticketing systems used in public transit networks. These systems capture detailed information about passenger loads, fare collection, and peak usage times. By analyzing ticketing data, planners can optimize bus routes, adjust schedules, and improve service delivery during high-demand periods. Furthermore, this data can help transportation authorities plan for capacity needs in

the future, ensuring that infrastructure and services are adequately scaled to meet growing demand.

Electronic ticketing data can also be integrated with mobile apps and smart card systems to enable seamless multimodal transport. This integration allows passengers to switch between different modes of transportation, such as buses, trains, and bicycles, with ease, creating a more efficient and interconnected urban mobility system.

Table 1: Common Data Sources for Transportation Analytic

Data Source	Description	Example Applications
Sensor-Based Data	Data from embedded traffic sensors, vehicle detection systems, etc.	Traffic flow, congestion analysis
Mobile and GPS Data	Location data from smartphones and GPS devices.	Route planning, real-time traffic updates
Social Media Data	Crowdsourced data from platforms like Twitter or Waze.	Incident detection, public sentiment analysis
Public Transit Data	Data from ticketing systems and transit apps.	Public transport optimization, demand forecasting

APPLICATIONS OF BIG DATA ANALYTICS IN TRANSPORTATION PLANNING

Traffic Flow Optimization

Traffic congestion remains one of the most significant challenges for urban mobility systems, contributing to inefficiencies, increased pollution, and a diminished quality of life for residents. Big Data analytics plays a crucial role in addressing this issue by providing real-time insights into traffic conditions, enabling cities to optimize traffic flow.

Using data from sensors embedded in roads, GPS devices, and mobile apps, traffic management systems can identify congestion hotspots, analyze traffic patterns, and predict future traffic flows. Predictive models can determine where traffic bottlenecks are likely to occur, helping traffic authorities adjust signal timings, ramp metering, and lane allocations.

For example, smart traffic lights can automatically adjust the duration of green and red lights based on the flow of traffic, reducing delays and improving vehicle throughput. Furthermore, Big Data can suggest alternate routes for drivers via navigation apps, alleviating congestion in overburdened areas.

In cities like Los Angeles and New York, real-time data analytics are already used to adjust traffic light patterns dynamically to smooth congestion and optimize vehicle movement. This has been particularly effective in reducing the time spent in traffic, thereby improving the efficiency of transportation networks.

Demand Forecasting

Predicting transportation demand is an essential aspect of infrastructure planning, as it allows authorities to allocate resources effectively and ensure that transportation systems can handle peak periods or unexpected surges in demand. Big Data analytics plays a crucial role in demand forecasting by analyzing historical travel data, time-of-day patterns, and external factors such as weather conditions, public holidays, and special events.

Predictive analytics can forecast fluctuations in transportation demand with remarkable accuracy, allowing cities to proactively adjust capacity and improve service delivery. For instance, during major sporting events or festivals, Big Data can predict the increase in passenger numbers and suggest adjustments to public transport schedules, such as adding extra buses or trains to meet demand. Similarly, data analytics can help manage congestion during rush hours by providing real-time traffic information and suggesting alternate routes to divert traffic away from busy roads.

Advanced machine learning models can also analyze past travel data to identify underlying trends in commuting behavior. This enables transportation agencies to forecast future demand for different transportation modes—whether it be cars, buses, trains, or bicycles—ensuring that resources are appropriately distributed.

Infrastructure Investment Planning

One of the most significant challenges in transportation planning is making long-term investments in infrastructure while ensuring that these investments are aligned with future

needs. Big Data can provide valuable insights to help optimize infrastructure planning by predicting future congestion hotspots, growth areas, and areas of high demand.

Data-driven simulations allow planners to model the potential impact of new roads, bridges, or transit systems on existing infrastructure. By analyzing real-time traffic and mobility data, planners can identify the specific regions that are most likely to experience congestion in the coming years. This helps prioritize which projects should be undertaken first to ensure maximum benefit.

For example, data from mobile GPS and traffic sensors can identify locations where traffic bottlenecks or crashes frequently occur. By analyzing these areas, planners can design targeted infrastructure projects, such as widening roads, building new intersections, or enhancing public transport networks. This predictive approach not only minimizes disruptions but also optimizes return on investment (ROI) by focusing on the areas that will benefit most from enhancements.

Additionally, the combination of data analytics and geographical information systems (GIS) allows for the creation of highly detailed models of transportation networks, which helps decision-makers visualize and plan infrastructure improvements with greater precision.

Public Transport Optimization

Big Data analytics has had a transformative impact on public transportation systems, enabling them to operate more efficiently, predict demand, and offer improved service reliability. By analyzing real-time and historical data from ticketing systems, GPS trackers on vehicles, and social media platforms, transit agencies can gain deeper insights into passenger behavior, travel patterns, and service gaps.

For example, historical data on bus or train ridership can be used to identify which routes are underperforming and which ones experience high demand during specific times of the day. This allows agencies to make data-driven decisions about adjusting routes, increasing the frequency of services, or providing additional buses during peak hours. Additionally, the real-time monitoring of transit vehicles provides the ability to reroute or reschedule services based on current conditions, ensuring that passengers experience minimal delays and congestion.

Public transport systems can also use predictive analytics to assess future demand. For example, if an event or surge in passenger numbers is anticipated, such as during holidays or concerts, Big Data can help plan ahead by adjusting schedules and dispatching extra vehicles to meet this demand.

Big Data is also helping to improve customer satisfaction. By collecting data from mobile apps, social media, and feedback platforms, transit agencies can identify customer pain points, such as overcrowding, delays, or poor service quality, and address these issues in a timely manner.

Sustainable Mobility Planning

The growing emphasis on sustainability in transportation planning is a key driver for the adoption of Big Data analytics. Environmental concerns, such as greenhouse gas emissions, air pollution, and traffic congestion, have made it essential for cities to prioritize sustainable mobility solutions. Big Data can aid in this effort by providing insights into emissions levels, evaluating the environmental impact of transportation systems, and promoting eco-friendly transport modes.

Data from environmental sensors placed along roadways and in urban centers can measure air quality, noise pollution, and traffic emissions in real time. This information is invaluable for urban planners and policymakers, enabling them to assess the environmental impact of different transportation modes and identify areas where improvements are needed.

Big Data also plays a crucial role in promoting the use of low-carbon transportation options such as cycling, walking, and electric vehicles (EVs). By analyzing transport usage data, planners can identify areas where cycling and walking infrastructure can be expanded to encourage active transport. Similarly, data from EV charging stations can provide valuable insights into the adoption and usage patterns of electric vehicles, enabling cities to optimize the placement of charging stations and encourage wider adoption.

Additionally, Big Data can be used to evaluate the overall sustainability of a city's transportation network, including the efficiency of public transit systems, the use of alternative fuels, and the effectiveness of car-sharing programs. By identifying trends and

gaps in the system, cities can make more informed decisions on investments in sustainable infrastructure, such as electric buses, bike lanes, and green corridors.

Table 2: Key Applications of Big Data in Transportation

Application	Description	Impact
Traffic Flow Optimization	Real-time monitoring and adjustments to reduce congestion.	Reduced travel times, improved traffic efficiency
Demand Forecasting	Predicting future travel needs based on data trends.	Better allocation of resources, reduced overcrowding
Public Transit Optimization	Enhancing routes and schedules using real-time data.	Improved service reliability, reduced wait times
Sustainable Mobility Planning	Using data to promote environmentally friendly transport modes.	Reduction in carbon emissions, increased adoption of green transport

CHALLENGES IN IMPLEMENTATION

Data Privacy and Ethical Concerns

One of the most pressing challenges in implementing Big Data Analytics in transportation is the protection of personal data. As transportation systems become increasingly data-driven, vast amounts of personal information are collected from individuals, including their travel routes, preferences, and behaviors. This data, often derived from GPS devices, mobile apps, and public transit systems, can reveal sensitive information about individuals' daily routines and habits.

Ensuring that this data is anonymized and used in compliance with privacy regulations, such as the General Data Protection Regulation (GDPR) in Europe, is critical. Transportation authorities must prioritize the ethical collection, storage, and sharing of data to maintain public trust. Public awareness campaigns about how data is collected and used can also help mitigate concerns. Furthermore, stringent data protection protocols must be established to prevent unauthorized access and misuse of personal data.

Another challenge is determining who owns the data and how it can be shared or sold. The issue of data ownership can create tension between private companies, government agencies, and the public, all of whom may have different interests in using this data.

Data Quality and Standardization

To fully harness the power of Big Data in transportation planning, the data being collected must be consistent, accurate, and standardized across all agencies. However, inconsistent formats, missing or incomplete data, and a lack of universal standards for data collection and reporting can severely hinder the reliability and effectiveness of analytics outcomes.

For example, data from GPS devices might be recorded in different formats by various transportation providers, and public transit data may be recorded in ways that are not compatible with road traffic data. Without standardization, combining and analyzing data from multiple sources becomes a difficult task. Inconsistent data can lead to flawed insights and, ultimately, poor decision-making.

To address this challenge, governments and agencies must collaborate on establishing common standards for data collection and sharing. Creating uniform data protocols will ensure that data can be integrated seamlessly and analyzed effectively, improving the accuracy of predictive models and decision-making.

Technical Infrastructure

Big Data analytics requires significant technical infrastructure to be effective. This includes robust data storage systems, fast processing capabilities, and high-speed communication networks that can handle the vast quantities of data being generated in real-time. For developed regions, these technical requirements may already be met, but for many developing countries or regions, these resources are often insufficient.

The lack of adequate infrastructure can present a significant barrier to the implementation of Big Data solutions. Without access to high-quality sensors, cloud computing services, or sufficient network bandwidth, cities may struggle to deploy and utilize data-driven transportation systems. Developing regions may also face challenges in ensuring equitable access to this technology.

To overcome this challenge, investments in digital infrastructure must be prioritized. Governments, in collaboration with the private sector, can play a pivotal role in improving access to modern technology and data storage solutions, particularly in areas with limited resources.

Skilled Workforce Shortage

The effective use of Big Data in transportation planning requires a multidisciplinary workforce with expertise in data science, machine learning, urban planning, and transportation engineering. These skill sets are not always readily available within public sector institutions or local governments, where resources are often stretched thin.

A shortage of skilled professionals can slow the implementation of Big Data analytics in transportation systems, as agencies may struggle to recruit or train the necessary workforce. Additionally, the complexity of analyzing large datasets and applying machine learning algorithms requires a deep understanding of both the data and the broader transportation context.

To address this challenge, governments and educational institutions must invest in training programs that equip professionals with the skills needed to work with Big Data in the context of transportation. Partnerships with private companies and international organizations can help bring expertise to areas with workforce gaps.

SCOPE FOR FUTURE DEVELOPMENT

Integration with AI and IoT

The future of transportation planning is deeply intertwined with the integration of Big Data, Artificial Intelligence (AI), and the Internet of Things (IoT). The combination of these technologies can lead to revolutionary advancements in urban mobility. AI, for example, can be used to analyze massive datasets and make real-time decisions, such as dynamically adjusting traffic lights based on current traffic conditions or rerouting vehicles in response to accidents or congestion.

IoT devices, such as sensors embedded in vehicles, traffic infrastructure, and public transport, can provide real-time data streams that are essential for monitoring and managing traffic flow.

These devices can also collect data on road conditions, weather, and even vehicle health, enabling predictive maintenance for transportation infrastructure.

This convergence will also enable the development of autonomous transportation systems. Self-driving cars, buses, and trucks will rely heavily on Big Data and AI for navigation, safety, and efficiency. As these systems become more widespread, the ability to analyze vast amounts of data in real-time will be crucial to their success.

Policy and Governance Models

As Big Data continues to reshape transportation planning, governments must develop frameworks that support data-driven decision-making while ensuring ethical standards and public trust. Policymakers will need to establish guidelines for data sharing, privacy, and transparency to maintain a balance between innovation and public interest.

Governments can play a critical role by creating open data initiatives, where transportation data is made publicly available for developers, researchers, and citizens to access. However, these efforts must be accompanied by clear data governance models that define who has access to the data, how it can be used, and how privacy is protected.

Moreover, international collaboration will be essential to create common data standards, enabling seamless integration of transportation systems across borders. This is particularly important in regions where transportation networks span multiple countries, as seen in cross-border transportation systems in Europe and North America.

Resilience and Disaster Management

The ability to respond to natural disasters, emergencies, or other disruptions in transportation systems is crucial for urban resilience. Big Data can significantly enhance disaster management strategies by providing real-time situational awareness. For example, during extreme weather events or natural disasters, transportation agencies can use Big Data to track the movement of people, assess the condition of infrastructure, and deploy resources where they are most needed.

Big Data can also be used to model evacuation scenarios, predict the flow of people during disasters, and optimize the allocation of emergency services. As cities face increasing risks from climate change, having robust, data-driven disaster management systems will be critical to ensuring the safety and well-being of residents.

Behavioral Modeling and Equity Analysis

A growing focus in urban transportation planning is ensuring that systems are equitable and accessible to all demographics. Big Data analytics can be used to uncover disparities in access to transportation services, identifying underserved areas and communities. This data can also reveal the impact of transportation policies on different groups, such as low-income households, the elderly, and people with disabilities.

Advanced behavioral models can simulate how different groups of people interact with transportation systems and predict how changes to the system (such as the introduction of new services or fare structures) will affect various populations. These insights can guide policy decisions that promote inclusive mobility and address social inequities.

CASE STUDIES OF SUCCESSFUL IMPLEMENTATION

Singapore's Intelligent Transport System

Singapore is a global leader in adopting Big Data for transportation planning. The Land Transport Authority (LTA) uses a sophisticated system that integrates data from GPS trackers, traffic cameras, and road sensors to manage real-time traffic conditions. The system not only helps alleviate congestion but also supports long-term infrastructure planning by providing insights into traffic patterns, future demand, and areas of congestion.

In addition to managing traffic, the system is used to optimize public transportation networks. For example, it adjusts bus schedules based on real-time demand, improving service reliability. The success of Singapore's system highlights the potential of Big Data in managing urban mobility at scale.

Los Angeles Mobility Data Specification (MDS)

The City of Los Angeles implemented the Mobility Data Specification (MDS), a framework for managing shared mobility services such as scooters and bikes. Using MDS, the city

collects data from service providers to monitor usage patterns, compliance with regulations, and the spatial distribution of vehicles. This data helps city officials make informed decisions on where to deploy vehicles, how to manage parking spaces, and how to improve the overall infrastructure for shared mobility.

London's Oyster Card System

London's Oyster Card system has revolutionized the way public transportation data is collected and used. By analyzing data from millions of card transactions, Transport for London (TfL) can monitor passenger trends, optimize route planning, and improve service scheduling. The data allows TfL to respond quickly to fluctuations in demand, adjust schedules during peak times, and plan for future growth in the transportation network.

CONCLUSION

Big Data Analytics is no longer a futuristic concept but an essential tool in the modern transportation planning toolkit. It provides valuable insights that enable cities to shift from reactive to proactive transportation planning, offering solutions that are more responsive, efficient, and sustainable. The challenges of data privacy, standardization, and infrastructure development remain, but they are surmountable through collaboration, innovation, and investment.

As cities continue to grow and mobility demands evolve, Big Data will play an increasingly central role in creating transportation systems that are equitable, efficient, and environmentally friendly. By integrating AI, IoT, and Big Data, we can build smarter cities and more resilient transportation infrastructures that are ready to meet the challenges of the 21st century.

With careful planning, the development of robust policy frameworks, and a commitment to data-driven decision-making, Big Data will be the cornerstone of urban mobility for future generations.

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