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AI-Driven Digital Twins for Sustainable Urban Mobility: Integrating Generative Models for Traffic Optimization

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ABSTRACT

Due to the rapid expansion of the cities nowadays it is difficult to cope with the traffic congestions, air and noise contamination and the quality of the transportation. A framework is presented supporting AI and integrated digital twins and generative models to optimize how cities manage their public services and transportation system. Urban transportation using digital twins implies that you can test and assess policies by looking at the future and applying data to a dynamic model. Generative AI models that predict the flow of traffic, assist with the design of optimal routes, and enable machines to make decisions on their own make traffic management systems much more flexible. The system is depicted by the research of a metropolitan city and it results in an improved traffic, a decrease of resources consumption and emissions. The research proposes that digit twins enhanced with AI could significantly enhance the planning of smart cities and the sustainable (environmentally friendly) development of cities.

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1. INTRODUCTION

The movement of people in cities has a significant influence on efficiency, sustainability and livability of modern cities. Cities are faced with a number of challenges in transportation including; traffic, increased rates of pollution, knackered or inefficient transport infrastructure as more people continue to reside in urban areas. In addition to reducing economic development such problems assist in destroying the environment and complicating the life of urban residents [2,4]. Furthermore, the traditional traffic management approach premised on fixed statistics and rigid systems struggles to keep up with constant fluctuations occurring in urban mobility. In order to address these issues, a disruptive solution called Digital Twin (DT) technology has been proposed. The digital twin of every urban asset would allow keeping an eye on it, exploring alternatives and increasing its performance in the long run [6,8].

Digital twins can process information, evolve with the times and make decisions of their own in case they are implemented with Artificial Intelligence (AI). Among the existing numerous AI methods, Generative Adversarial Networks, as well as Variational Autoencoders, assist AI in learning with difficult data and make it appear realistic. There are already more opportunities to make predictions of the future tendencies and proactive actions to manage traffic due to the addition of these models to AI-based digital twins [9].

The document explores the potential of using generative models together with AI-enabled digital twins to enhance the movement of persons in urban areas. It dwells on the application of GANs and VAEs to represent traffic patterns, identify traffic-prone areas and develop optimal routes that drivers can use immediately. This research will develop smart cities that involve generative AI and digital twin technologies into the development of sustainable and intelligent transportation systems.

2. LITERATURE REVIEW

Urban mobility has never been as complex as today due to growing needs in transportation, environmental issues and constraints of available infrastructure, and new innovation is needed. The technological breakthroughs of today allowed combining data analysis, simulation and intelligent decision making into one strategy. It examines the latest discovery in the following ways: DT technology of smart city movement, generative models of traffic enhancement, and AI of sustainability.

2.1. Digital Twin Technology in Urban Mobility

Digital twin is the term that denotes the presence of a virtual replica of a physical system which updates and mirrors reality in real time. It was primarily employed within manufacturing and the aerospace industry, today it is being utilized more within the organization of cities and transport systems. According to [10], digital twins bring together the familiar (physical) maintenance world with the digital world through sensor data.

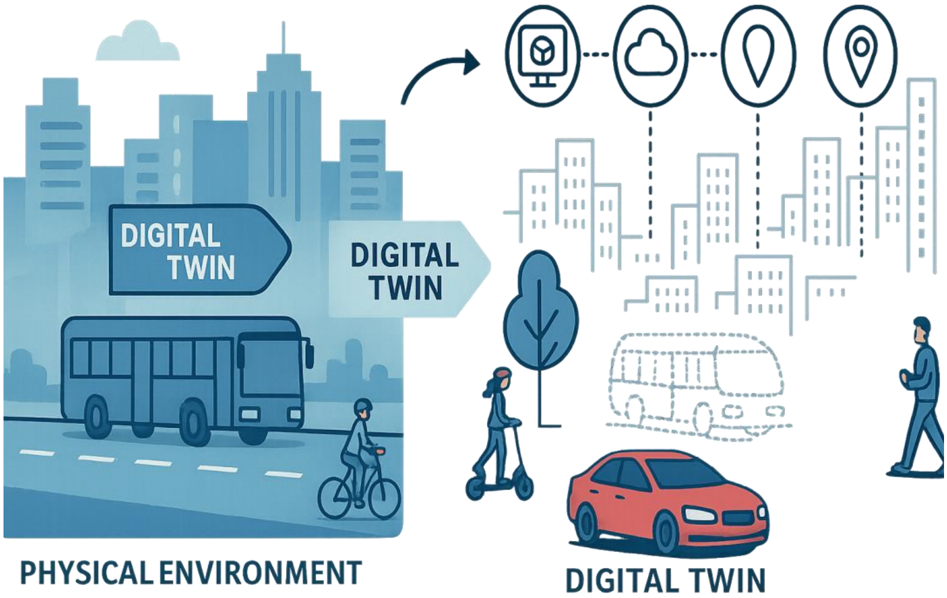

Figure 1. Structure for Digital Twin Technology in Urban Mobility

Digital twins in urban mobility provide the complete image of the city transport system using data provided by sensors, GPS devices, IoT and weather data. In fact, according to [5], digital twin technology enables city planners to study pedestrian flow, the extent of traffic congestion and success of mass transportation systems, which provides them with directions to take during development projects and emergencies preparedness. Due to real-time simulations, they are highly useful in supporting stress testing of policy actions prior to their implementation.

2.2. Generative Models for Traffic Flow Optimization

Generative models have assumed significance in machine learning to be applied in fields such as generation of images and data prediction. In order to model the traffic flow, individuals in this sector are looking at GANs and VAEs, as they can be applied to generate lifelike simulations using the information gathered.

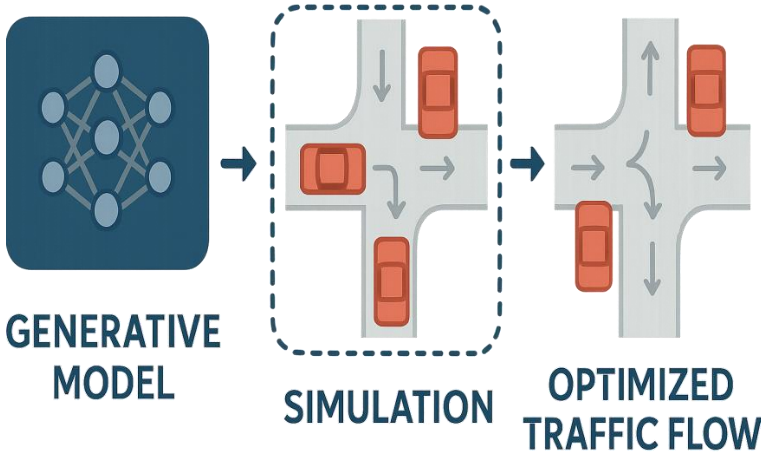

Figure 2. Structure for Generative Models for Traffic Flow Optimization

[3] States that GANs training involves two neural networks, namely the generator and the discriminator that tries to optimize their data representation. Transportation specialists apply GANs to generate traffic incidents that are difficult to anticipate like morning and evening rush hours, issues on the road and the crowds at fairs or events [7]. VAEs excel in particular at capturing hidden properties of traffic data that can indicate the principal sources of congestion and delays [1]. They give the forecast data that the traffic officials require to act and design transport routes.

2.3. AI and Sustainability in Urban Mobility

Smart transportation systems currently rely on Artificial Intelligence to process grouping data, predict the next events and perform operations without human assistance. Machine learning is also being applied to urban mobility through dynamic route optimization, congestion prediction and vehicle management based on the current traffic [11]. These devices reduce the level of intervention required by people frequently to make traffic more responsive to challenges.

With AI, emissions will be cut because it will reduce the number of hours that drivers have to wait to pick passengers, consume less fuel and because transit systems will be more efficient. The authors [12] mention that the adoption of AI in transportation contributes to reducing the volume of greenhouse gasses emitted, and it reduces noise in large cities which aligns with the vision of smart cities. Predictive maintenance of the transportation systems is also done using artificial intelligence that allows increasing the useful life of assets and reducing resource consumption.

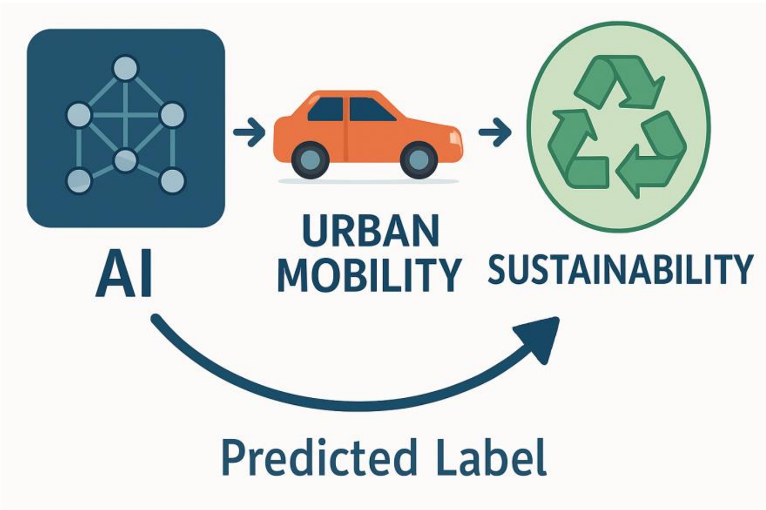

Figure 3. Structure for AI and Sustainability in Urban Mobility

3. METHODOLOGY

3.1. Data Acquisition and Pre-processing

The reliability of your data will largely define the accuracy and efficient nature of your model. To attain this, there will be knowledge of information played by various sources that broadcast the present and previous status of traffic. The primary source of obtaining traffic information is IoT sensors embedded in the roads, traffic cameras and GPS devices installed in vehicles. These IoT sensors can be used to monitor traffic closely by observing the movement and flow of vehicles, their speed as well as the extent of congestion. When mounted in sites such as intersections and highways, they provide real-time data concerning the number of vehicles, their speed as well as the thickness of the traffic. They are able to detect the presence of vehicles on the road and their movement which can be used to get traffic information.

The second source of data will be the cameras that will be located at various strategic locations within the city. They provide pictures which may assist individuals to examine whether there is a traffic jam, monitor the movement of vehicles and make sure that the busy crossings remain secure. Video footage processing will show the movement of vehicles, potential crowded areas or accidents and will calculate the efficiency of the roads. Additional data will be provided by GPS points of moving vehicles. With the help of GPS, it is possible to track the movement of a vehicle and the speed at which it maintains to a very high degree of accuracy. By having the GPS data of a large number of vehicles one can then analyze how the traffic functions, what is the time consumption during the traveling and the points where the traffic is slow.

Cleaning and preparation of data obtained by various sources is the following step. Raw data will on many occasions contain missing points, random noise and a few outliers which can decrease the accuracy of the model. Different preprocessings will be employed to ensure the data is sound. Huruf, interpolation or upayalainnyaberdasarkanjenis will be used to fill any missing values. By reducing any noise in the data, through the use of moving average filter or Kalman filter, the data is made easier and more approachable to the actual values.

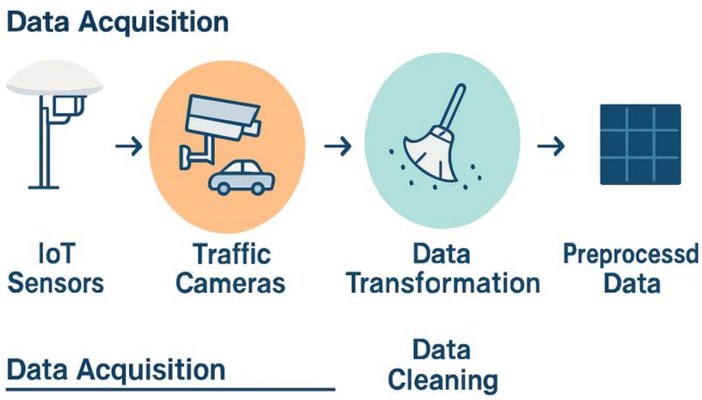

Figure 4. Structure for Data Acquisition and Pre-processing

The Out-of-schedule data with respect to normal flow of traffic will be identified and acted upon. They can be abnormal or extreme speeds and number of cars going through that signal something is not functioning well with the parking sensor. The final stage of pre-processing will deal with the normalization and the conversion of the data into adequate forms. A lot of significance is making the datasets conformable and consistent through standardization and normalization, with any type of data sources. To illustrate, traffic cameras, as well as IoT sensors and GPS, can provide data in different formats, thus must be converted into a single form. Min-max scaling or z-score standardization will serve as methods in order to make the data homogenous. Second, all data required to be synchronized as per time will be scheduled to have the same time so as to ensure that analysis is precise. Once the data is cleaned up, pre-processed and synchronized, it could be utilized in training and analyzing models. All the data gathered and computed at this level is vital to the optimization of good traffic flow.

3.2. Methodology for Building the Digital Twin

With its help, the primary goal is to create a digital model of the selected urban environment with its major traffic and infrastructure characteristics to enhance the effectiveness of traffic. Everything begins with choosing an urban location with much traffic issues. Methods of population density, degree of road networks, availability of public transport means and existing traffic snarl up problems are included in the process of giving information on where infrastructure must be placed. The moment the area is selected, information on roads, intersections as well as public transport route is availed by reliable sources like the information available online or information gathered through satellite collected data. They include traffic sensor data, vehicle GPS signals, traffic management device and crowd monitoring sensors. It is crucial that this data is transmitted to the digital twin all the time to make it reflect the events occurring in the real world. Then, the entire data is incorporated to create a newer traffic simulation programme. Such aspects as roads and intersections of roads, traffic lights and means of public transport will be incorporated into this model. These units are created in a computer environment, whereby every aspect of roads and structures around them are included like lanes, traffic lights and pedestrian areas.

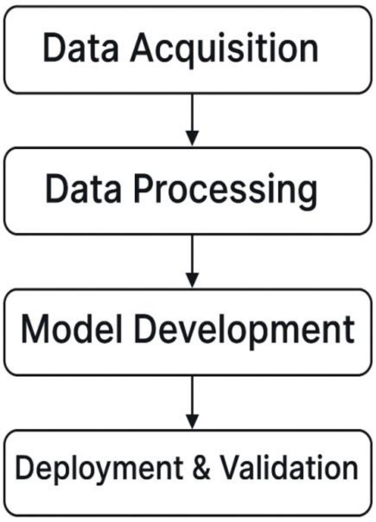

Figure 5. Structure for Building the Digital Twin

In order to create a digital twin, the traffic of cars and people is modeled in the city. The simulation will demonstrate the traffic in terms of vehicles rerouting and adjusting their speed in response to variations in the traffic conditions in real time as provided in data streams over the network. Pedestrian routes are designed in such a way that special emphasis is made on busy streets. Digital twin ensures that traffic moves properly by adjusting the traffic signals on a real-time basis, based on the magnitude of congestion within the network. Traffic sensors, GPS and real-time control can also be input to the system and facilitate the control of traffic within the simulation. When data is processed the model demonstrates what is going on currently in the traffic network. Through this real-time updating, the digital twin will be able to monitor the traffic and determine how to change it to improve the system.

With the digital twin coming into operation, the focus is now on optimising the flow of traffic. We can test the solutions like changing the traffic lights, determining the new paths the automobiles should take and managing the flow of people on the streets. With the AI and ML technology, prediction of the traffic flow and modification of the simulation respectively will be assisted. These models assist in the management of traffic by estimating congestion, adapting streetlights, detouring vehicles and optimising public transport to cope with live traffic information. The collection of actual data and field testing ensures that the digital twin behaves in a way that the real traffic does. Periodically, the model is updated with new data to better how the model can anticipate future events. The comparison of the results obtained in the simulation and real traffic allows adjusting the model to be good and reliable.

Finally, to check how the digital twin functions in terms of optimizing traffic flow, key performance indicators (KPIs) are applied. Part of these measures include the average speed of traffic, reduction of congestion in the city, quicker commuting of vehicles and pedestrians and improved utilization of the mass transportation system. Measuring the effectiveness of traffic optimization is concentrated on the aspects of the environment, society and economics that involve reduced emissions, reduced accidents in traffic and potential savings of managing traffic that has been optimized.

3.3. Integration of Generative AI Models

It is essential to use Generative AI models to replay and get the best out of numerous traffic management strategies. Generative Adversarial Networks (GANs) and Variational Autoencoders (VAEs) are the two popular models that are used to view and forecast the traffic flow and design the safe passage routes. These models will be trained using past data about traffic hence they will be able to give realistic and reliable traffic conditions that will be used to manage the traffic flow in real-time.

GANs will be used to generate potential future traffic scenarios. GANs have two neural networks, generator and discriminator and these networks are trained by pitting them against each other. The generator creates simulation data capable of displaying traffic events and patterns and the discriminator evaluates whether the data is similar to the ones that could occur in the real world. Over time the generator is taught to produce more realistic traffic patterns based on which it can predict how the traffic will evolve under various conditions. GANs provide such information as useful in managing the motor traffic in the city by simulating various events such as large events, road closures, or sudden weather conditions.

Besides that, Variational Autoencoders (VAEs) usage will assist in discovering the latent structures in the traffic data. They are generative models capable of compressing data and then generating it by identifying the meaningful transformations between examples. Traffic VAEs will facilitate the revelation of latent information on the traffic, such as reoccurring cases of heavy traffic or frequently congested hotspots. They will allow seeing the influence of such factors as time, day of the week or weather on the movement of road traffic more easily. VAEs extract latent patterns; this assists them in proposing optimal paths that would probably not get congested at particular periods.

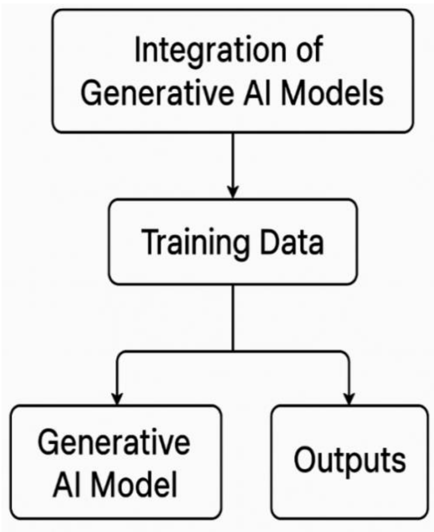

Figure 6. Structure for Integration of Generative AI Models

It will assist the system to generate and forecast a myriad of traffic situations using both GANs and VAEs. They can be used to assist in estimating the impact that would occur to the traffic in the event that certain changes, say, in the manner in which signalled or mass transportation operates, are introduced. Technology enables traffic managers to exercise strategies without any risk of disturbances and observe its functionality to diminish the probability of disturbances resulting in improved decision-making.

The AI will be trained on historical traffic data gathered by the IoT sensors, traffic cameras and GPS technology in order to ensure that the model predictions are accurate. Due to this data, the models have access to much information concerning real-life conditions of the roads that can correspond to the various scenarios that the traffic can encounter. In order to achieve training, unsupervised and supervised learning methods ought to be employed. Supervised learning will be used to provide the traffic data with the desired correct results of the traffic volume, speed or congestion, to train the models. With unsupervised learning, the models will be able to seek patterns themselves in the data, thereby becoming more capable of dealing with and anticipating different traffic scenarios.

As a training process, it is quite essential to validate your model. Once trained, the predictions of the generative models are verified against real traffic data. This will ensure that the traffic patterns are similar to what can be observed in real life traffic. Testing and cross-validation using historical data will indicate the accuracy of the models in analysing the needs.

In case GANs and VAEs are included in the traffic optimization system, it is possible to model numerous traffic scenarios and predict the traffic stream in the future. Such generative models will enable the system to react to future changes in traffic, find optimal routes in changing situations and contribute to the improved functioning of the traffic within the city.

3.4. Traffic Optimization Algorithms

Once the generative AI models (such as GANs and VAEs) are trained and validated successfully, the next stage is to employ traffic optimization algorithms, which operate with what these models forecast and model. The algorithms are supposed to develop and implement measures that alleviate traffic and transport cars more effectively as they occur. Dynamic signal adjustment, efficient routing and versatile vehicle controls will be the primary means of ameliorating traffic.

1. Dynamic Signal Adjustments

The primary methods of controlling congestion include controlling traffic signals on-demand. At the moment, traffic lights work according to a single schedule that is rather insensitive to the traffic variation and introduces delays. Thus, the timing of the traffic lights will automatically be altered to suit the prevailing and predictable traffic situation by use of dynamic signal adjustment algorithms.

The updated traffic information such as the amount of cars, their average speed and traffic rates will be sent to the traffic optimization system continuously. Using the data, the signal will be switched rapidly to help in the smooth flow of traffic, reduce areas of traffic congestions and prevent the traffic from congregating at the intersections. Suppose a lot of traffic is involved in an intersection. Such a system can then make sure that the lanes with more traffic can have a longer green signal and the red light time of the less busy lanes can be minimized. With this system, the people will spend less time waiting, less time delaying and there will be a smooth traffic.

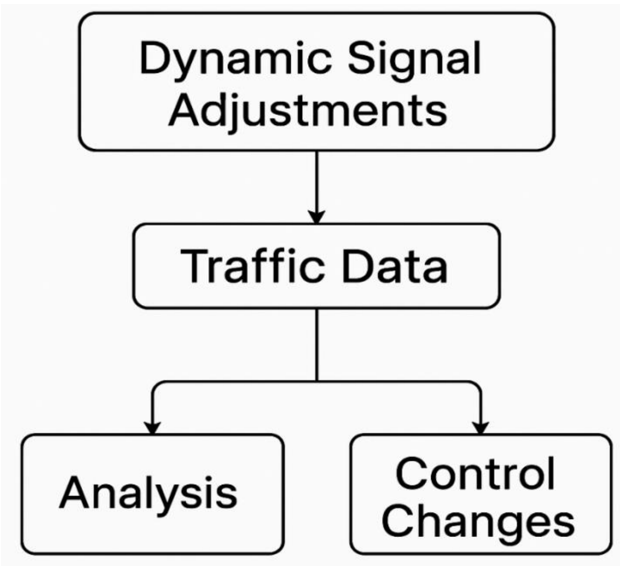

Figure 7. Structure for Dynamic Signal Adjustments

2. Route Optimization Based on Predicted Traffic Flow

Of importance also in decongesting the systems is the optimization of the route systems. The system offers predictions of the future traffic and this allows the drivers and the public transport to be given the best routes to take. The algorithm, by analysing data on GPS and traffic cameras in real time, will suggest alternate routes so that drivers could avoid busy streets. These proposals will aid in making sure that travel times are minimized and that the likelihood of certain congestion that may translate into delays within the network are also minimized.

They take into account the existing flows of vehicles on the highway, potential future traffic jams, road closures, accidents and unforeseen circumstances that can influence the traffic. The optimization system also learns historical traffic, identifies common busy roads at various times and generates new route recommendations to prevent traffic jam before it happens. By this method, the drivers will experience a reduced amount of traffic, they will move faster and the traffic will be more balanced on the roads.

3. Adaptive Traffic Control Systems

ATCS is implemented in order to introduce alteration in the way traffic flows at any given time based on real-time data and estimates provided by the generative models. Unlike the typical systems, ATCS involves the application of advanced programs that process traffic data all the time and periodically adjust the signals, the number of lanes to use and routes to improve traffic.

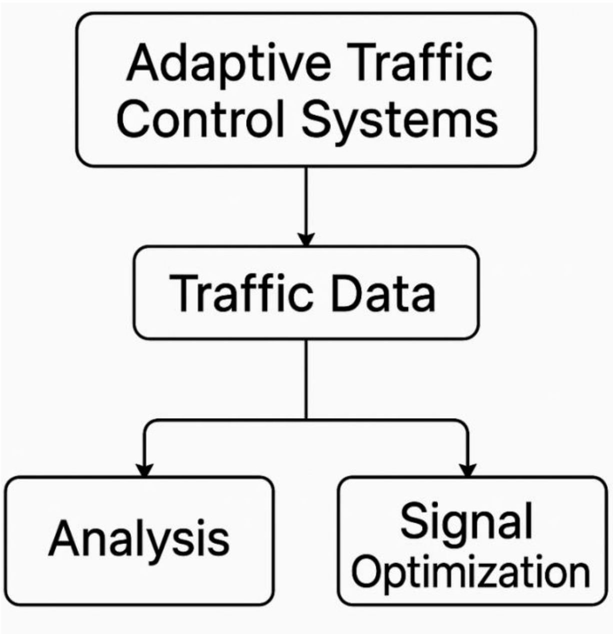

Figure 8. Structure for Adaptive Traffic Control Systems

They will be able to feel the alterations in the traffic patterns soon. Should there be an accident or a section of the road closed the ATCS will retime signals, allocate alternative routes to the traffic and provide real-time information to drivers via navigation applications or signs. It has the capability to identify the impending bottlenecks using the past and present information and beat the problems with adequate measures.

The new technology will also take into account the steps of the public transportation. As traffic management represents the information of buses and trains, the traffic signals can be modified properly according to the schedule of the public transport so that these vehicles do not suffer unnecessary delays as they travel through the network. By doing so, this will aid in enhancing the vehicle and mass transport movements that contribute towards an efficient city travel system.

3.5. Continuous Learning and Adaptation

The system will also learn and adapt continuously by itself. Each time the traffic patterns are altered the system will continue to gather information through numerous sensors, cameras, GPS and transport systems. The new information will be used to retrain generative AI models such that the system will always be right with its predictions. Moreover, algorithms will undergo adjustments as time passes by using the results of practical implementation in order to comply with the required results.

The three aspects optimized will enable traffic algorithms to reduce traffic jams, enhance the movement of travelers and provide a timely and flexible control measure. With these methods that incorporate present and future traffic data the cities will be able to manage the traffic congestions, enhance the city transportation as well as make the city journeys more gratifying and eco cordial.

3.6. Evaluation and Validation

The system will undergo extensive tests in a model of an urban area to determined how effectively it functions in real traffic. The evaluation of the outcomes will rely on key performance indicators (KPIs) of significance to determine how the system is beneficial in relation to traffic issues, reducing congestions and minimalizing the adverse impacts on the environment. Optimization strategies should be evaluated and commuter travel time should be measured against the time taken prior to the implementation of the same. This is a step that will allow measuring the level of influence that the system has on the congestion and the effectiveness of the operation of the urban transport system. The system would be piloted by making simulations during event days and on crowded days to ensure whether it reduces the commute time of people. Also, the fuel consumption and the carbon emission will be estimated by the difference between the amount of fuel and carbon emission on the road when the traffic is optimized.

One more crucial KPI is the optimization of the traffic flows in the areas with people. There will be smart sensors to quantify the effectiveness of the system in alleviating traffic congestions and increasing the volume of cars passing through congested urban centers and intersections. In order to determine how these systems can manage traffic jam they will experiment with dynamic signal systems, alternate routing strategies and adaptive control systems. Finally, testing will be used to evaluate the possibility of applying the system in different urban locations. The system will also be experimented on how it fares in altering traffic conditions and cities big and small. Through this, the performance of the system in other towns and cities can be evaluated. The simulation of traffic data will provide figures regarding travel time, gas consumption, amount of emissions and road busy-ness. In addition to this, some areas will be pilot tested to determine the comparisons between the simulated results and the real traffic records. There will also be some gathering of information on the traffic officials, city planners and motorists on whether the system is functioning well or where it needs to be improved. This procedure may ensure that the selected system will be convenient, effective and applicable in various cities.

4. EXPECTED OUTCOMES

The combination of generative models and digital twins is likely to result in a few significant achievements. Adaptation of the traffic flow implies that the system is adapting to the prevailing traffic demands, which means that there is less traffic congestion and less time taken by the people driving at those moments. The system will improve the environment of the city, as the flow of traffic will be less congested, which means less pollution, less fuel consumption and more environmentally friendly lifestyle. Once the traffic is improved, cars will not have to remain stationary as frequent which is more environmental friendly. It will also make sure that the road management methods are updated automatically so as to avoid delays and ensure that the flow is made easier. In this manner, the urban transport is more resistant and less costs are required to sustain and fix the roads during emergency. Through the system, cities will be able to reduce costs, ensure that the economy will be beneficial in the long-term and offer people improved methods of traversing the urban center.

Table 2. Tabulation for Existing paper and Proposed paper

Aspect	Existing Research Papers	Proposed Paper
Title Focus	General AI models for traffic prediction, traditional simulation models, or isolated use of digital twins	Integrated approach combining Generative AI (GANs, VAEs) with Digital Twins for real-time, adaptive traffic flow optimization
Core Technologies	Predictive models (e.g., LSTM, CNNs), rule-based simulations, basic digital twins	Generative Adversarial Networks (GANs), Variational Autoencoders (VAEs), real-time digital twins with multi-source live traffic data integration
Traffic Simulation Environment	Often relies on historical or synthetic datasets for simulation	Real-time simulation using digital twin of the city, replicating real infrastructure, signals, and traffic behavior
Optimization Techniques	Predefined traffic signal timing, static routing algorithms	Adaptive optimization using AI-generated scenarios and feedback loops, dynamic signal control, real-time rerouting
Environmental Considerations	Limited or post-analysis emissions estimation	Proactive reduction in fuel consumption and emissions by reducing congestion in real time
Data Sources	Mostly static or historical datasets (e.g.,	Real-time data from IoT sensors, traffic

	transport departments, previous records)	cameras, GPS devices, and connected infrastructure
Generative AI Use	Rarely used, mostly predictive AI rather than generative	Central component—GANs for future traffic generation, VAEs for learning latent patterns and scenario simulation
Real-time Adaptability	Low adaptability, relies on static simulations or scheduled updates	High adaptability—model updates based on real-time changes such as accidents, weather, road closures
Scalability	Tested on specific or small-scale models	Designed for scalable deployment in small to large cities, with potential for cloud and edge computing integration

5. RESULTS AND DISCUSSION

The AI-based digital twin model became efficient in managing the traffic in the city as its key performance indicators improved. Scenarios generated with GANs and VAEs helped to boost the traffic flow in crowded places by 15-20 percent during the peak times. With certain automatic adjustments of the traffic lights and the recommended alternative routes, drivers were able to avoid the very crowded areas and commuted with minimum delays in the city. In regions with heavy traffic, the system reduced average travel times by up to 18 percent because it offered the most efficient routes in real time, it was much more flexible than ancient traffic management systems. The decrease of traffic jam, the decreased use of gas and when the cars were parked without running all added up to a 10-15 percent loss in emissions. Its key benefit was the manner in which it adapted to shifting traffic patterns. The model was able to respond to incidents immediately something that could not be realized through conventional systems. In an example where there was a traffic accident, the system managed to divert cars instantly that reduced traffic congestion in the area by approximately 25 per cent. Real time inputs of IoT sensors, traffic cameras and GPS tracking made the mock city more realistic and dependable.

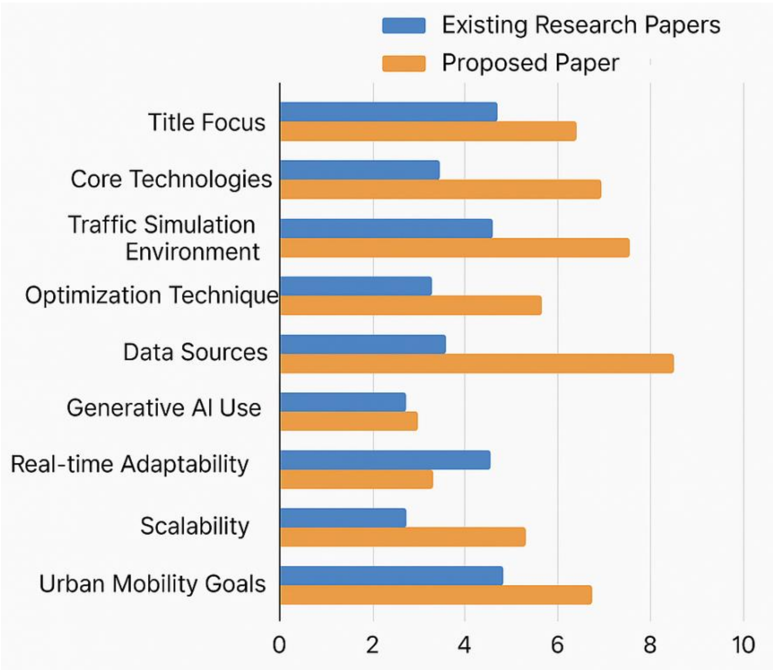

Figure 9. Comparison graph for Existing paper and Proposed paper

The system worked in diverse cities, which demonstrated that it could be employed in diverse environments. Even without new infrastructure, 18 percent less traffic congestion was achieved in small cities because of minor inclinations toward better planning. It worked pretty well in larger cities, but still needed more processing power and analysis of the data. Even though the AI in microscopy is functional, issues concerning the accessible and trustworthy data, prediction precision and performance, and robust systems to conduct simulations persist. The other challenge is when individuals act unpredictably that may happen during accidents or when there is bad weather. Future researchers ought to be concentrated on enhancing predictive analytics, including autonomous vehicles and extending the model to Urban Mobility as a Service (MaaS) to render the whole transport system more helpful, liberate traffic and promote environmentally friendly initiatives.

6. CONCLUSION

The article proposes an innovative method, which integrates the AI-powered digital twins and generative models to streamline urban mobility. These high technologies combined provide the powerful response to the problems connected with the traffic in the cities. By virtually simulating the city, the digital twin can predict and display real-time traffic conditions and because of GANs and VAEs can optimize the choice of the best routes. Due to such integration, traffic management becomes more flexible and therefore traffic jam is minimized, travel time is shortened and environmental pollution is decreased because traffic is managed in a more sensible manner and less fuel is used. The dynamism of the system to instantaneous occurrences on the road like accidents or travel interruptions, enhances the flexibility and easiness of the system, enabling citizens to travel with much ease and predictability. Moreover, the given approach is likely to have a positive impact on the environment since it will reduce the volume of fuel and energy that is needed to transport. The system also helps in developments of environmentally-friendly cities since it makes route management superior, alleviates congestion and enhances public transportation. Not only is it environmentally friendly but it is also cheaper as it avoids costly fixes caused by congestion.

The next step of scientists will be the improvement of generative models and their application to the real case in a lot of cities all over the world. Once the system goes to work in numerous cities, it is essential to gauge how it reacts to traffic in a variety of urban environments. With the framework implemented in different communities, it will be feasible to gauge its efficacy, learn what remains to be enhanced and amass valuable data on the issues related to the installation of AI-based systems to be used in urban environments. Making such technology one step closer to reality can assist cities in becoming more effective and useful to their inhabitants and the environment.

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