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Machine Learning in Transportation

Matthew N. O. Sadiku[1], Matthias Oteniya[2], Janet O. Sadiku[3]

[1,2]Roy G. Perry College of Engineering, Prairie View A&M University, Prairie View, TX, USA
[3]Juliana King University, Houston, TX, USA

ABSTRACT

To efficiently develop a sustainable transportation system, various countries are turning to emerging technologies like artificial intelligence (AI) and machine learning (ML) which have proved effective in various countries globally. They are integrating AI and ML technologies in transportation, giving a pivotal moment in the evolution of mobility systems. These technologies have not only redefined traditional approaches to managing traffic, optimizing routes, and enhancing safety but have also laid the foundation for entirely new paradigms, such as autonomous vehicles and smart cities. Researchers actively leverage approaches for AI/ML to transform America's transportation and energy systems, by addressing complex problems like congestion, energy efficiency, emergency response planning, and safety. The primary objective of this paper is to highlight the impact of machine learning on transportation.

KEYWORDS: *machine learning, artificial intelligence, deep learning, transportation, autonomous vehicles.*

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INTRODUCTION

Transportation systems are the backbone of modern society, facilitating the movement of people, goods, and services across vast urban and rural landscapes. Big cities in various countries across the globe are facing challenges of traffic, congestion, and transportation. As the human population is increasing, the number of vehicles on the road is not going to reduce anytime soon. Traffic congestion remains one of the most pressing problems faced by metropolitan areas worldwide. The surge in vehicle ownership, coupled with inadequate infrastructure in many regions, has led to widespread issues such as traffic congestion, inefficient resource utilization, heightened greenhouse gas emissions, and compromised safety [1].

Many industries, including transportation, are turning to artificial intelligence (AI) and machine learning (ML) to solve and prevent challenges. Transportation is becoming increasingly connected and data-rich, providing a robust foundation for AI and ML solutions. Artificial intelligence (AI) is revolutionizing every walk of life, allowing machines to learn from experience, adapt, and perform tasks that have historically required human cognition. Machine learning (ML), a sub-field of AI, uses data to improve performance with experience. Machine learning has enormous advantages for both the transportation industry and transportation engineering. Since machine learning anticipates data on real-time traffic, intricate data on roads, highways, accidents, weather, etc., the transportation sector benefits immensely from it.

WHAT IS MACHINE LEARNING?

Machine learning is a subfield of artificial intelligence that uses algorithms trained on data sets to create models capable of performing tasks that would otherwise only be possible for humans, such as categorizing images, analyzing data, or predicting price fluctuations. It uses algorithms (essentially lists of rules) trained on data sets to create self-learning models capable of predicting outcomes and classifying information without human intervention. It focuses on algorithms that can "learn" the patterns of training data and, subsequently, make accurate inferences about new data. This pattern recognition ability enables machine learning models to make decisions or predictions without explicit, hard-coded instructions. To ensure such algorithms work effectively, however, they must typically be refined many times until they accumulate a comprehensive list of instructions that allow them to function correctly [2]. A symbol of machine learning is shown in Figure 1 [3].

Generally speaking, a learning problem considers a set of samples of data and then tries to predict properties of unknown data. ML builds heavily on statistics because when we train a machine to learn, we have to give it a statistically significant random sample as training data. Intelligent machines are increasing doing incredible things: Facebook recognizes faces in photos, Siri understands voices, and Google translates websites [4].

Machine learning techniques are transforming many fields including computer science, engineering, mathematics, physics, neuroscience, and cognitive science. We are surrounded by ML-based technologies: search engines learn how to bring us the best results, digital cameras learn to detect faces, credit card transactions are secured by a software that detects frauds, and cars are equipped with accident prevention systems that are built using ML algorithms [5]. In ML, data plays an indispensable role, and the learning algorithm is used to learn from the data. ML algorithms are now easy to use. One can download packages in Python. Programming languages used in ML include C++, Java, Python.

As its name indicates, machine learning works by creating computer-based statistical models that are refined for a given purpose by evaluating training data, rather than by the classical approach where programmers develop a static algorithm that attempts to solve a problem. Because the algorithm adjusts as it evaluates training data, the process of exposure and calculation around new data trains the algorithm to become better at what it does. Algorithms are the computational part of a machine learning project. Once trained, algorithms produce models with a statistical probability of answering a question or achieving a goal. Unlike in expert systems, the logic by which a machine learning model operates is not explicitly programmed; it is learned through experience. Machine learning has come to dominate the field of AI: it provides the backbone of most modern AI systems, from forecasting models to autonomous vehicles to large language models (LLMs) and other generative AI tools. Machine learning has become a household term in recent years as the concept moved from science fiction to a key driver of how businesses and organizations process information [6].

As shown in Figure 2 [7], there are different types of machine learning. The four major types of machine learning are supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning, each suited to different kinds of data and outcomes. Different types of machine learning include the following [8]:

- *Supervised Learning*: The program is "trained" on a pre-defined set of "training examples" from a "teacher," which then facilitate its ability to reach an accurate conclusion when given new data. In this case, the data comes with additional attributes that we want to predict. A common case of supervised learning is to use historical data to predict statistically likely future events. Under supervised ML, we have regression ML and classification ML.
- *Unsupervised Learning:* As their name suggests, unsupervised learning algorithms can be broadly understood as somewhat "optimizing themselves." Unsupervised algorithms do not need to be trained with desired outcome data. The program is given a bunch of data and must find patterns and relationships therein. A typical goal of unsupervised learning may be as straightforward as discovering hidden patterns within a dataset. Without being told a "correct" answer, unsupervised learning methods can look at complex data and organize it in potentially meaningful ways.
- *Reinforcement Learning:* Reinforcement learning models are trained holistically through trial and error. Reinforcement learning is a method with reward values attached to the different steps that the algorithm must go through. So, the model's goal is to accumulate as many reward points as possible and eventually reach an end goal. Reinforcement learning is an area of machine learning concerned with how software agents ought to take actions in an environment so as to maximize some notion of cumulative reward.
- *Deep Learning:* Deep learning (DL) is a specialized form of machine learning that uses artificial neural networks to mimic the human brain. It is a type of machine learning technique that is modeled on the human brain. It is an advanced technique for handling complex tasks like image and speech recognition. The way in which neural networks are trained can be described as deep learning. It is called deep because the network of neurons is arranged in several hierarchical levels. Deep learning laid the foundation for advances in generative artificial intelligence.

MACHINE LEARNING IN TRANSPORTATION

Artificial intelligence (AI), machine learning (ML), and deep learning (DL) are revolutionizing transportation systems, addressing critical challenges such as congestion, inefficiency, safety, and sustainability. These have emerged as transformative forces in revolutionizing transportation systems and their potential is vast. These technologies enable data-driven decision-making, offering unprecedented capabilities in processing large-scale, real-time data to optimize operations, predict trends, and enhance system resilience. They have been increasingly leveraged to address long-standing issues in traffic management, route optimization, autonomous systems, and urban mobility. They have consistently demonstrated their ability to improve efficiency, reduce congestion, enhance safety, and support sustainability. While AI provides the foundation for intelligent systems that can adapt and respond dynamically to changing conditions, ML and DL techniques unlock deeper insights through pattern recognition and predictive modeling. ML in transportation is used to improve efficiency, safety, and user experience through applications like autonomous vehicles, which use ML to perceive their surroundings and make driving decisions. DL techniques, particularly in computer vision, are revolutionizing applications such as smart parking and infrastructure monitoring [1]. Figure 3 shows the key applications of these technologies in transportation systems [1].

Nation’s economy and quality of life are influenced by a well-behaved transportation system, which has an impact on the nation's economy, safety, and standard of living. Yet, demands in transportation are ever increasing due to trends in population growth, emerging technologies, and the increased globalization. Rapid urbanization has resulted in problems with pollution, traffic congestion, and public transportation in cities worldwide. The urbanization of the global population is proceeding at a pace that will lead to about 68% living in cities as opposed to outside. Access to safe, affordable, accessible, and sustainable public transportation will be critical [9]. Accurate prediction of future traffic conditions is essential to mitigate traffic congestion and to respond to the traffic incidents. Machine learning solution has already begun its promising marks in the transportation industry where it is proved to even have a higher return on investment compared to the conventional solutions [10]. Deep learning encloses powerful methods for reinforcement learning able to process a large amount of unstructured data. Its techniques are suited for big-data handling and computationally intense processes like image pattern recognition, speech recognition and synthesis, etc.

APPLICATIONS OF MACHINE LEARNING IN TRANSPORTATION

Machine learning (ML) is transforming the transportation industry by enhancing safety, efficiency, and sustainability across various applications such as autonomous vehicles, traffic management, logistics, rail transportation, parking management, public transportation, smart parking systems, public transit optimization, freight and logistics, sustainability initiatives, safety enhancements, and infrastructure monitoring.

Common areas of application of ML in transportation are explained as follows [11-13]:

- *Traffic Management*: Traffic congestion is one of the most persistent challenges in urban transportation, leading to wasted time, higher fuel consumption, and increased emissions. Artificial intelligence is already being used in traffic management systems across the globe. Over time, public transportation has become more advanced through AI-based Intelligent Transportation Systems (ITS) to ensure the traffic flow with the least disruptions. Machine learning models are particularly effective in identifying congestion trends by combining historical and live data. They can analyze data to predict traffic patterns and congestion, helping to manage traffic more effectively. ML-powered traffic lights dynamically adjust signal timings based on real-time traffic patterns and demand, reducing congestion and emissions. Cities like Singapore and Pittsburgh have set benchmarks in using AI-driven traffic management systems to address congestion. The transport and logistics sector in the middle east holds immense opportunities to accommodate AI/ML to enhance future mobility. For example, UAE and Qatar are planning to transform their urban transportation to create more productive lives by enabling technology and harnessing data. Uber Engineering has shared how we use machine learning (ML), artificial intelligence (AI), and advanced technologies to create more seamless and reliable experiences for our users. Figure 4 shows AI-based traffic flow management [1].
- *Autonomous Vehicles:* Autonomous vehicles (AVs) represent one of the most visible advancements in AI-driven transportation. They have immense scope in public transportation, including shared mobility and mass transit solutions. Transitioning to autonomy is a significant step, with many factors to consider:

safety, integration with existing logistics systems, required infrastructure, and uptime and operational support. ML algorithms for autonomous vehicles need a heap of data like lane marketing, traffic lights, pedestrians, seasonal situations, weather conditions, and the possibility of unidentified objects to make correct decisions like speed up, braking, turning, stopping, etc. ML algorithms, computer vision, and LiDAR help self-driving cars, trucks, and buses interpret their environment, recognize traffic signals, and make real-time driving decisions. Popular self-driving cars like Tesla Autopilot illustrate the employment of autonomous vehicles in private transportation. Several state transportation agencies and the Department of Motor Vehicles have set up programs that issue permits to manufacturers of autonomous vehicles to test their vehicles on public roads. Figure 5 shows an Uber self-driving car [14], while Figure 6 shows training model for self-driving [14].

- *Rail Transportation:* GE Transportation has made significant contributions in building intelligent locomotives using AI/ML to improve the efficiency of rail transportation. The smart fright locomotives by GE transportation capture numerous data from the computer vision technology and feed them to machine learning algorithms to enhance the real-time decision-making of the locomotives. AI/ML helps manage the slower freight trains, control speedy passenger trains, reduce the number of uncertain delays, optimize maintenance schedules, reroute trains, etc. A typical railway transportation is displayed in Figure 7 [15].
- *Parking Management:* Parking inefficiency is a major contributor to urban congestion, with drivers often spending significant time searching for available spaces. Parking management is an integral part of the public transport system as haphazard parking may cause congestion and disruption in road safety. Parking applications are developed to effectively track availability in parking lots, and offer some reservation options to the users, and even some parking detection and notification mechanisms. Artificial intelligence can effectively provide parking management solutions, including accurate queue time estimation, detecting unauthorized parking, automated number plate reading, easier time tracking and billing, enhanced parking security, and many more. Figure 8 shows parking and traffic regulation by AI [1].
- *Pubic Transportation:* Demand for public transportation is highly affected by passengers' experience and the level of service provided. The public transport networks of dense cities such as London serve passengers with widely different travel patterns.
- *Smart Transportation:* Smart transportation is considered to be an umbrella term that covers route optimization, parking, street lights, accident prevention/detection, road anomalies, and infrastructure applications. It has become a popular area of research interest, since it encounters many everyday problems, with a huge footprint in a modern smart city. Cities are getting "smarter" and smart city applications are developed to take advance of the latest technological improvements. The field of smart transportation has attracted many researchers and it has been approached with both ML and IoT techniques. Statistical machine learning algorithms have also found their way in supporting smart transportation. Using sensors embedded to the vehicles, or mobile devices and devices installed in the city, it is possible to offer optimized route suggestions, easy parking reservations, economic street lighting, telematics for public means of transportation, accident prevention, and autonomous driving. Figure 9 shows smart transportation systems [1].
- *Freight and Logistics:* Freight and logistics are critical components of modern transportation systems, enabling the movement of goods across local, regional, and global scales. Beyond urban mobility, freight and logistics systems have embraced AI for route optimization, predictive maintenance, and warehouse automation, ensuring faster deliveries and cost efficiency. AI, ML, and DL technologies are transforming this sector by optimizing processes, improving operational efficiency, and enhancing customer satisfaction. Companies like Amazon and DHL have redefined logistics using AI-driven optimization tools.
- *Accident Detection/Prevention:* Accident detection and prevention is a domain of smart transportation and a crucial activity for every city since an operating prevention method can help save human lives. An accident prevention system can notify the driver about critical situations and allow them to act in a timely manner. ML has been proven very useful in detecting road accidents, or detect patterns that could lead in new accidents and notify drivers in order to avoid them. Road anomalies detection has a significant

role in smart transportation since the road conditions have an immediate impact on many aspects of transportation. Several DOTs are exploring the potential of ML to support traffic incident management.

BENEFITS

Key benefits include optimizing logistics through demand forecasting and inventory management, managing traffic flow with predictive modeling, and enabling predictive maintenance to prevent breakdowns. AI has the potential to improve transportation system safety through enhanced incident response and prediction, improved video detection to avoid pedestrian-vehicle conflicts, and better monitoring and management of assets to keep infrastructure in proper condition. ML models enable real-time hazard detection by processing data from cameras, drones, and IoT-enabled sensors. Other benefits include the following [1]:

- *Automation:* Drones equipped with AI-driven cameras and sensors are increasingly used for infrastructure monitoring. They provide access to hard-to-reach areas, such as the underside of bridges or high-altitude structures, without the need for manual inspections.
- *Urban Planning:* AI and ML are integral to the development of smart cities, where transportation systems interact seamlessly with energy grids, housing, and public services. ML models help urban planners simulate the effects of new infrastructure or policies on traffic volumes and travel behavior, aiding in long-term strategic decision-making. They can predict demand for services like bike-sharing, informing decisions on where to build new stations and infrastructure.
- *Route Optimization:* Traffic congestion is a common issue in urban areas and it is only getting worse as the number of vehicles increases. Route optimization is a method to propose the best route for a specified destination, in order to minimize traffic congestion. By minimizing the traffic congestion, both the traveling time and vehicle emissions are reduced. ML algorithms analyze numerous parameters, including traffic, road conditions, and delivery locations, to determine the most efficient routes, reducing travel times, and fuel consumption.
- *Predictive Analytics*: AI-driven predictive analytics use historical data on accidents, traffic patterns, and driver behavior to identify high-risk locations and situations. Short-term demand predictions, typically defined as less than an hour into the future, are essential for implementing dynamic control strategies and providing useful customer information in transit applications. Being able to predict the actual stop sequence that a human driver would follow can help to improve route planning in last-mile delivery. These predictions enable authorities to anticipate high-traffic areas and implement interventions before gridlock occurs.
- *Predictive Maintenance*: Predictive maintenance leverages machine learning models to analyze historical and real-time data from IoT-enabled sensors embedded in infrastructure. Predictive maintenance systems, powered by ML and IoT, monitor the health of fleet vehicles and predict potential failures before they occur. Sensors collect data on vehicle and infrastructure health, which ML algorithms analyze to detect potential issues and schedule maintenance before breakdowns occur, minimizing downtime and costs. ML algorithms can predict when a vehicle is likely to fail, allowing for maintenance to be performed before a breakdown occurs, which improves safety and reduces delays.
- *Multimodal Transportation*: AI for ITS has the potential to improve mobility for multimodal transportation users. AI can be used to service all modes of transportation by predicting vehicle and pedestrian arrivals, queues, and delays. AI-powered tools enable seamless multimodal transportation planning, encouraging the use of public transit, biking, and walking over private vehicle use. These systems integrate data from various modes of transportation to recommend eco-friendly travel options based on user preferences and real-time conditions.
- *Smart Lights:* An important part of a smart city, which we consider a part of the smart transportation services, are the Smart Street Lights (SSL). Smart lights can reduce energy consumption and offer dynamic operation and manageability. Intelligent traffic signal systems are another technology area that agencies are exploring.

CHALLENGES

While these technologies hold immense promise, their real-world implementation is fraught with challenges, including data availability, algorithmic limitations, and scalability, data scarcity, limited model generalization, and high computational demands. These limitations stem from various technical, operational, and ethical factors that hinder their effectiveness, reliability, and scalability. Ethical and regulatory issues, including bias, accountability, and privacy concerns, further complicate adoption. Other challenges include the following [1]:

- *Technical Challenges:* The technical challenges of implementing AI, ML, and DL in transportation are multifaceted, ranging from data-related issues to computational demands and integration complexities. While AI and DL algorithms have shown remarkable capabilities, they often struggle with generalizability. For example, an autonomous vehicle trained on data from suburban roads may face difficulties navigating dense urban traffic.
- *Cost:* The high costs associated with developing, deploying, and maintaining AI systems pose a significant barrier, especially for resource-constrained municipalities. AI-driven transportation solutions often require substantial investments in infrastructure upgrades, such as IoT networks, cloud computing platforms, and advanced hardware like GPUs for real-time data processing. For smaller cities or developing regions, these financial constraints often delay or entirely prevent the adoption of AI-based solutions.
- *Ethical Concerns:* The integration of AI, ML, and DL into transportation raises critical ethical and social issues that must be addressed to ensure fairness, accountability, social impact, and inclusivity. Although researchers increasingly adopt machine learning to model travel behavior, they predominantly focus on prediction accuracy, ignoring the ethical challenges embedded in ML algorithms. The automation enabled by AI technologies has raised concerns about job displacement in sectors such as logistics, public transit, and freight. Autonomous vehicles and robotic systems in warehouses and delivery networks are increasingly replacing human labor, leading to fears of widespread unemployment.
- *Bias:* Major areas of concern center on equity, discrimination, and biases. Algorithmic bias is a significant ethical concern in AI-driven transportation systems. AI models trained on biased datasets can inadvertently perpetuate or even exacerbate inequalities. Bias in training data or model design can lead to exclusionary outcomes, such as unequal access to transit or unsafe behavior in marginalized communities. For example, bias in autonomous vehicle training data could result in unequal performance across different demographics or environments, raising safety concerns. Facial recognition used by transit agencies might be subject to racial discrimination, as the identity data these tools are trained on is predominantly white and male.
- *Safety and Security:* Safety and security remain top priorities in transportation systems, as millions of road accidents and security breaches occur annually, causing significant economic and human losses. AI, ML, and DL technologies are transforming how transportation systems address these challenges, introducing intelligent and proactive measures to enhance safety and security across all modes of travel. The reliability and safety of transportation systems depend heavily on well-maintained infrastructure, including roads, bridges, tunnels, and railways.
- *Scalability:* While many applications achieve success in pilot programs or localized settings, scaling them to larger regions often requires significant adjustments. Successful scalability hinges on adapting technology to local conditions rather than employing a one-size-fits-all approach. One of the most pressing operational challenges is scaling AI-driven solutions from pilot projects to citywide or nationwide implementations. While many applications demonstrate success in controlled environments or limited trials, deploying them at a larger scale often reveals unforeseen complexities.
- *Sustainability:* Sustainability is a major concern in transportation, as the sector is one of the largest contributors to greenhouse gas emissions. AI, ML, and DL technologies play a vital role in reducing the environmental impact of transportation systems by improving energy efficiency, promoting cleaner alternatives, and optimizing resource utilization. AI implementations in transportation increasingly align with global sustainability goals. AI-driven traffic management systems reduce fuel consumption by optimizing traffic flow and minimizing vehicle idle times. AI technologies are also driving sustainability in transportation. Cities like Los Angeles have implemented AI-powered systems to optimize traffic flow and reduce vehicle emissions.
- *Cybersecurity:* With the rise of autonomous and connected vehicles, cybersecurity has become a critical concern. AI and ML are used to secure vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications by detecting anomalies and preventing unauthorized access.
- *Collaboration:* Effective implementation of AI-driven transportation solutions requires collaboration among multiple stakeholders,

including governments, private companies, researchers, and the public. Multidisciplinary collaboration with ethicists, legal scholars, and public interest groups will be key to ensuring technology advances align with societal values. Initiatives like Singapore's integrated traffic management system or New York's AI-powered transit optimizations have benefited from strong partnerships between public and private entities.

- *Data Quality:* The increasing deployment of AI and ML in transportation relies heavily on data from connected vehicles, infrastructure sensors, and user interactions. The success of AI and ML models depends heavily on the availability, quality, and consistency of data. However, many transportation systems struggle with data scarcity, particularly in regions with limited infrastructure for data collection. Integrating diverse data sources—such as IoT devices, GPS systems, and user-generated inputs—creates a comprehensive foundation for informed decision-making.
- *Legacy Systems:* Integrating AI solutions with legacy transportation infrastructure is a complex task. Many existing systems were not designed to accommodate modern AI technologies, leading to compatibility issues.

FUTURE OF MACHINE LEARNING IN TRANSPORTATION

The continuous evolution of artificial intelligence (AI), machine learning (ML), and deep learning (DL) presents transformative opportunities for advancing transportation systems. The analysis of real-world applications of AI, ML, and DL technologies in transportation reveals critical insights that can guide future implementations. Understanding how transportation works as a system is critical to identifying and alleviating traffic issues and supporting future planning.

AI will increasingly integrate into our transportation system, and be powered by data we can collect, aggregate, and analyze. Future work should develop domain-specific AI tools tailored for stakeholders such as urban planners, operators, and regulators. It should emphasize the co-creation of AI solutions, involving diverse partners from the outset. Future research should focus on developing scalable, low-latency AI pipelines capable of integrating multimodal sensor data in real-time. It should focus on building interpretable, scenario-based tools that are accessible to non-technical stakeholders. This should include ethical AI design principles tailored to mobility contexts.

CONCLUSION

Because the number of automobiles is increasing at a rate that is sometimes faster than the population as a whole, roads are becoming increasingly congested and dangerous. This problem will no longer be resolved by merely adding more roads. In recent years, machine learning techniques have become an integral part of realizing smart transportation, where it has been demonstrated that they even offer a greater return on investment than the conventional methods. The major objectives of the ML algorithms include reducing road congestion, boosting safety and reducing human error, mitigating negative environmental consequences, maximizing energy performance, and improving productivity and efficiency of transportation.

While AI/ML methods have a promising future, the path to success is rarely a straight line. In some cases, ML/AI solutions just may not be mature enough for deployment by transportation agencies. Sophisticated ML algorithms have been minimally used and the transportation industry has not yet taken full advantage of ML. This is partly due to a lack of effective collaboration between the ML and transportation experts, resulting in the most accessible transportation applications being used as a case study to test or enhance a given ML algorithm and not necessarily to enhance a mobility or safety issue. In addition, the transportation community does not define transportation issues clearly and does not provide publicly available transportation datasets [16]. More information on the use of machine learning in the transportation industry is available in the books in [5,17-22] and the following related journals:

- Cities
- Journal of Advanced Transportation
- IEEE Transactions on Intelligent Transportation Systems

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Figure 1 A symbol of machine learning [3].

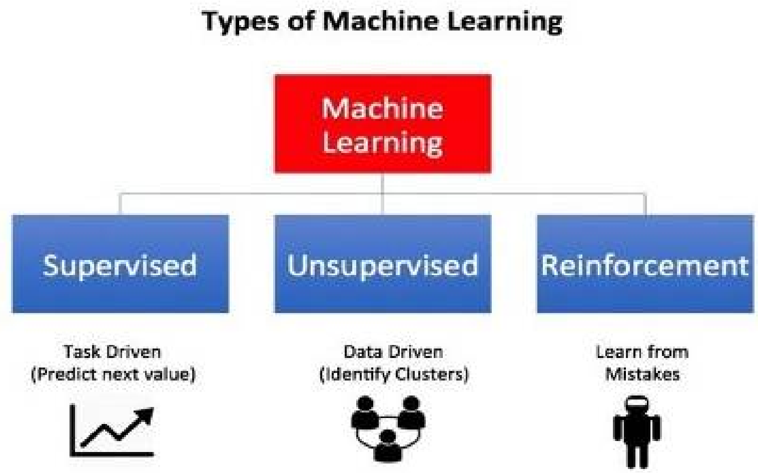

Figure 2 Different types of machine learning [7].

Figure 3 Key applications of AI/ML/DL technologies in transportation systems [1].

Figure 4 AI-based traffic flow management [1].

Figure 5 An Uber self-driving car [14].

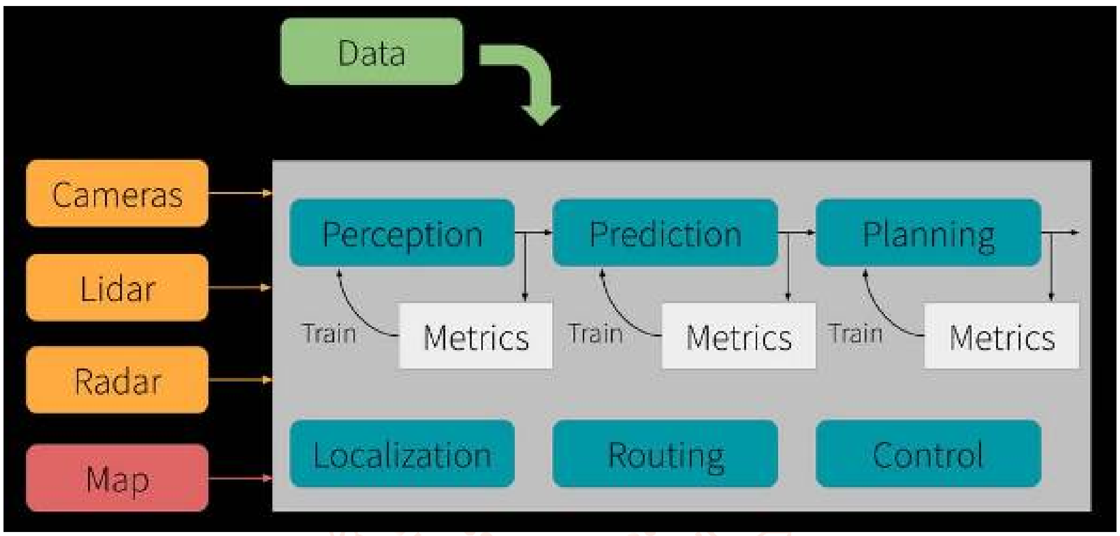

Figure 6 Training model for self-driving [14].

Figure 7 A typical railway transportation [15].

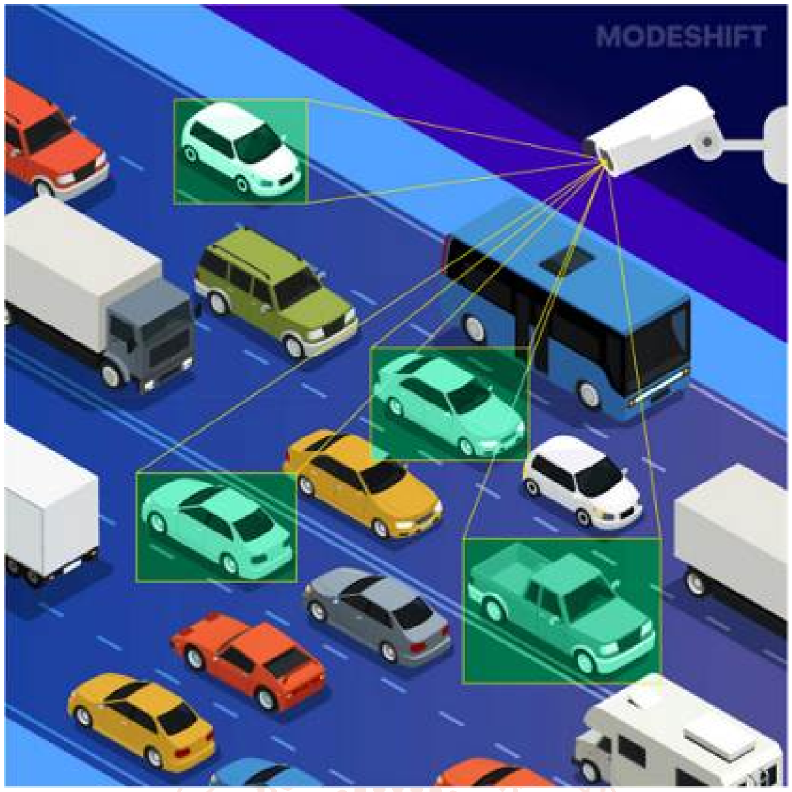

Figure 8 Parking and traffic regulation by AI [1].

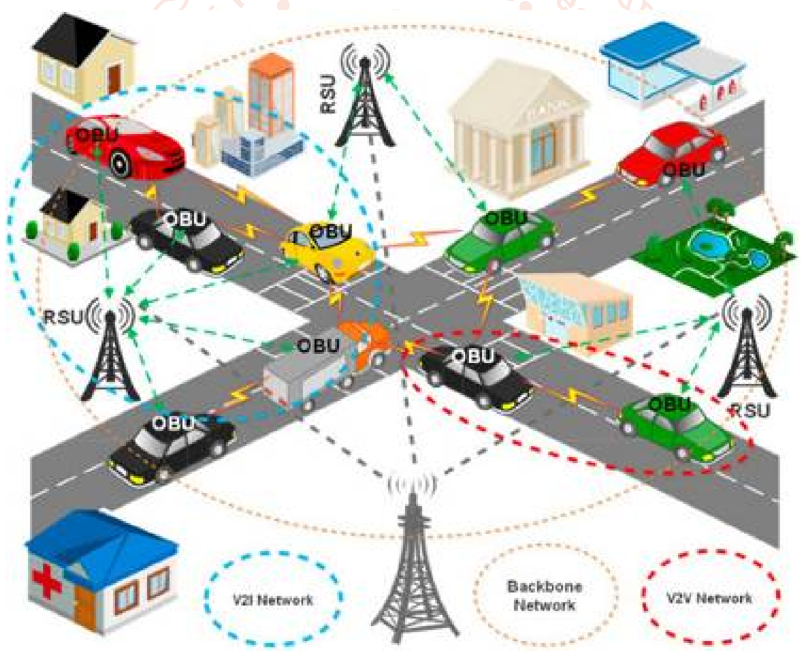

Figure 9 Smart transportation systems [1].