Predicting Pedestrian Crossing Behavior at Urban Intersections Using Machine Learning Techniques : Evidence from Hyderabad, India

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Abstract. Rapid urbanization and increasing traffic volumes have intensified conflicts between vehicles and pedestrians at urban crossings, making pedestrian safety a critical concern. This study investigates pedestrian crossing behavior using machine learning techniques at five major intersections in Hyderabad, India: Uppal, Dilsukhnagar, LB Nagar, Chaitanyapuri, and Meerpet. Data were collected from 400 pedestrians through a structured questionnaire covering demographic characteristics, trip attributes, traffic conditions, signal compliance, and perceptions of pedestrian facilities. Logistic Regression, Support Vector Machine (SVM), Random Forest, Gradient Boosting, and Artificial Neural Network (ANN) models were developed and evaluated using accuracy, precision, recall, and F1-score. The results demonstrate that machine learning models effectively predict pedestrian crossing behavior under diverse urban traffic conditions. Among the evaluated models, Random Forest achieved the highest prediction accuracy (82.19%), followed by Gradient Boosting (79.45%) and SVM (76.71%). Age, gender, traffic volume, signal waiting time, trip purpose, and the quality of pedestrian infrastructure were identified as the most influential factors affecting crossing decisions. Safety, accessibility, and walking distance also significantly influenced the choice of crossing facilities. The findings provide valuable insights into pedestrian decision-making and support data-driven strategies for enhancing pedestrian safety, optimizing signal operations, and improving sustainable urban mobility planning.

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1. Introduction

1.1 Background

As the main means of access to public transportation, business districts, educational institutions, and residential neighbourhoods, walking is a crucial part of urban transportation systems. Pedestrian mobility has grown in significance as cities continue to grow in order to guarantee accessibility, sustainability, and social inclusion [1]. However, interactions between pedestrians and motorized traffic have become more intense due to growing urbanization and rising automobile ownership, especially at congested urban crossings [2]. Pedestrian behavior analysis is a crucial field of transportation study since these interactions can lead to operational inefficiencies and safety issues.

A large percentage of daily road users in India is pedestrians. Despite its importance, infrastructure for walkers has sometimes received less attention than that for cars [3].

Improper road crossing facilities, uneven sidewalks and improper signal timings will increase the chances of pedestrian vehicle accidents and these conditions increase the chances of pedestrian-vehicle incidents very frequently and likely to place persons in dangerous crossing situations [4].

In the last 20 Years, out of all major metropolitan cities in India, Hyderabad witnessed a notable growth of transportation activity, residential and commercial activity. Large pedestrian volume and traffic volume is witnessed in the study area of Hyderabad city at crossroads like Uppal, Dilsukhnagar, LB Nagar, Chaitanyapuri, and Meerpet. The key factors like increasing traffic, heterogenous traffic conditions and inadequate pedestrian facilities impact the crossing behavior of pedestrains. Therefore, there is a need to study the pedestrian behavioral patterns to improve the pedestrian safety and urban mobility. Pedestrain crossing behavior is also greatly influenced by demographics, infrastructure quality, traffic patterns and individual risk perceptions

1.2 Pedestrian Behavior Analysis Using Machine Learning

New opportunities for transportation research emerged due to recent innovations in Data analytics and Machine Learning. In large data sets, the patterns can be identified and the complex non-linear relation between the variables without relying on statistical assumptions can be done by Machine learning algorithms [5]. Hence, all these techniques widely used in Intelligent transportation systems, accident investigation, traffic prediction and travel behavior modelling.

In pedestrian behavior studies, Machine learning techniques provides a methodological framework for analyzing the variables influenced by crossing decisions. Techniques including Artificial Neural Networks (ANN), Support Vector Machine (SVM), Gradient Boosting, Logistic Regression and Random Forest demonstrated important outcomes in classification and pedestrian behavioral prediction applications. By distinguishing different algorithms, planners can identify suitable techniques for modeling pedestrian decision-making processes and to improve prediction accuracy.

1.3 Research Gap

There are still a lot of unanswered questions, even after the vast studies on pedestrian behavior. Based on the machine learning-based research conducted for pedestrian behavior in developed countries, it is found that traffic patterns and infrastructure differ greatly from those in Indian cities. Lot of research identified on trajectory datasets, video analytics, or sensor-based observations but few studies done on pedestrian questionnaire-based behavioral data.

Only Few studies witnessed machine learning techniques of pedestrian crossing bahavior for Hyderabad City.

However, there were no comparative studies of various machine learning techniques for mixed traffic situations. Therefore, there is a need to combine field-based pedestrian survey data with state-of-the-art machine learning techniques enhances understanding of pedestrian decision-making variables and identify factors influencing crossing behavior.

1.4 Objectives of the Study

To examine pedestrian crossing behavior at identified urban intersections in Hyderabad City and develop predictive machine learning models. The key objectives are:

1. Identification of pedestrian characteristics and crossing patterns at specific intersections of Hyderabad.
2. Investigation of the traffic, infrastructure, and demographic variables which will influence pedestrian crossing choices.
3. Development of prediction models using Machine learning techniques like Logistic Regression, Random Forest, Artificial Neural Networks, Support Vector Machines, and Gradient Boosting.
4. Comparing the efficacy of different machine learning models using standard evaluation metrics.

1.5 Contribution of the Study

It is contributed to the increasing of research on pedestrian behavior by providing empirical data from a major Indian metropolitan city like Hyderabad. The study assesses and develops numerous machine learning models from field-collected pedestrian survey in order to identify the significant factors influencing crossing decisions. The key findings are expected to assist transportation planners and legislators in developing countries like India for offering data-driven methods for safer pedestrian facilities, improvement of signal operations to increase pedestrian safety.

2. Literature review

2.1 Pedestrian Behavior and Crossing Decisions

In view of traffic efficiency and road safety which is impacted by pedestrian behaviour has been thoroughly researched. Pedestrian crossing behaviour influenced by demographics, perceived safety, infrastructure quality and traffic circumstances [6]. Decision-making process of pedestrians is a dynamic process that is influenced by environmental, interpersonal and societal factors [7]. However, in urban environments, factors such as crossing position, age and traffic volume impacted on pedestrian risk exposure [8].

Recent research also revealed the significance of traffic conditions, waiting time and gap acceptance which influences the pedestrian crossing behaviour. However, judgments of pedestrian are highly affected by vehicle speed, traffic gaps and perceived risk [9]. Pedestrians are changing their crossing strategies by local traffic conditions rather than the behavioural patterns. However, In crowded urban intersections, pedestrian interactions influence individual decision-making process which will lead to crossing behaviours.

2.2 Machine Learning Applications in Transportation

The machine learning techniques usage for behavioral analysis and prediction has increased based on the availability of transportation data.
Machine learning models are highly superior in capturing nonlinear relation between several factors with increased prediction accuracy when compared to conventional statistical techniques. Machine learning algorithms demonstrated the ensemble learning approaches which performed accurately than the traditional models in predicting the severity of pedestrian injuries [10].

Similarly, it also proved that machine learning methods effectively relate between traffic, demographic variables, and environmental factors which offers prediction capabilities [11].

Due to outstanding capacity to handle diverse datasets, Artificial Neural Networks (ANN) Gradient Boosting, Support Vector Machine (SVM) and Random Forest have gained much popularity in transport sector. All these machine learning algorithms have been effectively used in traffic prediction, accident investigation, intelligent transportation systems and travel behavior modelling

2.3 Machine Learning Models for Pedestrian Behavior Prediction

Prediction of crossing behaviour of pedestrians has significant importance because of its implications of traffic safety and intelligent transportation systems. Predicting pedestrian crossing behavior has grown in importance as a subject of study because of its implications for and traffic safety. Prediction of pedestrians crossing intents, traffic gaps, vehicle speed, characteristics of pedestrians are highly influencing variables for crossing behavior decisions.

Vast studies indicated that ensemble learning algorithms will outperform conventional classification methods. Gradient Boosting and Random Forest Models consistently proved high prediction accuracy because of variable interactions and nonlinear linkages. Prediction performance has greatly improved by traffic-related data combined with behavioral characteristics [12]. Investigations were done for artificial intelligence-based methods for forecasting pedestrian crossing intentions in urban sector. Prediction models were studied by combining behavioral, environmental, and traffic-related variables in which machine learning algorithms models may successfully recognize pedestrian crossing behaviour prior to crossing actions [13]. Deep learning-based framework for pedestrian prediction intention indicates that crossing intents are highly influenced by motion characteristics, pedestrian posture and surrounding traffic conditions.

Based on the study, artificial intelligence techniques demonstrated that it can improve pedestrian behavior prediction [14]. Development of trajectory prediction models, surrounding road conditions, traffic environment and pedestrian interactions are highly significant factors in predicting pedestrian movements.

Artificial intelligence techniques proved that it can improve pedestrian behavior prediction patterns. The results showed how important it is for behavioral models to incorporate contextual information.

Furthermore, study conducted at unsignalized intersections proved that machine learning techniques accurately predict crossing compliance and gap acceptance. The findings show that understanding pedestrian behavior in complex traffic scenarios have the potential of data-driven approaches.

2.4 Deep Learning and Advanced Approaches

Recent advances in artificial intelligence have markable significance in Pedestrian studies. However, pedestrian studies advanced beyond conventional machine learning methods. Long Short-Term Memory (LSTM) networks, Convolutional Neural Networks (CNN) and Recurrent Neural Networks (RNN) and Transformer models are examples of deep learning architectures which are used in crossing intention and pedestrian trajectory prediction analysis.

Capturing long-term movement patterns proved more effectively by Transformer-based models [05], effectiveness of deep learning techniques for trajectory prediction is not with stranded using large-scale datasets. Because of their high computational resource and training data requirements, the methods' usefulness in many developing-country environments is limited.

Reinforcement learning frameworks for simulating pedestrian decision-making have also been investigated in recent research. Reinforcement learning may effectively depict pedestrian adaptation to traffic conditions and explain crossing decisions based on constrained rational behavior. These advancements point to intriguing avenues for further study of pedestrian behavior.

2.5 Explainable Artificial Intelligence

Recent transportation research has placed more emphasis on model transparency and interpretability, even though forecast accuracy is still crucial. Explainable machine learning framework created for analyzing pedestrian safety and showed how feature importance techniques may pinpoint important elements influencing dangerous pedestrian behavior. By supporting evidence-based transportation planning and offering insights into the decision-making process, Explainable Artificial Intelligence (XAI) approaches like SHAP analysis have enhanced the practical value of machine learning models.

2.6 Research Gap

The analysis of current research shows that machine learning methods for predicting pedestrian behavior have advanced significantly. There are still a few gaps, though. The majority of research has been done in industrialized nations; thus, it might not accurately reflect the mixed-traffic situations that are frequently seen in Indian cities. Furthermore, despite Hyderabad City's fast urban growth and rising pedestrian activity, little research has been done on the city. While very few research have used questionnaire-based pedestrian survey data, existing studies often rely on trajectory records and video analytics. Furthermore, there are still few comparative analyses of Artificial Neural Networks, Random Forest, Gradient Boosting, Logistic Regression, and Support Vector Machine under Indian urban traffic situations.

The current work uses pedestrian survey data gathered at significant crossings in Hyderabad City to develop and compare several machine learning models in order to fill in these gaps. In addition to assessing the feasibility of various machine learning algorithms for behavioral prediction, the study seeks to uncover important elements impacting pedestrian crossing behavior.

3. Methodology

The methodology adopted for the study is given in the figure 1.

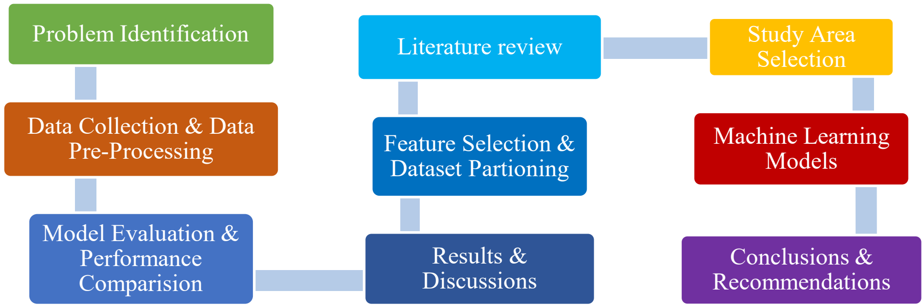

Figure 1. Methodology adopted in the study

3.1 Study Area

Five major urban crossroads in Hyderabad City, India were identified as Data Collection centres as given in figure2. They are: Meerpet, Uppal, Chaitanyapuri, Dilsukhnagar, and LB Nagar.Above data collection centres are identified due to the heterogenous traffic condition of which continuous pedestrian usage and strategic importance with transportation network. Because of the existence of educational institutions, businesses, residential areas, and public transportation there is a substantial pedestrian–vehicle interactions at study area.

Over last 20 years, the India's fastest growing city i.e., Hyderabad has tremendous increase in vehicular traffic. It is observed that minor portion of the road at the selected crossroads is shared by private vehicles, buses, motorcyclists, autorickshaws, and pedestrians. To analyse the pedestrian crossing behaviour, the above conditions provide appropriate environment inorder to determine the variables influencing decision making process of pedestrians.

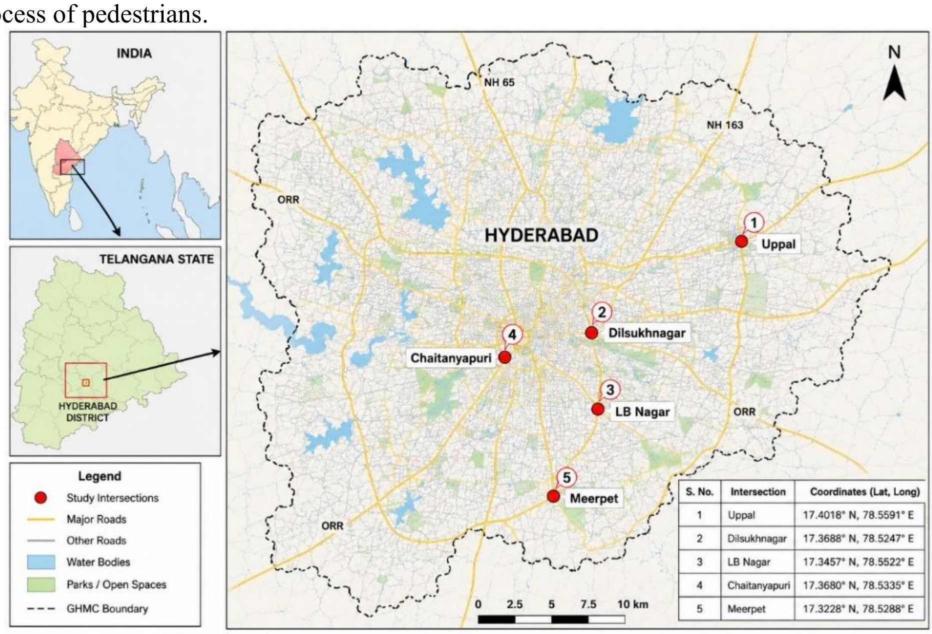

Figure 2. Location of Selected Study Intersections in Hyderabad City, India

3.2 Data Collection

At the selected crossings, a standard questionnaire survey was used to collect data on pedestrian behaviour. During peak and off-peak hours, the study was carried out to find the changes in pedestrain behaviour under prevailing traffic conditions. 400 valid responses recorded by pedestrians crossing the intersections at the specified locations.
The category of data included in the questionnaire are:

- Demographic characteristics (age, gender, occupation)
- Travel characteristics (trip purpose and travel frequency)
- Pedestrian crossing behavior
- Signal compliance behavior
- Waiting time at intersections
- Perception of pedestrian facilities
- Safety and accessibility preferences

In addition to survey responses, field observations were conducted to understand traffic conditions and pedestrian movement patterns at the selected intersections.

3.3 Variables Considered

Several explanatory variables were considered for the model's construction based on previous studies and field observations. These variables were divided into three groups.

a) Demographic Variables
   i. Age
   ii. Gender
   iii. Occupation
b) Traffic Variables
   i. Traffic volume
   ii. Waiting time at signals
   iii. Crossing frequency
   iv. Perceived traffic risk
c) Infrastructure Variables
   i. Sidewalk condition
   ii. Availability of crossing facilities
   iii. Lighting condition
   iv. Accessibility of pedestrian infrastructure

Pedestrian crossing behavior, as indicated by crossing compliance and crossing choice characteristics, was the target variable.

3.4 Machine Learning Framework

Before developing the model, the gathered dataset was preprocessed. Categorical variables were encoded for machine learning applications, and missing values were handled appropriately. After that, an 80:20 split ratio was used to separate the dataset into training and testing datasets.

Five machine learning algorithms were employed for pedestrian behavior prediction:

A. Logistic Regression (LR)

The probability of pedestrian behavioral outcomes was estimated using Logistic Regression as a baseline classification model.

B. Support Vector Machine (SVM)

The SVM model was created to determine the best decision boundaries for categorizing pedestrian behavior in various traffic scenarios.

C. Random Forest (RF)

Nonlinear correlations between explanatory variables were captured by using Random Forest, an ensemble learning technique based on numerous decision trees.

D. Gradient Boosting (GB)

Gradient Boosting was applied to enhance prediction performance via error minimization and sequential learning.

E. Artificial Neural Network (ANN)

To capture the intricate relationships between demographic, traffic, and infrastructure-related data, an artificial neural network model was created.

3.5 Model Evaluation Criteria

Commonly used categorization criteria were used to evaluate the proposed models' prediction ability.

Accuracy

The percentage of correctly identified observations relative to all observations is known as accuracy.

Precision

Among all expected positive observations, precision measures the percentage of accurately predicted positive observations.

Recall

Recall gauges how well the model can recognize real positive observations.

F1-Score

When assessing classification skills, the F1-score is especially helpful as it offers a balanced assessment of precision and recall.

The best machine learning method for forecasting pedestrian crossing behavior in Hyderabad City under mixed traffic situations was determined by comparing the performance of all models.

4. Results and discussion

4.1 Descriptive Analysis of Pedestrian Characteristics

Four hundred pedestrian answers were gathered from Hyderabad City's five main crossroads. The information gathered shed light on pedestrian demographics, travel habits, crossing patterns, and opinions about pedestrian amenities. The deomographic characteristics of survey respondents is given in table1.

a) Age Distribution

The age distribution of respondents indicated that the majority of pedestrians belonged to the economically active age group of 18–45 years. This group accounted for the highest proportion of road users and exhibited frequent crossing activity at urban intersections. The percentage of elderly pedestrians in the sample was lower, and they tended to cross the street more carefully.

b) Gender Distribution

The poll data showed that a greater proportion of respondents were male pedestrians than female pedestrians. However, female pedestrians showed relatively higher adherence to pedestrian signals and crossing facilities. The two groups' opinions of risk and safety issues differed.

c) Trip Purpose

The primary causes of pedestrian trips are access to public transportation, employment, education, and shopping. The importance of establishing safe pedestrian facilities near commercial and institutional venues is highlighted by the fact that most pedestrian movements were related to employment and education.

d) Crossing Frequency

Most respondents reported crossing roads multiple times a day. Regular drivers regularly adjusted their crossing strategies to suit the current traffic conditions and shown a greater familiarity with local traffic patterns.

Table 1. Demographic Characteristics of Survey Respondents (n = 400)

Variable	Category	Frequency	Percentage (%)
Age Group	18–25 Years	112	28.0
	26–35 Years	128	32.0
	36–45 Years	84	21.0
	46–55 Years	48	12.0
	Above 55 Years	28	7.0
Gender	Male	248	62.0
	Female	152	38.0
Occupation	Student	96	24.0
	Employee	154	38.5
	Business	72	18.0
	Homemaker	38	9.5
	Others	40	10.0
Trip Purpose	Work	148	37.0
	Education	102	25.5
	Shopping	84	21.0
	Recreation	32	8.0
	Others	34	8.5

4.2 Pedestrian Infrastructure and Safety Perception

The survey asked questions on pedestrian infrastructure quality and user perceptions of safety.

a) Sidewalk Condition

A significant portion of those surveyed expressed dissatisfaction with the condition and continuity of the walkways. Encroachments, inadequate width, and poor maintenance were identified to be common issues affecting pedestrian mobility.

b) Crossing Facilities

The availability and accessibility of pedestrian crossings had a significant influence on crossing behavior. Respondents reported that inadequate crossing facilities frequently encouraged people to cross outside of designated places.

c) Signal Waiting Time

Signal waiting time was determined to be one of the most significant factors affecting pedestrian compliance. Increased wait times frequently resulted in risky crossing behaviors and signal violations.

d) Safety Perception

In general, pedestrians considered rapid cars and heavy traffic to be serious safety issues. Respondents gave locations with inadequate pedestrian infrastructure poorer safety ratings.

4.3 Machine Learning Model Performance

Using the gathered dataset, five machine learning algorithms were created and assessed. Classification criteria such as accuracy, precision, recall, and F1-score were used to evaluate the models' performance. The performance evaluation of machine learning models given in table2.

Table 2. Performance Evaluation of Machine Learning Models

Model	Accuracy (%)	Precision	Recall	F1-Score
Logistic Regression (LR)	60.27	0.61	0.59	0.60
Support Vector Machine (SVM)	76.71	0.75	0.77	0.76
Random Forest (RF)	82.19	0.83	0.81	0.82
Gradient Boosting (GB)	79.45	0.80	0.78	0.79
Artificial Neural Network (ANN)	79.45	0.79	0.79	0.79

Note: Out of all the models assessed, Random Forest had the best prediction performance.

According to the obtained findings, Random Forest outperformed Gradient Boosting and Artificial Neural Network models in terms of prediction accuracy (82.19%). Among the models that were assessed, logistic regression yielded the lowest accuracy.

Random Forest's ensemble learning structure, which successfully captures nonlinear correlations and interactions among demographic, transportation, and infrastructure-related variables, is responsible for its exceptional performance. Results obtained are in line with prior transportation research that found that ensemble learning techniques outperformed conventional statistical methods in terms of prediction performance.

4.4 Important Factors Influencing Pedestrian Behavior

Several factors that have a major impact on pedestrian crossing decisions were found via feature importance analysis. The importance analysis of variables is given in figure3.

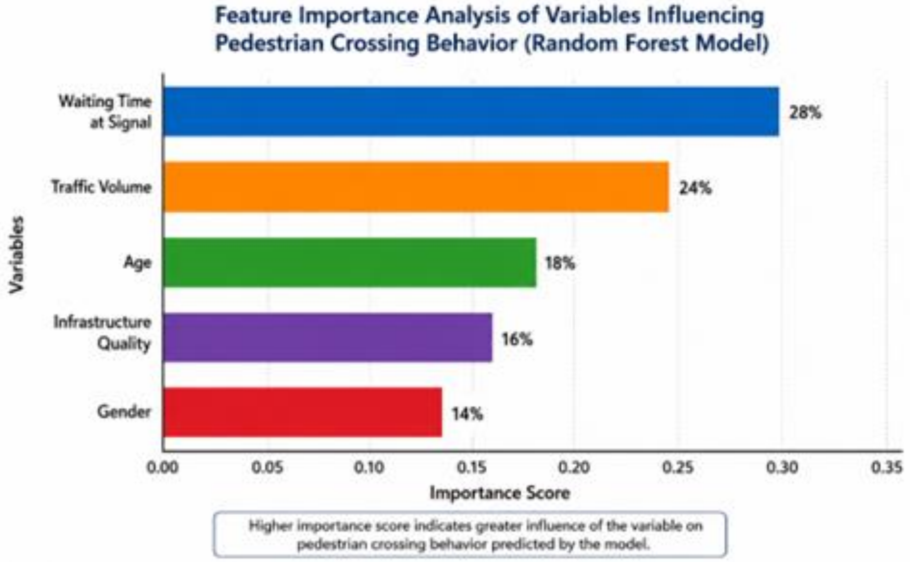

Figure 3. Importance analysis of variables influencing pedestrian crossing behavior

a) Age

One of the most important factors was found to be age. Compared to younger walkers, older pedestrians typically showed more cautious crossing behavior and greater adherence to traffic laws.

b) Gender

Gender differences were observed in risk perception and crossing decisions. Female pedestrians expressed greater concern for their safety and were more likely to use permitted crossing facilities.

c) Traffic Volume

Waiting time of pedestrian is increased and decisions of crossing behaviour were impacted by heavy traffic. Pedestrians were more likely to tolerate smaller gaps in traffic in crowded situations.

d) Signal Waiting Time

Intersections Waiting periods have a highest impact on pedestrian movements. It is observed that longer wait durations were associated with unsafe crossing practices and more signal violations.

e) Infrastructure Quality

Pedestrian decisions are greatly influenced by pedestrian infrastructure quality such as sidewalks and crossing facilities. Higher levels of compliance are associated with perceived safety for better infrastructure facilities.

4.5 Discussion

Pedestrian behavior is greatly effected by a complex interaction of infrastructure, traffic, and demographic factors. Random Forest and Gradient Boosting models confirms the improved performance of ensemble learning techniques to study pedestrian behavior under varied urban traffic scenarios.

Traffic and pedestrian factors significantly influence crossing decisions based on consistent research. Similarly, to improve forecast accuracy, the behavioral and traffic-related aspects of pedestrians must be included.

4.6 Practical Implications

Based on the study, safer crossing practices are greatly influenced by improving pedestrian infrastructure and reducing signal wait times. Choosing pedestrian-focused strategies and develop evidence-based traffic management plans will be done by transportation organizations. The findings have several practical implications for transportation planning and pedestrian safety:

1. Improving the pedestrian crossings infrastructure at significant intersections.
2. Improving signal timings of pedestrian to cut down on waiting times.
3. Constructing of pedestrian-friendly infrastructure in areas with high demand.
4. Use of machine learning-based behavioral models in intelligent transportation systems.
5. Using the data-driven techniques to find pedestrian safety and plan urban mobility.

5.Conclusions

Based on the machine learning techniques, examination of pedestrian crossing behavior at five significant urban crossroads in Hyderabad City were—Uppal, Dilsukhnagar, LB Nagar, Chaitanyapuri, and Meerpet. 400 pedestrians took part in a standard questionnaire survey in order to investigate how traffic, infrastructure, and demographics affect crossing decision behavior.

Random Forest (RF), Support Vector Machine (SVM), Gradient Boosting (GB), Artificial Neural Network (ANN) and Logistic Regression (LR) are the five machine learning models that were developed and evaluated.

Based on the results obtained, pedestrian crossing behavior is highly influenced by trip intent age, signal waiting time, traffic volume, gender and the quality of pedestrian infrastructure. Random Forest achieved the highest prediction accuracy of 82.19%, followed by Gradient Boosting (79.45%), Artificial Neural Network (79.45%), and Support Vector Machine (76.71%). Random Forest has superior performance when compared to other models of which demonstrates how effectively ensemble learning techniques capture complex relationships between pedestrian behavioral elements. Feature importance analysis proved that the most significant factors impacting pedestrian crossing decisions were signal waiting time, traffic volume and age. Practically speaking, the study also highlights the need for enhanced pedestrian infrastructure, optimal pedestrian signal timings, and better crossing facilities at major metropolitan crossings. The machine learning methods proposed can assist transportation agencies and improve urban mobility in developing data-driven pedestrian safety measures.

However the study provides useful information about pedestrian behavior in Hyderabad City, it is limited to questionnaire-based survey data collected at specific crossings. Future research may use video-based observations, larger datasets, trajectory analysis, explainable artificial intelligence (XAI), and real-time pedestrian surveillance systems to further improve forecast accuracy and model interpretability.

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