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Original Article

A Hybrid Indo-HCM, Fuzzy Inference and Regression Framework for Pedestrian Level-of-Service Assessment at Urban Crosswalks

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Abstract *- This study investigates the Pedestrian Level of Service (PLOS) at crosswalks. It employs Fuzzy Inference, Regression Analysis and the Indo-HCM guideline to evaluate and compare PLOS. Data are collected on important aspects of traffic and pedestrians, including perceptions and behaviour, using videography techniques and questionnaire surveys. This detailed study was conducted at five selected sites to assess pedestrian experience and factors affecting Pedestrian Level of Service (PLOS). The purpose of this study is to evaluate PLOS using the Indo-HCM guideline, Fuzzy Inference, Regression Analysis method. This study also aims to identify and evaluate the factors that influence PLOS. Finally, it compares the results of the two approaches, emphasizing the advantages and disadvantages of each strategy, and provides a basis for future PLOS assessments. The evaluation of these approaches, along with extensive data collection, leads to a better understanding of PLOS at crosswalks, which will provide valuable insights towards improving pedestrian safety, infrastructure and urban planning.*

Keywords *- Crosswalks, Fuzzy inference system, Indo-HCM, Pedestrian Level of Service, Regression analysis.*

1. Introduction

Ahmedabad has experienced significant growth in traffic volume over the last decade. Despite investments in road infrastructure, many pedestrian crossing facilities continue to face operational and safety challenges. Almost every journey starts with a pedestrian stage, whether it is an independent walk or travelling through public transport, private vehicles, up to parking facilities, etc. Walking is still preferred as the primary choice of travel for shorter distances in a growing city like Ahmedabad. There are several research conducted where it had been observed that pedestrian infrastructure is neglected in favour of vehicular traffic. This study mainly emphasises on how walkability can be improved by protecting the interests of pedestrians. Mixed traffic is the most common scenario in developing countries like India. In such conditions, vehicles and pedestrians share the same path. This will increase the risk of accidents and required more strict rules to improve pedestrians' safety. In 2022, India saw a record number of deaths due to road crashes, with more than 1.68 lakh lives lost. Daily, around 462 numbers of deaths happen in India, means one death every three minutes, which is much higher in compared to total number of fatalities in entire Japan and European Union.

As per the latest annual report published in 2021 from Accidental Deaths & Suicides in India (ADSI), around 162 numbers of pedestrian deaths took place in Ahmedabad region only, which is highest among the 52 Indian cities where such survey was conducted. This means that only in Ahmedabad, three pedestrian died every week. The data shows that 40% of the deaths were pedestrians [1]. Lack of proper infrastructure often makes pedestrians vulnerable, as they don't have any option but to walk on the roads.

In developing countries, generally sidewalks are often poorly maintained. Also, these are not child or senior citizen friendly. Even fewer crossings are constructed for crossing the road, such as underpasses or foot overbridges. This makes it extremely difficult for pedestrians to use the walkways freely, and which causes to walk them on the narrow paths. Such conditions will force vehicle drivers for sudden breaking and ultimately put many lives in danger. This interruption also causes delays in travel time.

The pedestrian level of service at crossroads via the Fuzzy Linear Regression and Indo-HCM method is used for assessing the safety of pedestrians at various intersections.

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The Indo-HCM method (i.e., crossing distance, speed factor of vehicles, and volume of pedestrians) is used to check the various factors that are causing problems at crossroads/intersections. The main factors considered for a higher rating of Pedestrian Level of Services (PLOS) are wider crossroads or shorter wait time at signals, or clear marking of signs. The rating are mainly categories between "A" to "F" scale, where "A" stands for a higher rating and "F" stands for poor/lower rating. The higher rating "A" is mainly contributed by good visible signs, lower wait time at signals, and sufficient space for road crossing, however for the rating "F" is considered where insufficient waiting time, no clear marking for pedestrians, and lower safety for pedestrians.

This pedestrian level of service is derived considering the codes recommended by the Indo-HCM method [2].

1.1. Objectives of Study

- To Analyse PLOS using the Indo-HCM guideline, Fuzzy Inference System & Linear Regression Approach.
- To assess the factors affecting PLOS using these approaches.
- To conduct a comparative analysis between these approaches.

1.2. Need for Study

Previous transportation studies have paid little attention to crosswalk operations, especially at midblock sections.

The Highway Capacity Manual (HCM) defines Level of Service (LOS) based on the average stopped delay, which may not reflect users' perceptions of the quality of service, comfort, and convenience. The proposed study will fill this research gap by developing a methodology based on fuzzy logic to determine crosswalk LOS which explicitly considers user perceptions.

2. Literature Review

In urban areas, the pedestrian facilities play a vital role for the people to commute with safety and comfortably in a proper manner. When the city expands, the traffic volume will substantially increase, and the safety of pedestrians will become the main concern. This is the most common concern is the developing countries. Assessing the quality level of services for pedestrians and reducing the conflicts between vehicular traffic and pedestrians. PLOS is widely accepted method in most countries. Since many years, several research is done for the improvement of pedestrians' safety and mobility at crosswalks, studying both quantitative factors, such as traffic features and delay, and qualitative characteristics, including user awareness and comfort.

In past studies, the pedestrian level of service was conducted based on the concept presented in Highway Capacity Manual (HCM), which is developed by Transport Research Board (TRB). The studies were mainly based on uniform vehicle movements, where the PLOS method was used to identify the key parameters like delay, walking speed, and available pedestrian space. On the other hand, due to lack of pedestrian pathways, traffic conditions will have a major effect on pedestrian movements in developing countries. Due to this, the conventional HCM method will not generate accurate results in such environments.

Several studies in developing countries are conducted to identify the Level of Safety (LOS) for pedestrians, where it is observed that LOS is not only affected by pedestrian delays but also has impact on safety, road crossing delay, traffic flow, and speed of vehicle. Hence, due to such mixed traffic conditions in Indian cities, it is observed that the PLOS method is more appropriate [3].

The Indian Roads Congress and Indo-HCM introduced guidelines for evaluating pedestrian facilities in Indian conditions. Indo-HCM defines PLOS with A to F categories based mainly on delay faced by at crosswalks and intersections. Although the Indo-HCM offers a structured methodology for assessing pedestrian infrastructure, its evaluation criteria are heavily skewed toward quantitative metrics. Consequently, the framework fails to sufficiently integrate qualitative, user-centric variables such as perceived safety, psychological comfort, and personal convenience [2].

An important advancement in pedestrian LOS modelling was introduced by S. Marisamynathan and P. Vedagiri through the application of Fuzzy Linear Regression (FLR) techniques for signalized intersection crosswalks. Their study argued that pedestrian perceptions regarding safety and comfort are uncertain and subjective in nature, making conventional regression methods less effective. To overcome this limitation, the researchers used fuzzy linear regression and fuzzy clustering techniques to develop a perception-based pedestrian LOS model. The study demonstrated that fuzzy approaches provide more reliable and realistic estimation of pedestrian LOS under mixed traffic conditions [4].

There were several studies conducted for the improvement of LOS based on traffic conditions. R. Nagraj and P. Vedagiri established a pedestrian LOS model at intersection crosswalks in Mumbai using pedestrian awareness along with variables such as pedestrian delay, turning traffic, and through traffic. Their study explained that pedestrian experience is the key factor in calculating pedestrian crossing facilities under mixed kinds of traffic conditions [5].

Similarly, Xiaofei Ye and co-authors studied pedestrian LOS at crosswalks under mixed kind of traffic conditions and observed that pedestrian delay, turning vehicles, pedestrian volume, and traffic interactions significantly affect pedestrian service quality [6].

Studies have shown that land use characteristics significantly influence pedestrian crossing behaviour and service quality. Studies evaluating pedestrian LOS at crosswalks from different land-use perspectives observed that commercial areas, schools, hospitals, and transit corridors generate higher pedestrian interactions and crossing complexity. Parameters such as pedestrian flow, crossing width, traffic volume, median refuge, and crossing difficulty were found to have considerable influence on pedestrian LOS [7].

Raad and Burke have focused on incorporating qualitative factors such as pedestrian comfort, security, convenience, and perceived risk into pedestrian LOS evaluation. Systematic reviews conducted by various researchers concluded that traditional LOS models based solely on pedestrian flow and delay are insufficient for evaluating pedestrian facilities in urban areas. Researchers recommended integrating subjective user perception with quantitative traffic parameters for more realistic pedestrian LOS assessment [8].

Md Imran Nazir et al. (2026) analysed pedestrian flow and walkway conditions in Dhaka and Chattogram using video data from 6 locations. Results showed males walked faster than females, younger pedestrians were fastest in Dhaka, and middle-aged pedestrians were fastest in Chattogram. Dhaka pedestrians moved faster with higher flow and density than Chattogram. Most walkways had good Pedestrian Service Levels (PLOS A), though Asad Avenue and Chittagong New Market showed lower service levels in some cases [9].

K. Sangeeth and Lorke found that LOS differs based on the parameter used, leading to a detailed study of pedestrian speed. Research showed that speed of pedestrians is influenced by age, gender, group size, and trip purpose. Based on the results, a new pedestrian LOS chart using pedestrian speed was developed and validated [10].

Andrikopoulou & Spyropoulou compared two key measures of pedestrian infrastructure, i.e., walkability and PLOS. Walkability focuses on qualitative parameters like safety, comfort, accessibility, and aesthetics, while PLOS measures operational factors like pedestrian flow, density, and speed. A review of 115 studies found that walkability is often treated as static and lacks standardization, while PLOS usually ignores social and spatial aspects. They concluded that when both approaches are combined, it can better support the safe, sustainable planning and design of cities [11].

On five different streets of the Ernakulam district, a survey was conducted on 405 pedestrians, including 55 physically challenged, by Sangeeth and Roy, which is mainly focused on age, gender, pedestrian physical ability, and trip purpose. This study was performed based on the QoS-CpM evaluation method along with Kendall's W and Friedman's ANOVA methods. The conclusion of the study shows that gender, age or trip purpose will have very little impact on the pedestrian satisfaction level, but if the pedestrian paths are available based on the analysis by QoS-CpM method, then the mobility of pedestrians will be easy [12].

Fatema et al. evaluated pedestrian walkability on selected footpaths in Khulna using PLOS framework. Twenty-one factors related to geometry, obstructions, amenities, and pedestrian traffic were analysed through the Analytical Hierarchy Process (AHP). The findings identified major important factors such as lighting, adequate footpath width, maintenance, permanent obstructions, and cleanliness. None of the surveyed footpaths achieved a satisfactory PLOS rating, with all classifieds under grades C, D, or E. Since a significant share of daily trips in Khulna are made on foot. The study concluded that there is an urgent requirement for improvement of infrastructure for pedestrians and prioritized interventions to support healthier and more walkable urban environments [13].

Kuo et al. investigated pedestrian crash risks among older adults in Taipei by with age group: young-old (65-74), middle-old (75-84), and oldest-old (85+). Using 783 intersection crash records and a Geographically Weighted Negative Binomial Regression (GWNBR) model, the study identifies environmental factors affecting crash frequency. Results show that intersections with high motorcycle activity and more nearby restaurants increase crash risks for all older adults. Subway stations and supermarkets mainly affect younger and middle-old groups, while nursing homes and shorter signal cycles significantly increase risks for the oldest-old due to slower walking speeds. The study emphasizes the need for age-specific pedestrian safety measures, including improved infrastructure and adjusted signal timings near high-risk locations [14].

Acela et al. examined pedestrian crossing behaviour in the culturally diverse cities of Bucaramanga and Guimarães, focusing on the influence of social and cultural factors. The research analyses walking speed, group spacing, group size, and gender composition during street crossings. Findings reveal that cultural context and informal social rules significantly affect pedestrian movement, particularly crossing speed and group organization. The study recommends culturally sensitive safety interventions and educational programs to improve pedestrian safety and infrastructure planning [15].

Silva et al. evaluated changes in pedestrian crash severity and related risk factors in Fortaleza during the Decade of Action for Road Safety (2009-2019). Using mixed logit models, the research analysed pedestrian crash data across three time periods, considering demographic, environmental, vehicle, and roadway factors. The findings show an overall

reduction in severe and fatal pedestrian crashes over time, indicating improvements in road safety. However, certain risk factors such as crashes involving heavy vehicles, expressways, arterial roads, nighttime conditions, and weekends continued to show high severity impacts. The study also found a significant reduction in severe and fatal crashes among older pedestrians (60+). Overall, the results suggest progress toward safer road systems, although some crash conditions remain insufficiently addressed by existing safety policies [16].

Dai et al. developed a walkability evaluation framework for residential neighbourhoods by analysing pedestrian-environment interactions across four dimensions using Agent-based Modelling (ABM). Data were collected from 13 streets in Shenzhen through field surveys and questionnaires. Using NetLogo, AutoCAD, and ArcGIS, street networks were simulated under different scenarios. Results showed that streets with higher walkability scores had more stable pedestrian activity throughout the day, while lower-rated streets experienced greater fluctuations. Street interface design and greenery significantly influenced walking behaviour, with greenery encouraging leisure activities but reducing commercial and recreational activities. The study concludes that different optimization strategies produce varying impacts on walkability, and simulation-based approaches can effectively support urban street design and planning [17].

Moslem et al. evaluated pedestrian behaviour factors affecting road safety using the Analytic Hierarchy Process (AHP) with Triangular Fuzzy Sets (TFS) and Kendall's correlation analysis. Pairwise comparisons with fuzzy linguistic variables were applied to identify and rank the influencing factors for older and younger pedestrian groups. Results revealed that psychological factors were the most significant contributors to pedestrian safety at Level 1, while being "hurried" was the most critical sub-factor at Level 2 for both age groups. Kendall's correlation indicated strong similarity between older and younger pedestrians for main factors, though differences existed in sub-factors. The study helps identify key behavioural criteria influencing pedestrian road safety [18].

Chai et al. used a fuzzy logic-based approach to model pedestrian decision-making behaviour at signalized crosswalks and during jaywalking, considering factors such as age and gender. Unlike traditional statistical methods, the study modelled pedestrian cognition and behavioural patterns using fuzzy sets and rules derived from field observations. Results showed that both older and younger pedestrians were less risk-taking compared to adults. Significant gender differences were observed only in highly hazardous situations, where men demonstrated better ability to recognize danger than women. The study shows the usefulness of fuzzy logic for understanding pedestrian behaviour for design of safer pedestrian crossing facilities and microscopic simulation models [19]. Duives et al. 2024 used four case studies on the Pedestrian Level-of-Service (PLOS) at mass gatherings, shopping places, festivals, and tourist hotspots. They investigate the relation between the PLOS and the dynamics for the crowd movements using a mix of survey and monitoring data. The research supports that the perception of LOS is somehow related to the crowd dynamics, and the use of in situ surveys and monitoring data gives a more holistic view of pedestrians' perceptions of space [20].

Amprasi V. et al. 2020, Thessaloniki, Greece, field measurements and microsimulation software Viswalk to evaluate the walking conditions across three time periods ("before, during, and after the peak"). Although objective analyses showed a high level of service and favourable conditions, subjective feedback from users showed a remarkable sense of discomfort and insecurity among pedestrians on the coastal front [21].

2.1. Synthesis of the Literature

Considering the outcomes of the literature review, the safety of pedestrians and the PLOS depends on various factors like operational, social, and environmental ones. The established PLOS models are mainly followed by the HCM or Indo-HCM methods or principles, considering delay, walking speed, and available space. However, when it comes to representing traffic variation, these models fall short. Many researchers have identified that the pedestrian service quality is affected by crossing difficulty, safety, comfort, and convenience. These studies are mainly conducted on mixed and diverse traffic, where several aspects are used, like pedestrian intersections, speed of vehicle, and crossing behaviour of pedestrians.

In the current research, the trend shows that Fuzzy Linear Regression (FLR), Fuzzy Logic, Analytic Hierarchy Process (AHP), Triangular Fuzzy Sets (TFS), and Agent-based Modelling (ABM) intelligent modelling practices are used. These methods can precisely correspond to the ambiguity and biases of pedestrian experiences and behaviours in reference to conventional statistical methods.

The study also focused on the behaviour of pedestrians, the purpose of their travel, and physical ability for designing and accessing the pedestrian facilities. These research findings are also shared about the lighting, design of walkways, vegetation, and maintenance.

The literature review suggests that for the future, the Pedestrian Level of Service (PLOS) shall focus mainly on building the integrated model-based framework, so the safety aspect, urban design elements, and operational aspects are considered.

Table 1. Comparative study of literature review

Category	Studies	Summary of Findings
PLOS under Mixed Traffic Conditions	Kadali & Vedagiri (2016), Nagraj & Vedagiri (2013), Ye et al. (2015), K & Lokre (2019)	Pedestrian LOS is affected by delay, traffic interaction, pedestrian speed, vehicle movement, and mixed traffic conditions.
Fuzzy and Perception-Based Modelling	Marisamynathan & Vedagiri (2019), Moslem et al. (2026), Chai et al. (2016)	Fuzzy logic and perception-based approaches better represent pedestrian behaviour, safety perception, and uncertainty.
Walkability and Sidewalk Assessment	Fatema et al. (2025), Sangeeth & Roy (2026), Dai et al. (2025), Andrikopoulou & Spyropoulou (2026)	Walkability depends on safety, comfort, greenery, lighting, sidewalk width, maintenance, and accessibility.
Pedestrian Safety and Behaviour	Kuo et al. (2025), Acela et al. (2025), Silva et al. (2025), Chai et al. (2016)	Age, gender, cultural factors, signal timing, and traffic conditions significantly influence pedestrian safety and crossing behaviour.
Review and Framework Studies	Raad & Burke (2018), Andrikopoulou & Spyropoulou (2026)	Existing LOS methods need integrated frameworks combining operational and qualitative parameters.
Pedestrian Flow Characteristics	Nazir et al. (2026), K & Lokre (2019)	Walking speed of pedestrians and flow vary according to demographic and operational characteristics.

The literature review reveals that a number of factors influence pedestrian LOS at crosswalks like pedestrian delay, pedestrian volume, traffic volume, vehicle speed, turning movements, crossing width, land use characteristics, and pedestrian comfort and safety and perception. Most previous studies conducted in developed countries focused on homogeneous traffic conditions, whereas limited studies are available for Indian urban roads operating under heterogeneous traffic conditions. Conventional regression techniques have limitations in handling uncertain and subjective pedestrian perception data. Hence, the application of Indo-HCM along with FIS methods can provide a realistic and reliable assessment of PLOS for crosswalks under heterogeneous traffic conditions.

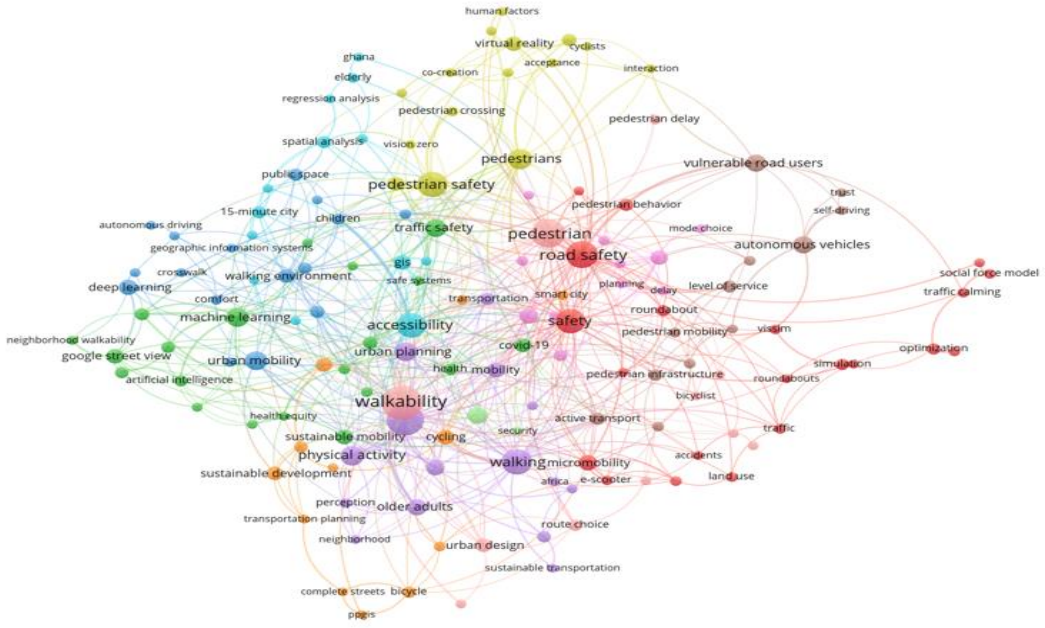


Fig. 1 Bibliometric visualization in VOSviewer

The bibliometric analysis using VOSviewer shows that the major research themes are centred around walkability, pedestrian safety, accessibility, walking, and road safety. These keywords appear as highly connected nodes, indicating their importance in pedestrian transportation research.

The network highlights several research clusters related to pedestrian safety and behaviour, urban mobility and accessibility, machine learning and GIS applications, sustainable transportation and physical activity, autonomous vehicles and smart transportation systems.

The analysis indicates that recent pedestrian studies are increasingly focusing on safety, sustainability, urban planning, and advanced technologies such as artificial intelligence, virtual reality, and simulation techniques.

It also shows growing interest in perception-based and technology-oriented approaches for improving pedestrian infrastructure facilities and evaluating PLOS.

3. Study Area & Methodology

3.1 Study Area

To study the typical roadway traffic and roadway conditions in India, 3 midblock crosswalks and 2 junctions with signals have been identified intersections and midblock intersections in Ahmedabad urban area having more pedestrian demand.

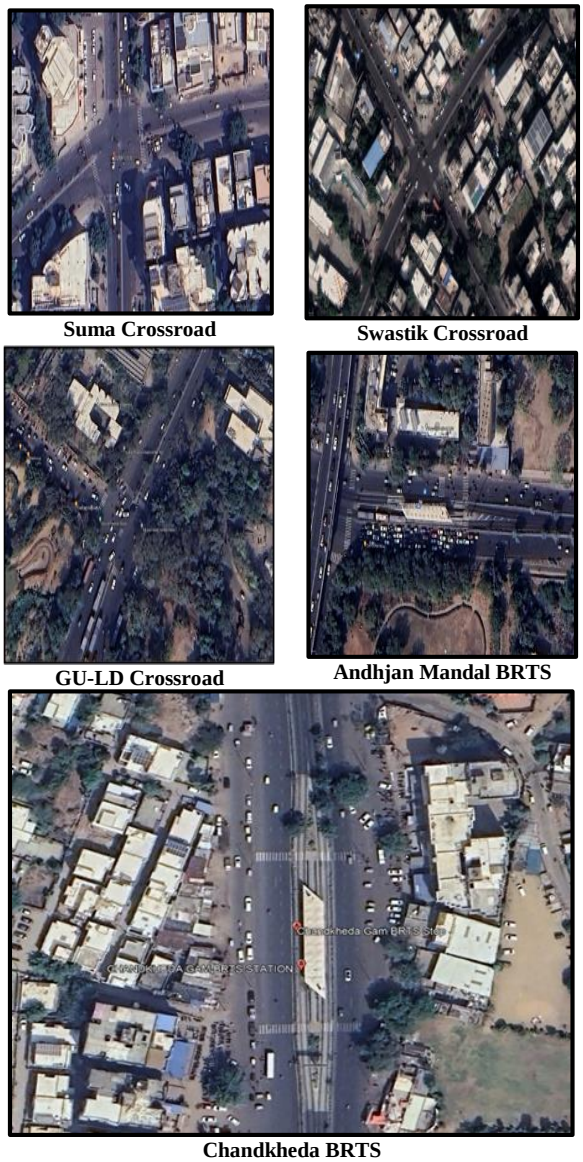


Fig. 2 Location of study area

The five locations are Suma crossroad, Swastik crossroad, LD-GU crossroad, Andhjan mandal BRTS, Chandkheda BRTS.

3.2. Methodology

Methodology is the process used to conduct a research study, project, or experiment. It explains how the work is carried out, including data collection, methods, tools, and analysis used to achieve the objectives.

In this study, Multiple Linear Regression (MLR) and a rule-based fuzzy inference system as two separate approaches were used. MLR was used to quantify statistical relationships between the selected variables, while the fuzzy inference system used membership functions and IF-THEN rules to represent gradual changes in pedestrian performance conditions.

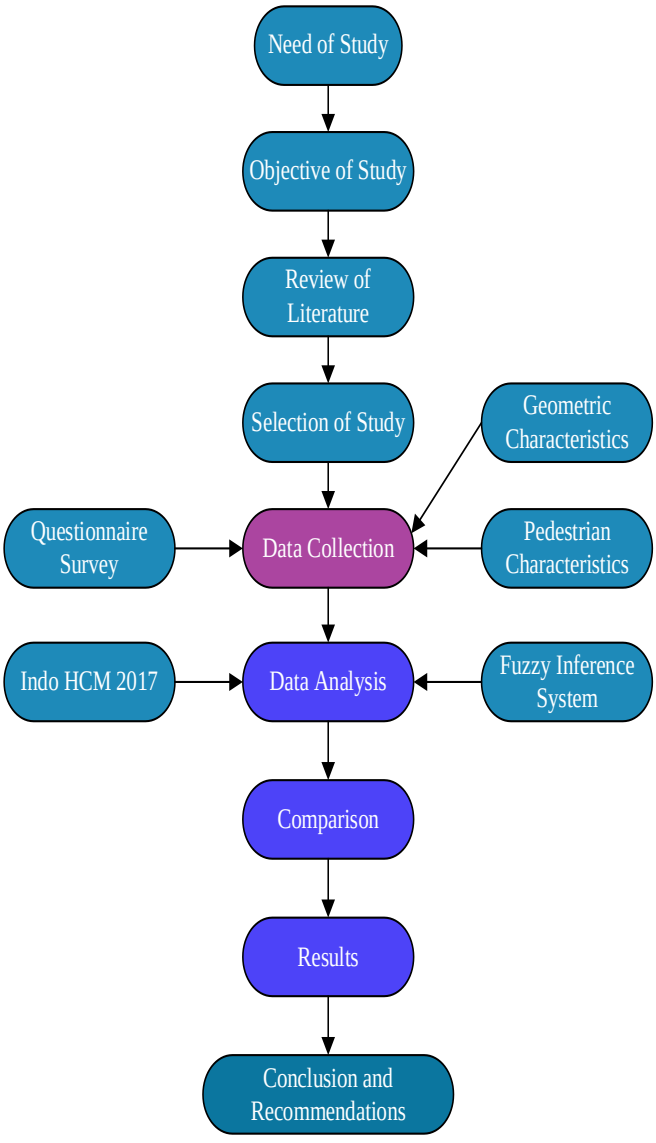


Fig. 3 Methodology chart

4. Data Collection

The data gathering process involved three main stages, namely, inventory survey, pedestrian perception survey, and pedestrian travel time survey at selected crosswalk locations.

Data Gathering Process: The factors considered for data collection are traffic volume, crosswalk width, timing of signals, width of road, lighting in the area, vehicle speeds, and nearby facilities.

Pedestrian Awareness Survey: The pedestrian awareness survey was performed on the crosswalks with some predefined questionnaires about safety, comfort, difficulty level, waiting time, and satisfaction in general for the pedestrian facilities.

Field Survey (Pedestrian Travel Time): Videography and in personal observations at crosswalk were used to collect information on speed, delay and crossing behaviour, and traffic conditions.

4.1. Sample Size Calculation

The sample size for a pedestrian survey depends on statistical adequacy rather than comparison with vehicular traffic. For pedestrian studies such as PLOS, crossing behaviour, and safety perception, sample size is commonly estimated using:

$$n_0 = \frac{z^2\, pq}{e^2} \quad (1)$$

Where:

n0 = sample size, Z = confidence level value (1.96 for 95%), p = estimated proportion (0.5 if unknown), (q = 1-p), e = allowable error. Typical sample sizes are 96 samples for 10% error, 196 samples for 7% error and 384 samples for 5% error. When pedestrian volume is low, complete enumeration or finite population correction can be used as mentioned below [22].

$$n_f = \frac{n_0}{1+\left(\frac{n_0-1}{N}\right)} \quad (2)$$

Where:

nf = Corrected sample size, N = Total pedestrian population

For low-volume pedestrian studies, 80-150 responses are commonly accepted in transportation research. If pedestrian movement is very low, it is academically acceptable to survey all available pedestrians during peak and off-peak periods using complete enumeration/saturated sampling.

Manyara et al. found that smaller sample sizes in Delphi surveys can still produce reliable results. A sample size of 60-80 participants achieved high replicability (≥80%), while subgroup analyses showed that even 20-30 participants per stakeholder group provided moderate and acceptable replicability.

The findings suggest that relatively small sample sizes are sufficient for obtaining stable and dependable Delphi survey results. [23] Forsyth et al. highlighted that many pedestrian and cycling surveys use inadequate sampling methods, which can limit the reliability and generalizability of results.

To address this, the Pedestrian and Bicycling Survey (PABS) project proposed a simple, low-cost, and statistically reliable probabilistic sampling method that can be implemented by local agencies. The study emphasized that well-designed smaller samples can still provide meaningful and generalizable data for pedestrian and cycling analysis [24].

Table 2. Confidence intervals for sample size-related variability

	Errors by percentage of Characteristic Prevalence				
Sample Size	5/95	10/90	20/80	30/70	50/50
35	7.0	10.0	14.0	15.0	17.0
50	6.0	8.0	11.0	13.0	14
75	5.0	7.0	9.0	11.0	12.0
100	4.0	6.0	8.0	9.0	10.0
200	3.0	4.0	6.0	6.0	7.0
300	3.0	3.0	5.0	5.0	6.0
500	2.0	3.0	4.0	4.0	4.0
1,000	1.0	2.0	3.0	3.0	3.0
1,500	1.0	2.0	2.0	2.0	2.0

Source: [24]

4.2. Road Inventory Data Collection

Geometric parameters of the road, such as Crosswalk width, Crosswalk length, Shoulder width, Median width, Roadway Condition, Distance from signalized intersection and control parameters such as signal timing sign board presence were collected manually. Table 3 shows road inventory data.

Table 3. Road inventory data

Parameters/Site	Suma Crossroad	Swastik Crossroad	LD-GU Crossroad	Andhjan Mandal BRTS	Chandkheda BRTS
Crosswalk width	4.0 m	4.0 m	4.0 m	4.0 m	4.0 m
Crosswalk length	Approaches 1st - 20.8 m 2nd -19.3 m 3rd -19.2 m 4th -21.4 m	Approaches 1st -18.4 m 2nd -18.6 m 3rd -18.2 m 4th - 18.6 m	26.37 m	10.50 m	10.50 m
Shoulder width	2.5 m	2.5 m	2.5 m	2.5 m	2.5 m
Median width	0.92 m	1.0 m	3.22 m	10.91 m (with exclusive BRTS lane)	10.91 m (with exclusive BRTS lane)
Roadway condition	Good	Good	Good	Good	Good
Distance from signalized intersection	-	-	322.95 m	121.18 m	1st crosswalk - 124.48 m 2nd crosswalk - 186.01 m

Pedestrian data collection was carried out during peak hours at crosswalks using two methods, i.e. user perception surveys and videographic surveys. Investigators stationed at these intersections conducted user perception surveys, engaging pedestrians to gauge their safety perceptions, comfort and efficiency. Simultaneously, videographic surveys captured quantitative data on key factors impacting Pedestrian Level of Service (PLOS). These factors encompassed pedestrian volumes, crossing times, signal operations, vehicular interactions, and other variables affecting pedestrian movement and safety. A thorough understanding of pedestrian experiences at the crossing intersection is obtained through a videographic survey, which helps achieve the objective of PLOS. This combined approach aids in devising targeted improvements to enhance pedestrian safety and optimize pedestrian management strategies.

4.3. Videography Survey

Data were collected at peak periods on the crosswalks through two approaches: user perception survey and videographic survey. The user perception survey was conducted by investigators located at these points through engaging pedestrians to assess their feeling regarding safety, efficiency, and comfort while crossing the road. At the same time, the videographic survey was used to gather quantitative data regarding the determinants of Pedestrian Level of Service (PLOS).

Combination of both qualitative and quantitative information collected through videographic survey was helpful in having a full view of the pedestrians' experience and the objective factors that affect PLOS.

Information on pedestrians' movements, the flow of traffic, and the intersection layouts was collected through the videographic survey. The mobile cameras had been installed in such a way that pedestrians' movements towards and from the intersection at the designated crosswalks could be recorded.

This comprehensive survey focused on recording pedestrian activity within the entire study area. To ensure accuracy and detail, data extraction occurred manually in a laboratory setting. While this method is time-consuming, it offers distinct advantages, such as precision and the creation of a durable record of events. The survey's setup involved cameras oriented to track the flow of pedestrians entering and exiting the junctions through defined crosswalks.

This precise documentation comprised several factors: pedestrians' movements, vehicle movement, and physical characteristics of the junction. With the help of manual data collection from the lab, the procedure ensured accuracy with a view to producing a complete and permanent database. Although it's a time-consuming procedure, it ensures accuracy and understanding of the pedestrians' behaviour at crossing intersections.



Fig. 4 Videographic survey at Andhjan Mandal BRTS

The data was gathered at 2-hour intervals from 9:30 am to 11:30 am in the morning and from 5:00 pm to 7:00 pm in the evening using a video recording apparatus. The recordings provided details regarding various aspects such as total pedestrian time, crossing duration, waiting duration, pedestrian crossing speed (measured in both meters per minute and meters per second), ideal crossing duration, crossing delay, and pedestrian delay.

Various pedestrian characteristics parameters such as waiting time, crossing time, total time, crossing speed, crossing delay, ideal crossing time and pedestrian delay. The data presented in Graph is a compilation of information obtained from video recordings for each specific location. The graph illustrates the comparison of each parameter across various locations. The table displays the average values for each of these parameters.

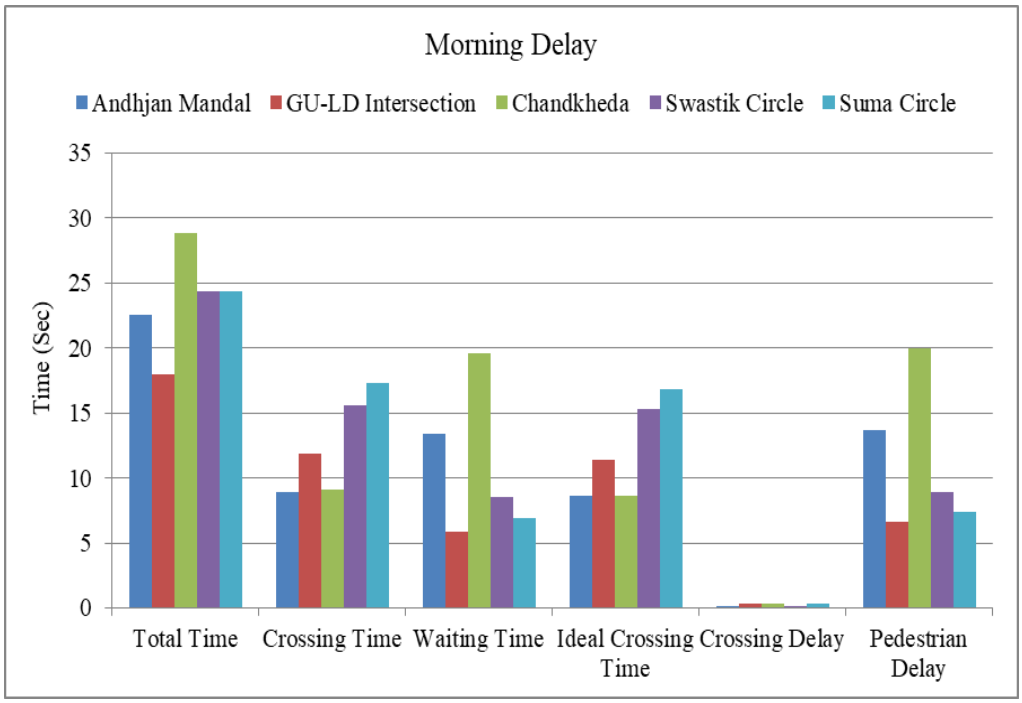


Fig. 5 Pedestrian characteristics parameters comparison (Morning peak hour)

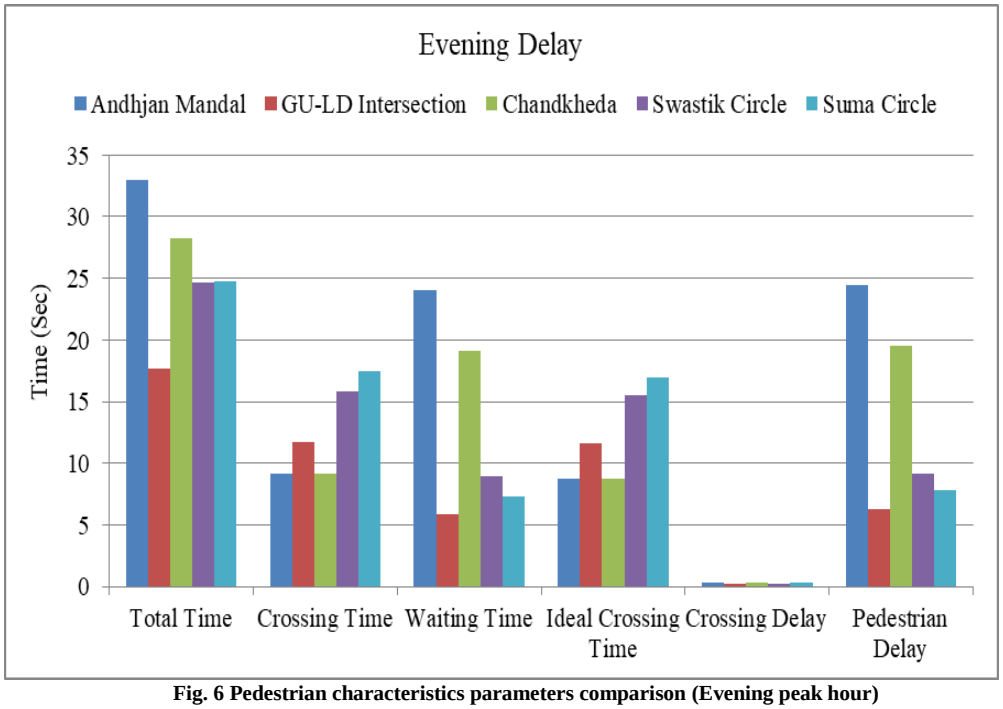


Fig. 6 Pedestrian characteristics parameters comparison (Evening peak hour)

Figures 5 and 6 depict the comparison of various parameters across the study area during morning and evening peak hours.

4.4. User Perception Survey

The survey was conducted with the support of trained surveyors positioned on both sides of crossing, with two questionnaires set of predefined question. An explanation was provided to each pedestrian before gathering the data, along with the detailed questions and its rating.

Customized questions were prepared based on the specific types of groups: pedestrians with physical impairments and pedestrians without physical impairments.

Data collection of pedestrians with physical impairments was done at the Andhjan Mandal location; however, other four locations (GU-LD intersection, Chandkheda, Swastik Crossroad, and Suma Crossroad) were used for data collection for pedestrians without physical impairments.

A five-point scaling range (1 to 5) was used to collect parameters like safety, efficiency, difficulty level, and convenience. The data was collected via survey in the form of predefined questionnaires for 135 pedestrians.

Out of these, 100 respondents were without physical impairments, while 35 were with physical impairments. Furthermore, the ratio of female respondents is higher compared to male respondents.

4.4.1. Reliability Analysis of the Questionnaire

Based on the responses received on the questionnaire items, Cronbach's Alpha was calculated. The reliability coefficient was determined using:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k} \sigma_1^2}{\sigma_T^2}\right) \quad (3)$$

Where:

α = Cronbach's Alpha coefficient;

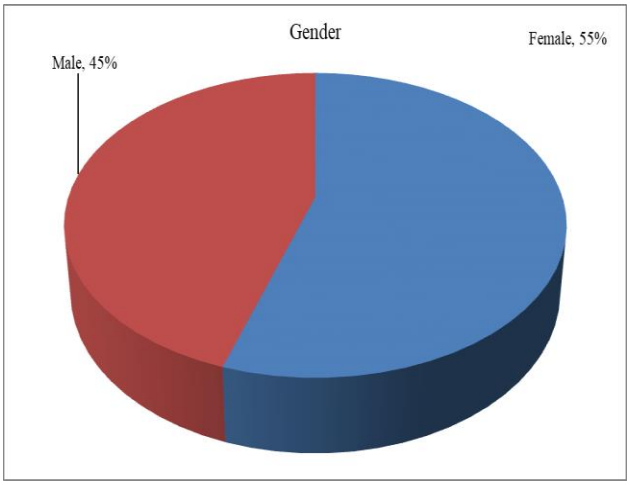
k = Number of questionnaire items included in the scale;

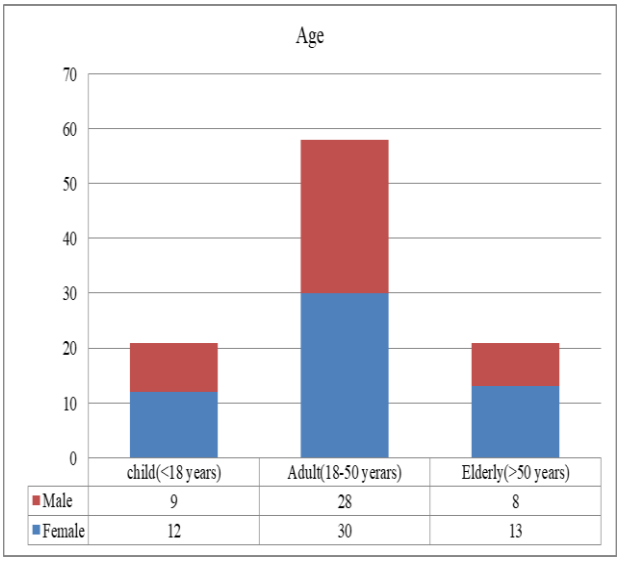
σ2 = Variance of the scores for the ith questionnaire item;

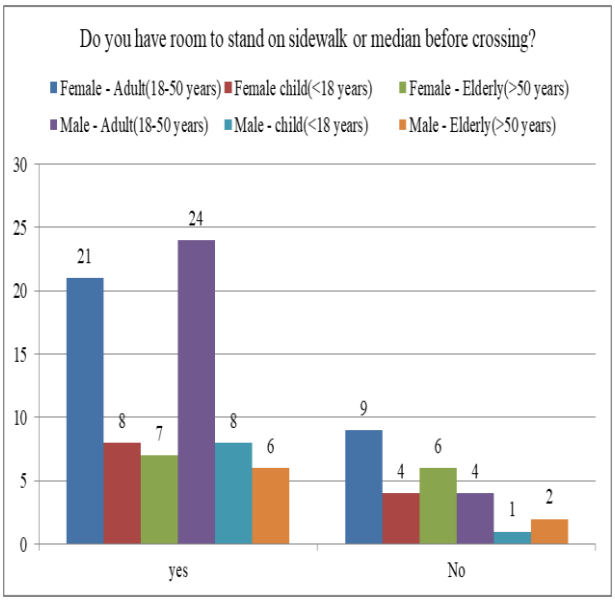
$\sum_{i=1}^{k} \sigma i2$ = Sum of the variances of all individual items;

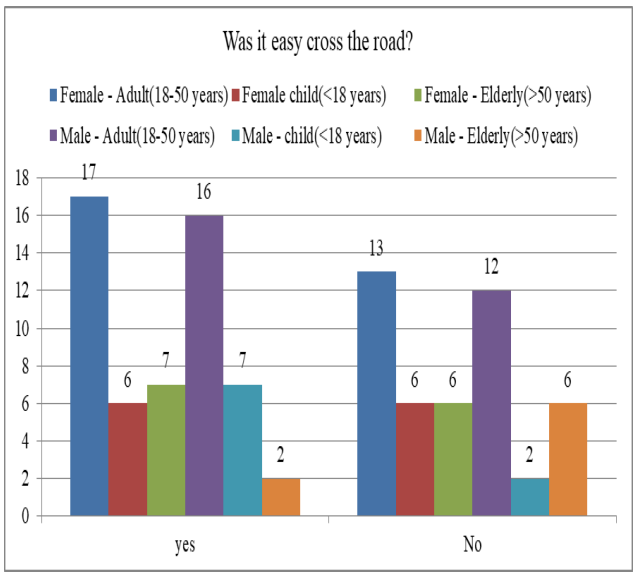
σT2 = Variance of the total questionnaire score obtained by summing the item scores for each respondent.

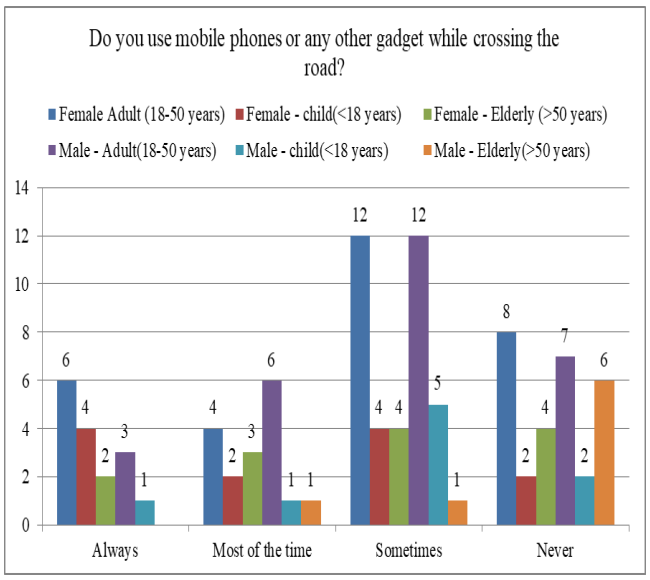
Based on the responses received from the questionnaire, Cronbach's Alpha was calculated as 0.751, which is considered an acceptable limit.

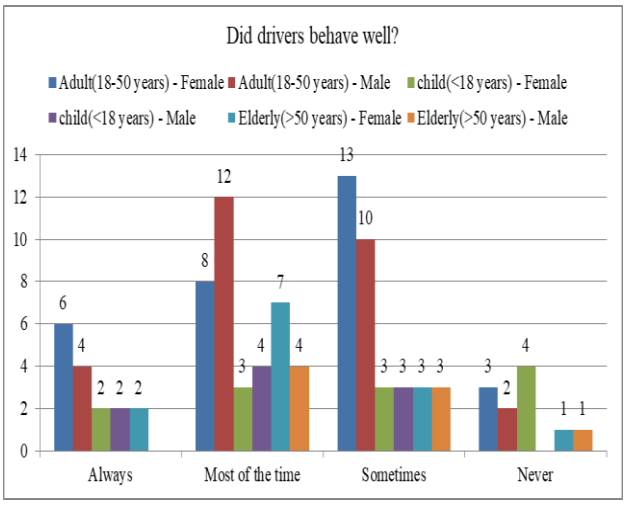


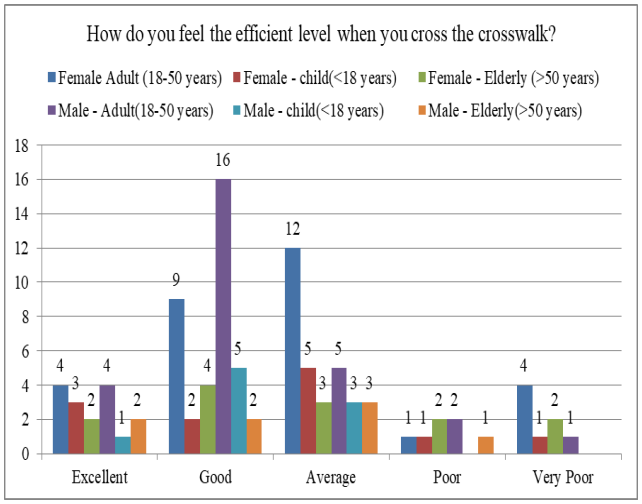


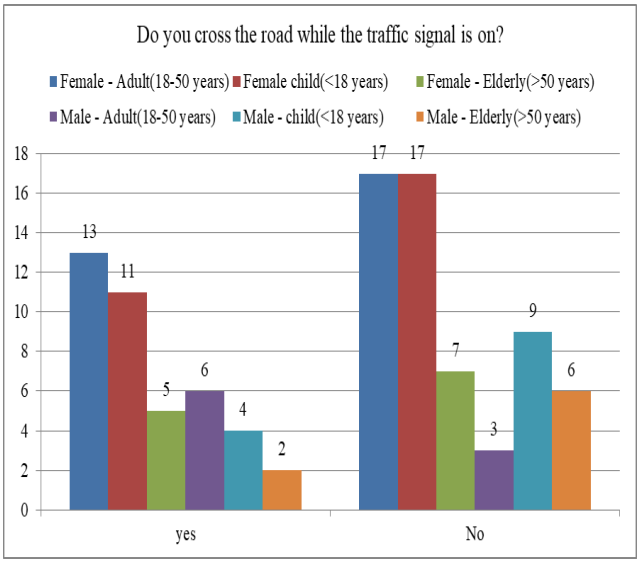


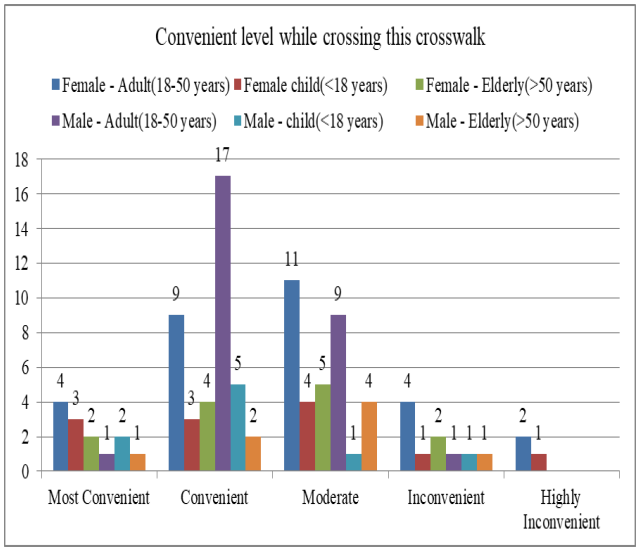

Was it easy cross the road?
Female - Adult(18-50 years)
Female child(<18 years)
Female - Elderly(>50 years)
Male - Adult(18-50 years)
Male - child(<18 years)
Male - Elderly(>50 years)
yes
No

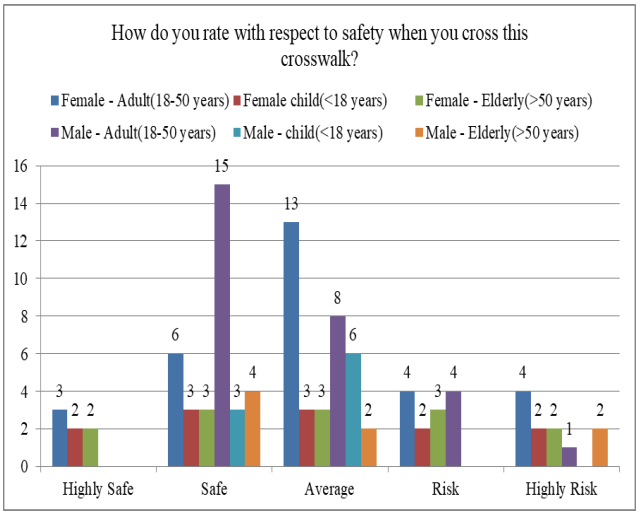

Do you use mobile phones or any other gadget while crossing the road?
Female Adult (18-50 years)
Female - child(<18 years)
Female - Elderly (>50 years)
Male - Adult(18-50 years)
Male - child(<18 years)
Male - Elderly(>50 years)
Always
Most of the time
Sometimes
Never

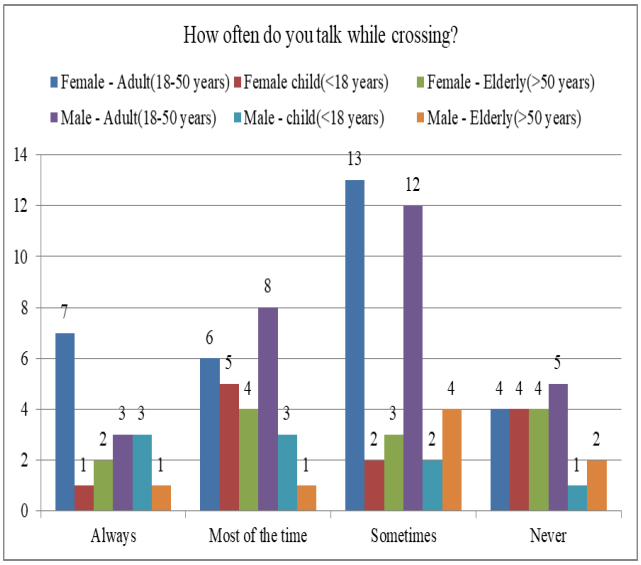

Did drivers behave well?
Adult(18-50 years) - Female
Adult(18-50 years) - Male
child(<18 years) - Female
child(<18 years) - Male
Elderly(>50 years) - Female
Elderly(>50 years) - Male
Always
Most of the time
Sometimes
Never


How do you feel the efficient level when you cross the crosswalk?
Female Adult (18-50 years)
Female - child(<18 years)
Female - Elderly (>50 years)
Male - Adult(18-50 years)
Male - child(<18 years)
Male - Elderly(>50 years)
Excellent
Good
Average
Poor
Very Poor


Do you cross the road while the traffic signal is on?
Female - Adult(18-50 years)
Female child(<18 years)
Female - Elderly(>50 years)
Male - Adult(18-50 years)
Male - child(<18 years)
Male - Elderly(>50 years)
yes
No


Convenient level while crossing this crosswalk
Female - Adult(18-50 years)
Female child(<18 years)
Female - Elderly(>50 years)
Male - Adult(18-50 years)
Male - child(<18 years)
Male - Elderly(>50 years)
Most Convenient
Convenient
Moderate
Inconvenient
Highly Inconvenient





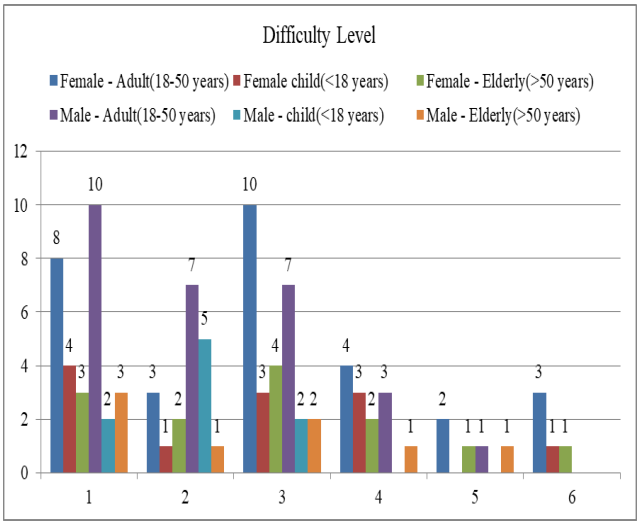


Fig. 7 Questionnaire survey result (Pedestrians without physical disabilities)

More details have been considered regarding the survey about pedestrian behaviours and experiences crossing the road. 74% of the people reported that they love staying at the right place while road crossing, while 26% of the people says that they do not follow this practice. That means that pedestrians use different practices to secure themselves during road crossing.

About 55% of the pedestrians said that road crossing seems easy for them, while 45% reported as hard. Experiences of crossing roads may vary depending on certain factors such as traffic situations and road designs.

Regarding the experience of interaction between pedestrians and drivers, 38% of the people reported good experiences because they said that some drivers behave in a polite manner and follow traffic laws, while 11% of the people reported bad experiences because they stated that some drivers ignore pedestrians and treat them in an impolite manner.

Different opinions are considered whether pedestrians abide by traffic lights while crossing the roads or not. Only 41% of the people reported that they follow traffic signals, while 59% reported the opposite.

The survey also includes the behaviour of use of mobile phones while crossing the roads, where it has been observed that around 41% of females use phones during road crossing, against the ratio of 31% in comparison to males.

Around 16% of the pedestrians from the survey found that the road crossing is well organized; however, only 8% of the pedestrian respondents said that the road crossing conditions are unsatisfactory, mainly due to traffic congestion and inefficient pedestrian services.

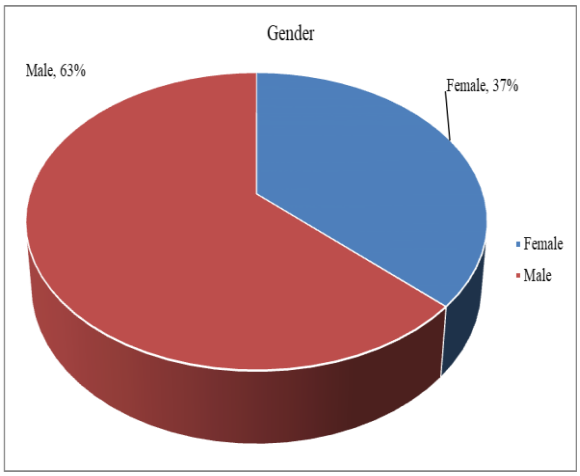
The survey results make clear that pedestrians' opinions vary widely. While 7% of the respondents considered crosswalks to be highly safe, 34% considered crosswalks to be safe. In contrast, 24% of pedestrians say crosswalks are dangerous. This shows that individuals' views vary depending on safety and road conditions.

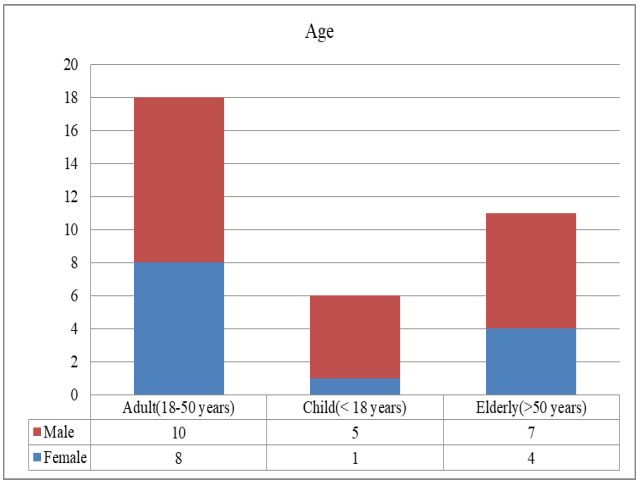
Considering the differing opinions, still 87% of pedestrians feel that road crossings are convenient in one way or another. Only 13% of pedestrians were dissatisfied with the road crossing conditions.

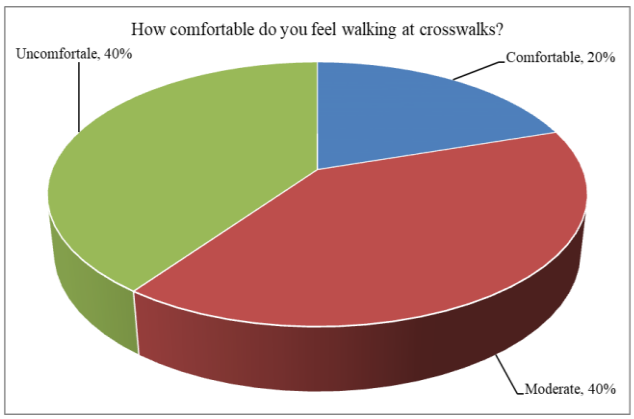
In addition to the above, the survey also covers the communication behaviour of pedestrians during road crossings. 43% of women and 37% of men claimed that they communicate either via phone or in person while road crossing. In total, 30% of people claimed that it was quite easy for them to cross the road, while 5% of people faced difficulties.

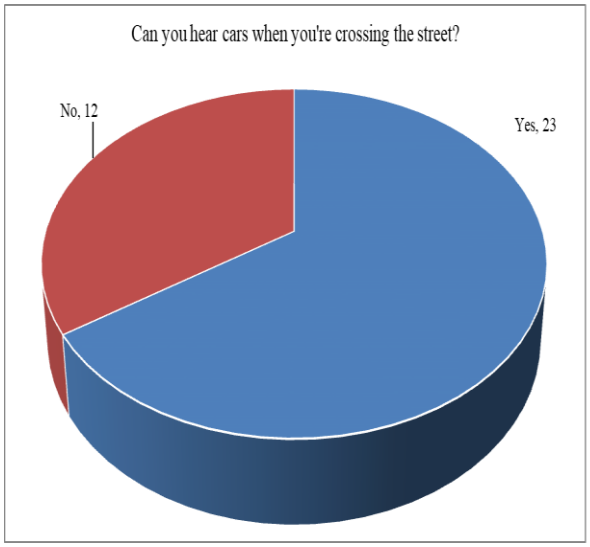
4.4.2. Survey for Pedestrian with Physical Impairment

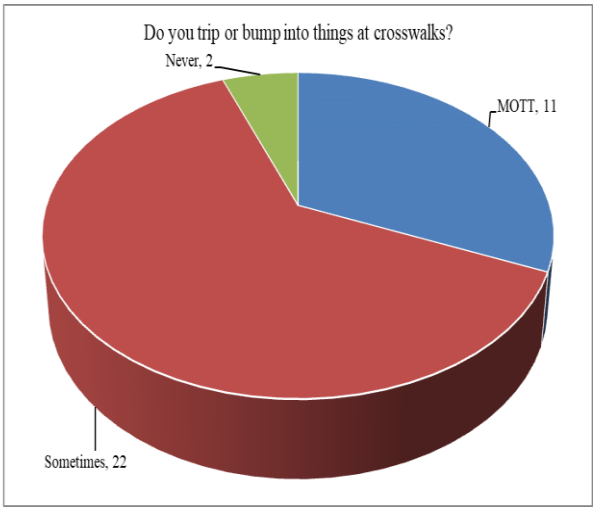
The Andhjan Mandal crossroads were one of the spots used as an area for research, and here the building of the blind people's association was located near the crossroads. This means that there were quite many pedestrians with physical impairment walking across the crossroads. A survey was carried out on pedestrian with physical impairments. Figure 8 below shows the results of the analysis of the survey data.

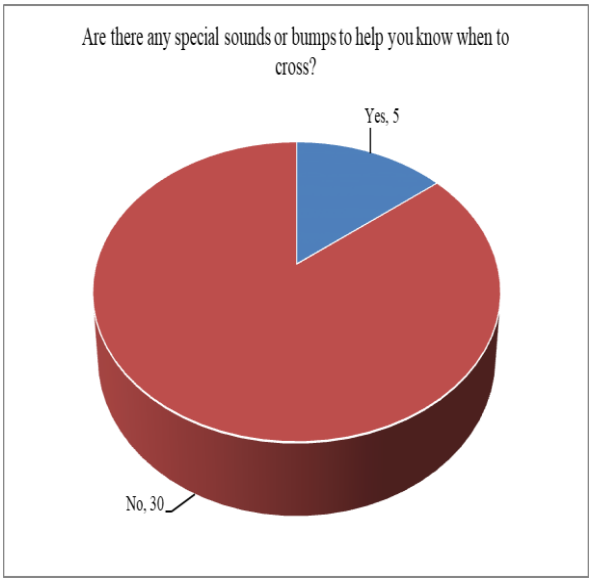


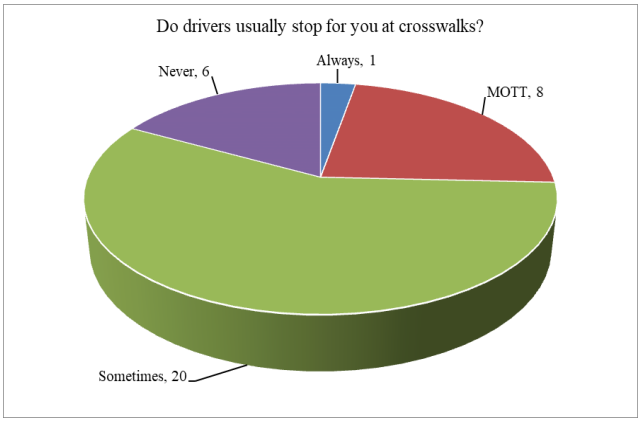


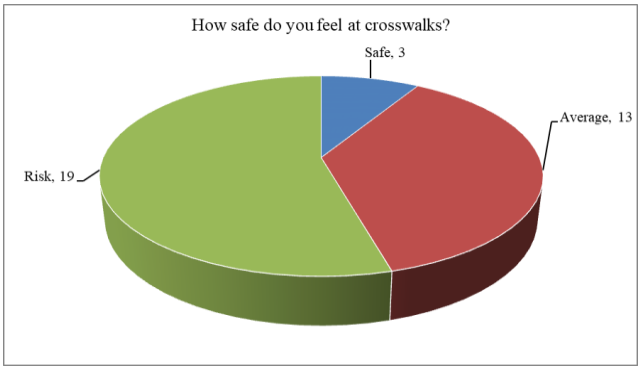


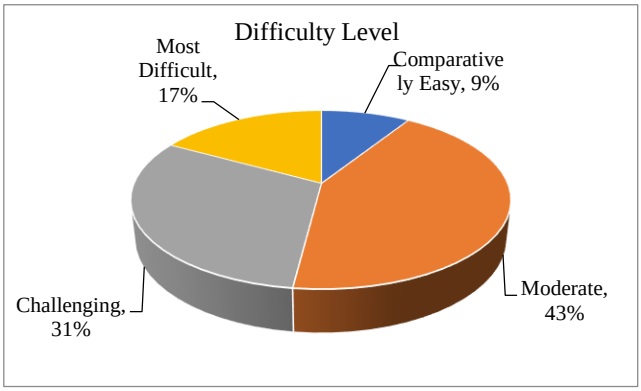












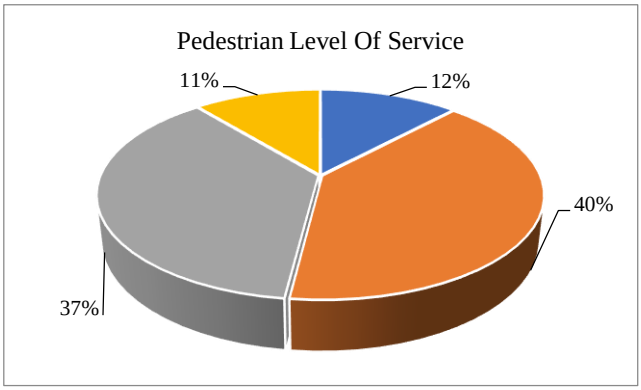


Fig. 8 Questionnaire survey results (Pedestrians with physical disabilities)

In terms of the gender distribution, there was an observation that more men (60%) were part of the sample than women (40%). In addition, there was a revelation from demographic segmentation that 52% of the participants were adults, 16% of the sample size were children and 32% elderly pedestrians.

The responses showed the complexity associated with comfort and discomfort associated with pedestrian with physical impairment individuals when crossing crosswalks. This is because 56% of the individuals felt comfortable crossing the crosswalks, while others felt entirely uncomfortable crossing the roads, making up 44% of the sample size.

The responses regarding the perception of sounds that indicate the coming of vehicles revealed that 64% could hear the oncoming vehicles while 36% had problems in hearing these sounds. The number of people who were tripped or bumped when crossing roads was significant; 28% had this experience most of the time while 68% occasionally experienced it. Only 4% said that they never experienced this problem.

Only 16% of the entire sample data mentioned about use of audio signals or signs for physically challenged people. However, a vast number of pedestrians 84% reported that they do not use such audio signals, but still, they welcome such improvement in signals and infrastructure. Driver attitudes also play a major role at crossings, where 84% of the pedestrians experienced drivers allowing pedestrians to cross the road; however, 16% of drivers ignored them during the crossing.

There were mixed responses on the safety aspects, as 44% feel comfortable while crossing the road; however, 54% still feel it is challenging. There was a wide range of responses from the pedestrians regarding the difficulty level at the road crossing: 8% considered it easy, 40% felt moderate, 36% felt difficult, and 16% stated it was most difficult. The above results suggest that more inclusiveness and accessibility are required to create such environments.

5. Data Analysis & Determination of PLOS

This section shows a brief overview of the data analysis, focusing on the application of fuzzy logic and the Indo-HCM methodology, explaining their respective procedures, and examining their relationship.

5.1. Determination of PLOS using Indo-HCM 2017

Indo-HCM primarily defines the concept of PLOS and presents different facility ranges. These methodologies for PLOS are identified in terms of different forms of pedestrian facilities such as crossings, footpaths, footbridges, and stairways considered in the paper.

Table 4. LOS based on delay (Indo HCM) [2]

LOS	A	B	C	D	E	F
Pedestrian delay in sec	<5	5-10	11-25	26-45	46-80	>80

According to the Indo HCM guideline, LOS A is considered the best operating condition for pedestrians, while LOS F is defined as poor.

5.2. Methodology for PLOS Determination of Crosswalks

Methodology is required to systematically evaluate the performance and safety of crosswalk facilities. By measuring the delay time experienced by pedestrians and determining the PLOS, the study helps in understanding the comfort, convenience, and efficiency of pedestrian movement at crossing locations. The methodology also assists in identifying problematic crosswalks with excessive delays and unsafe conditions, which can support traffic planners and authorities in improving pedestrian infrastructure, enhancing road safety, and promoting sustainable urban transportation.

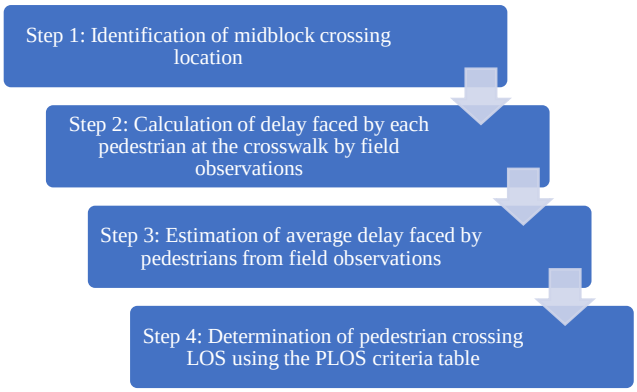


Fig. 9 Methodology flow chart for PLOS determination of crosswalks

A step-by-step procedure is specified in Figure 9 above for identifying PLOS at different crosswalk locations. In the first step, crossing locations are identified based on pedestrian activities, traffic volume, and site characteristics. Subsequently, a field study for the delay has been conducted on pedestrians while crossing the road. The delay time mainly represents the waiting time for safely crossing the road. In the third step, the average delay has been calculated considering the different crossroad locations. In the fourth and final step, average delay is calculated in comparison to the standard PLOS table. This method helps evaluate safety conditions and operational performance of pedestrians at crossroads.

The method of data collection involved capturing video footage, followed by manual extraction of pertinent information. Subsequently, the extracted data underwent organization into tabular formats, facilitating the calculation of various parameters. Key parameters such as crossing time, waiting time, total time, crossing speed, and crossing delay were computed. Pedestrian delay was then determined based on these parameters, employing a predefined formula for calculation.

$$PD = (TT - CT) + CD = WT + CD \quad (4)$$

$$CD = (CT - ICT \quad (5)$$

Where: PD= pedestrian delay (s), TT=total time (s), CT=observed crossing time (s), WT=waiting time(s), CD=crossing delay (s) and ICT=ideal crossing time

$$ICT = \frac{L}{V_i} \quad (6)$$

L = effective crossing length, m

V_i = adopted ideal crossing speed, m/s

Whereas adopted Ideal Crossing speed V_i is 1.2 m/s provided in IRC 103.2012. [25].

Table 5 presents the PLOS utilizing the Indo-HCM PLOS table for both kinds of pedestrians, i.e. pedestrians with impairment and without impairment.

Table 5 shows the PLOS employing the Indo HCM methodology for both kinds of pedestrian.

Table 5. PLOS based on Indo HCM for morning and evening peak hour

	Location	Crossing Time CT (s)	Waiting Time WT (s)	Total time (s)	Ideal Crossing time ICT (s)	Crossing Delay (s)	Pedestrian Delay PD (s)	Crossing speed (m/sec)	PLOS Indo HCM
Morning	Andhjan Mandal	9.10	13.56	22.66	8.75	0.35	13.91	1.19	C
	Gu-LD Intersection	12.02	6.12	18.14	11.58	0.44	6.56	1.20	B
	Chandkheda	9.21	19.74	28.95	8.75	0.46	20.20	1.17	C
	Swastik Crossroad	15.75	8.69	24.44	15.5	0.25	8.94	1.20	C
	Suma Crossroad	17.41	7.07	24.48	16.94	0.47	7.54	1.18	C

Evening	Andhjan Mandal	9.19	23.98	33.17	8.75	0.44	24.42	1.17	C
	Gu-LD Intersection	11.70	5.92	17.62	11.58	0.12	6.04	1.24	B
	Chandkheda	9.09	19.19	28.28	8.75	0.34	19.53	1.18	C
	Swastik Crossroad	15.75	8.89	24.64	15.50	0.25	9.14	1.18	C
	Suma Crossroad	17.52	7.22	24.74	16.94	0.58	7.80	1.15	C

5.3. Fuzzy Logic for PLOS Determination

A mathematical approach using fuzzy logic is considered for making the calculations. Fuzzy logic is very useful for complex system analysis; however, it is tough to specify the exact values and conditions. The fuzzy rules are framed considering "If-Then" which shows the relation between input and output variables. These fuzzy relationships are built by assigning different membership functions to each input variable. Each rule is considered as a specific combination of input conditions against the output response in each case.

Mainly, fuzzy logic will help researchers to clear the uncertainty regarding human perception, making the result more flexible and realistic for making correct decisions in research.

5.3.1. Step by Step Process for Fuzzy Logic

The following preprocessing step was essential for the application of the fuzzy logic algorithm on the pedestrian's perception data provided by each of the users free of any physical disability.This step was aimed at the translation of qualitative linguistic terms used for different parameters into numerical values. This procedure was dictated by the nature of the fuzzy logic algorithm since this is a mathematical approach that operates with numeric values only.

As an example, let us take the parameter 'safety level,' which represents a series of perceptions varying from 'highly safe' to 'highly risky.' Each category of data use to assess this qualitative information mathematically, a numeric value is allocated for each of the categories of data. The procedure required the allocation of a numeric value to each of the members of every parameter.

As an example, 'highly safe' would have a numeric value of 1, 'safe' - a value of 2, 'average' - a value of 3, 'risky' - a value of 4, and 'highly risky' - a value of 5.

It allows the qualitative perception to be converted into a quantitative one. This conversion also allows the use of mathematical operations and algorithms of fuzzy logic analysis. This preprocessing step makes the pedestrian perception data suitable for rigorous mathematical analysis. Thus, fuzzy logic analysis can be formulated and evaluated to infer relationships and make informed decisions. Likewise, the standardized numerical interpretation improves the transparency and comparability of the data across different parameters and datasets and thus contributes to robustness and reliability of the subsequent analysis. In Fuzzy Logic Analysis, the behaviour of driver, gadget usage, level of efficiency, continence level, and chatting were used.

Table 6. Assigned numerical values to each member of the input parameters

Parameters' frequency	Always	Most of the Time	Sometimes	Never
Parameters' Values	1	2	3	4

Table 7. Linguistic input parameters and their values

Driver's Good Behaviour	Assigned Values	Gadget Usage	Assigned Values	Chatting	Assigned Values
Always	1	Always	1	Always	1
Most of the Time	2	Most of the Time	2	Most of the Time	2
Sometimes	3	Sometimes	3	Sometimes	3
Never	4	Never	4	Never	4

Table 8. Linguistic input parameters and their values

Efficiency Level	Assigned Values	Safety Level	Assigned Values	Convenience Level	Assigned Values
Excellent	1	Highly safe	1	Highly convenient	1
Good	2	Safe	2	convenient	2
Average	3	Average	3	Moderate	3
Poor	4	Risk	4	Inconvenient	4
Very poor	5	Highly Risk	5	Highly inconvenient	5

Table 9. Output of fuzzy logic as PLOS

Values	1	2	3	4	5	6
PLOS	A	B	C	D	E	F

Step-1 Problem Definition: The problem at hand is clearly defined, and the variables involved are identified. Inputs, outputs, and any intermediate variables relevant to the analysis are determined.

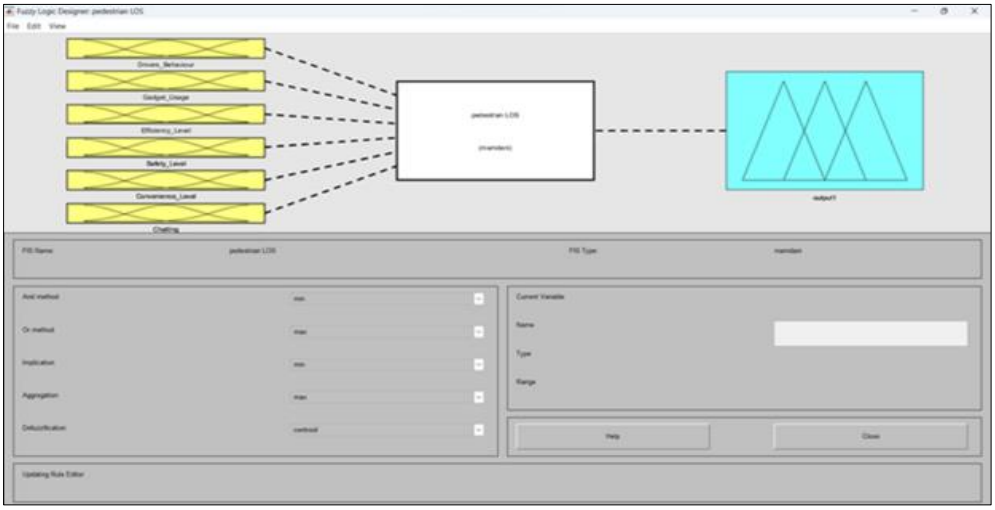


Fig. 10 Creating input variables

During Analysis, input variables were identified, i.e., including Driver's behaviour, gadget usage, efficiency level, safety level, convenience level, and chatting behaviour. These variables are pivotal in understanding pedestrian experiences and perceptions within urban environments. Furthermore, the research endeavours to derive a single output variable from these inputs, thereby advancing the comprehension of pedestrian dynamics and informing strategies aimed at improving pedestrian safety and convenience.

Step-2 Membership Function Definition: For Each variable has been assigned a membership function. These functions describe the degree to which each variable belongs to specific linguistic terms or categories, utilizing shapes such as triangular, trapezoidal, or Gaussian.

Gaussian membership functions were used for the input variables because it provides smooth and gradual transitions between linguistic categories, efficiently demonstrating the uncertainty inherent in subjective questionnaire-based perceptions and behaviours.

Triangular membership functions were used for the output PLOS because LOS A-F are ordered and clearly defined linguistic categories, making triangular functions simple, transparent, and easy to interpret.

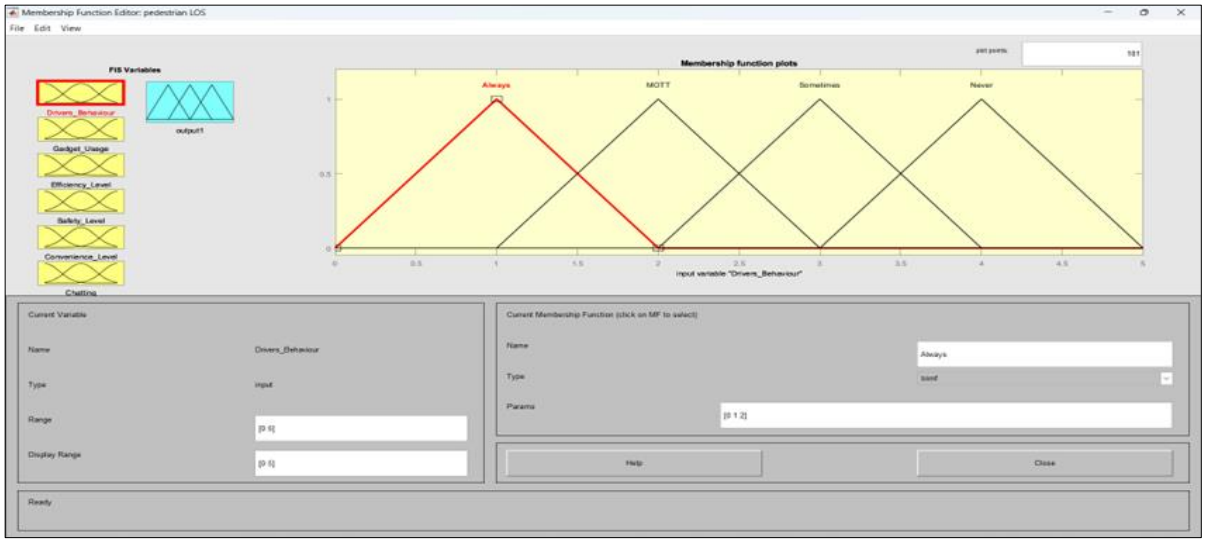


Fig. 11 Assigning membership function to each input variable

The input variables are assigned to an individual number of membership functions. There are four membership functions assigned to the behaviours of the driver and gadget for the various degrees of the variable.

On the other hand, the three factors, convenience, safety and efficiency, are assigned with five membership functions.

The chatting behaviour is defined by four membership functions. Specifying the contribution of people at various locations around the city.

This systematic distribution of the membership functions allows a universal representation of the input variables, which opens the avenue for a nuanced analysis within the fuzzy logic framework.

Step-3: Fuzzification: The crisp (numerical) inputs are fuzzified. Each input value is mapped to the corresponding membership function. This process calculates the degree of membership of each input value for each linguistic term defined by its membership function.

The output variable has been assigned six membership functions in a systematic way that represent the different Levels of Service (LOS) from LOS A to LOS F. This detailed classification allows a more detailed assessment of the experience and perception of pedestrians, such as different degrees of service quality. The output variable is split into six different membership functions which makes it possible for the analysis to include the full spectrum of pedestrian service levels and offer useful insights into the effectiveness of urban pedestrian infrastructure and direct targeted interventions for improving pedestrian experiences.

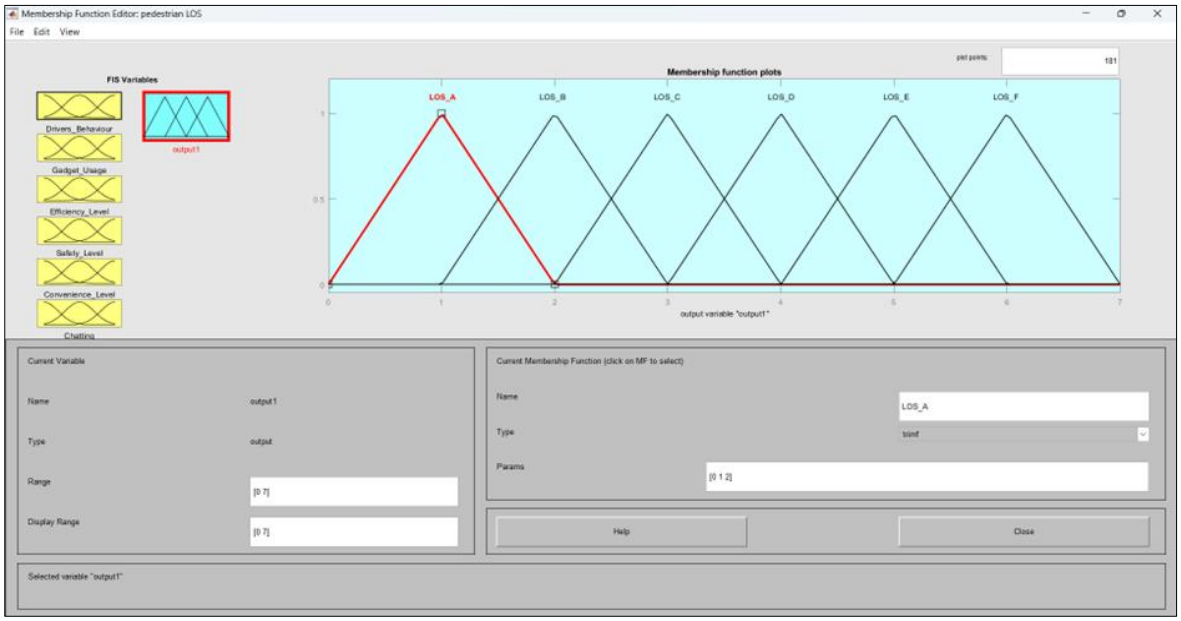


Fig. 12 Assigning membership function to output variable

The assignment of membership functions to the output factors in the interface system built for PLOS evaluation is shown in Figure 12. The output variable, named “output1”, is divided into six linguistic classes ranging from LOS_A to LOS_F. For each category, triangular membership functions (trimf) were considered to represent the transition between service levels gradually. The output was defined from 0 to 7 to support overlapping triangular membership functions, with the six LOS variable values from 1 to 6.

The graph indicates that the membership functions are uniformly distributed over the output range of 0-7, providing smooth overlap between the neighbouring LOS categories. This overlapping feature enables the fuzzy system to deal efficiently with uncertainty and ambiguity in pedestrian perception data. Figure presents the membership function of LOS_A where the maximum membership value is located at the centre point of the range [0 1 2]. The other remaining service levels (LOS_B to LOS_F) are also assigned sequentially in overlapping triangular ranges.

Triangular membership functions are used to ease the computation process and provide enough sensitivity for categorizing the pedestrian service quality. In this way, the fuzzy logic can systematically and realistically transform the qualitative perceptions of pedestrians into quantitative PLOS categories.

Step-4 Rule Base Formation: The guideline set is developed for the If-Then rules to determine the link between inputs and outputs. Such guidance is derived from expert knowledge and a practical dataset, or considering both. These

rules are developed based on past conditions of input variables and the actions of output variables. The IF-THEN rule is considered to identify the level of each term in output variables. Later, these rules are combined with fuzzy outputs via fuzzy logic operators like AND, OR, and NOT. This was built through 972 rules for deep analysis.

Although the full factorial structure leads to 8,000 possible combinations, however, after removing repetitive, unrealistic, contradictory, and unsupported combinations, 972 relevant rules remained. This complete set of rules captures the complex relations between both input and output variables and provides a solid base for the analysis of pedestrian experiences and perceptions in urban environments.

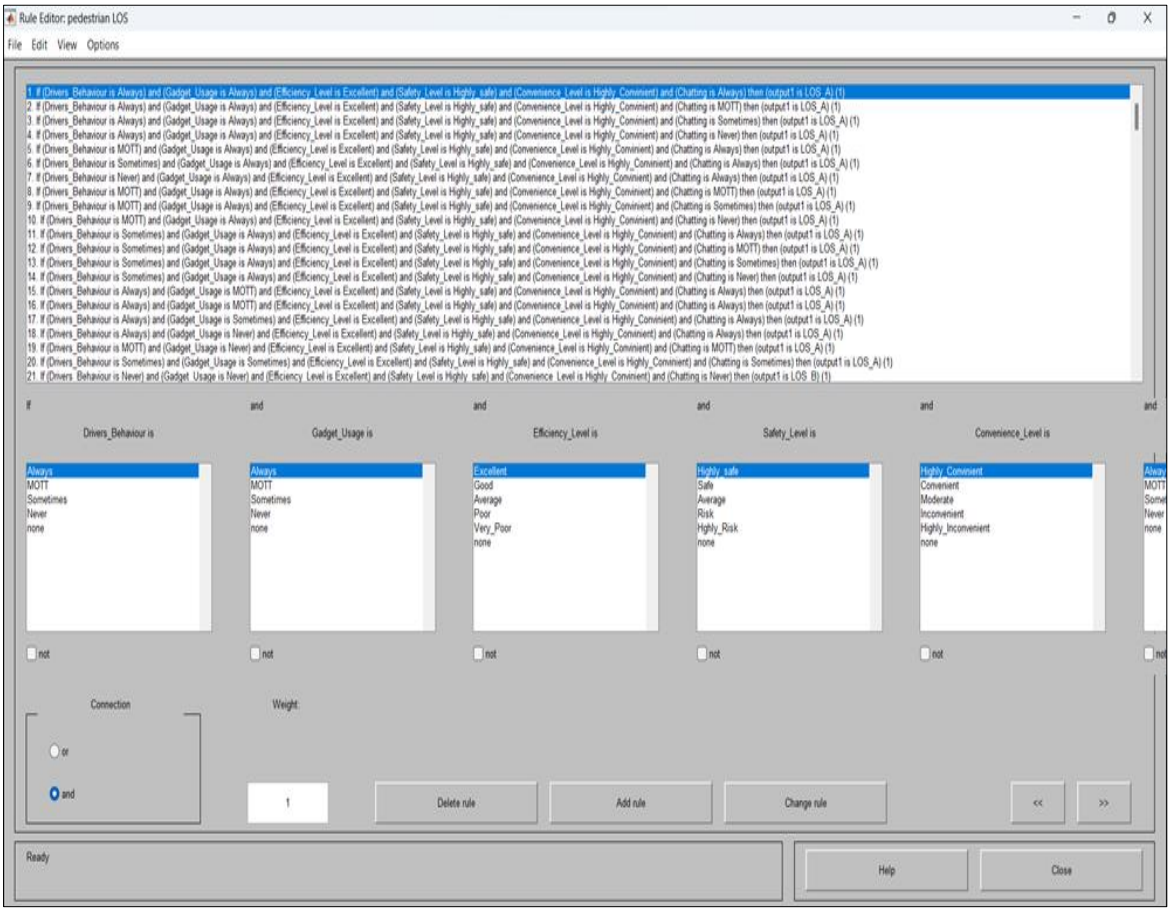


Fig. 13 Construction of rules

Figure 13 shows the construction of fuzzy inference rules for Pedestrian Level of Service (PLOS) evaluation using Mamdani Fuzzy Inference System. The rule editor accepts various input variables like Driver's Behaviour, Gadget Usage, Efficiency Level, Safety Level, Convenience Level and Chatting behaviour to determine the corresponding output LOS category.

Every rule has an IF-THEN format that determines the different types of combinations of the linguistic input variables determining the LOS. For instance, safe driving, high technology usage, and excellent safety, and an extreme convenience level correspond to LOS_A, which stands for good conditions for crossing the streets. The other combinations will represent lower LOS categories.

The picture shows us that the conjunction "AND" is used when combining the conditions stated in the rules. All conditions are treated equally since their weight is set to 1. This approach helps create a unique rule base that allows the fuzzy evaluation to imitate human decisions under uncertainty. The process of constructing rules constitutes the central element of fuzzy inference system, which helps transform qualitative perceptions of pedestrians into quantitative data on PLOS statuses.

Step 5: Defuzzification - in this stage, the fuzzy output is converted into a real number that corresponds to the crisp output. The defuzzification methods employed include centroid, mean of maximum and weighted average in order to define the most suitable number with respect to the aggregated fuzzy outputs.

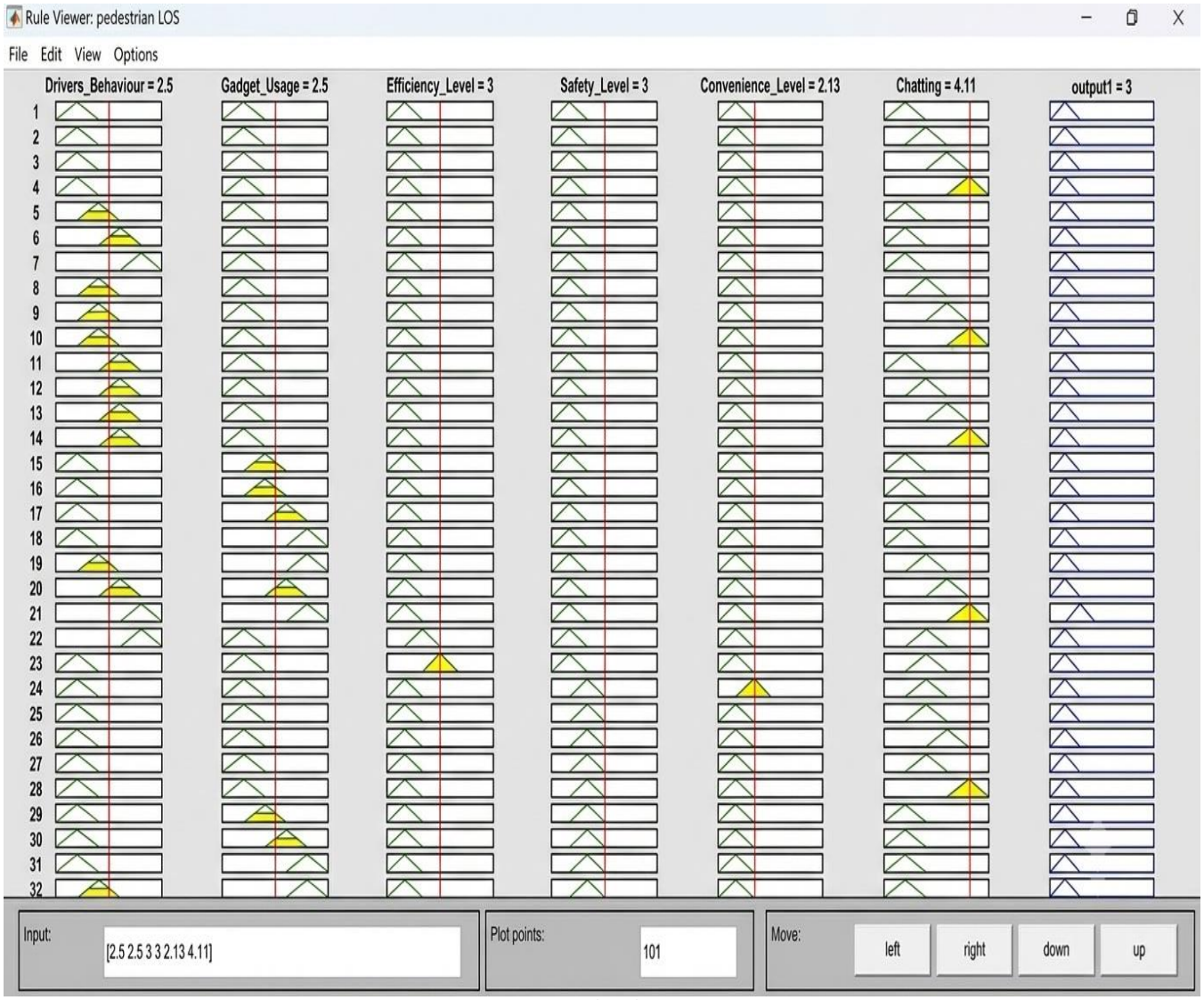


Fig. 14 Defuzzification

From the above Figure 14, defuzzification is obtained based on the PLOS, and from the developed FIS, the figure presents the input parameters which are used in evaluation of FIS output, such as driver behaviour, use of gadgets, efficiency level, safety or convenience level. Further, the procedure through which the fuzzy logic analysis produces output values is shown.

There are specific input variables with the yellow highlighted areas that represent the membership functions which are currently activated. These are the vertical lines represented in red from the numerical inputs entered the system, and the fuzzy conditions are applied on multiple rule sets at the same time.

The column on the right side of the figure presents projected value of pedestrian level of service PLOS considering the execution of logic rules and defuzzification process. Based on the various input parameters, the defuzzufied value come near 3 for the level of service.

The data collected from different sources may contain uncertain and qualitative information about pedestrian behaviour. The FIS helps convert this information into a clear statistical value.

As shown in the figure, the fuzzy logic analysis can imitate human reasoning under different traffic and pedestrian conditions. The defuzzification process gives a final PLOS value, which can be used to assess pedestrian facilities. The output can be obtained using the Rule Viewer. The input values are entered in the lower-left part of the interface, and the output is shown in the lower-right part. This can be easily check and understand, based on the input data.

5.3.2. Analysis of LOS using Fuzzy Logic for Pedestrian with Physical Impairment

The analysis using fuzzy logic was conducted for pedestrians with physical impairment on the basis of the survey conducted by the users at selected pedestrian crossings. The graphic representation of the responses received from the pedestrians in terms of comfort level while walking, hearing of vehicles from behind, obstacles while crossing, availability of special crossing facilities, yielding behaviour of drivers, and safety level perceived in crossing is available in Figure 15. After analysing the input parameters, it becomes possible to arrive at an output value which denotes the value of PLOS.

Fuzzy Output Prediction is represented in a numeric scale from 1 to 6 where 1 is LOS A that means very good pedestrian crossing, while 6 is LOS F, which means very bad and uncomfortable pedestrian crossing. Different outputs are an indication of different pedestrian conditions experienced by the pedestrians. It is noted that pedestrian with physical impairments find it hard to use crosswalks in certain locations due to lack of adequate facilities, driver obedience and poor safety standards. Fuzzy logic helps to transform the subjective experience of pedestrians to measurable level of service, thus enabling one to evaluate accessibilities and safety standards for pedestrians with physical impairment.

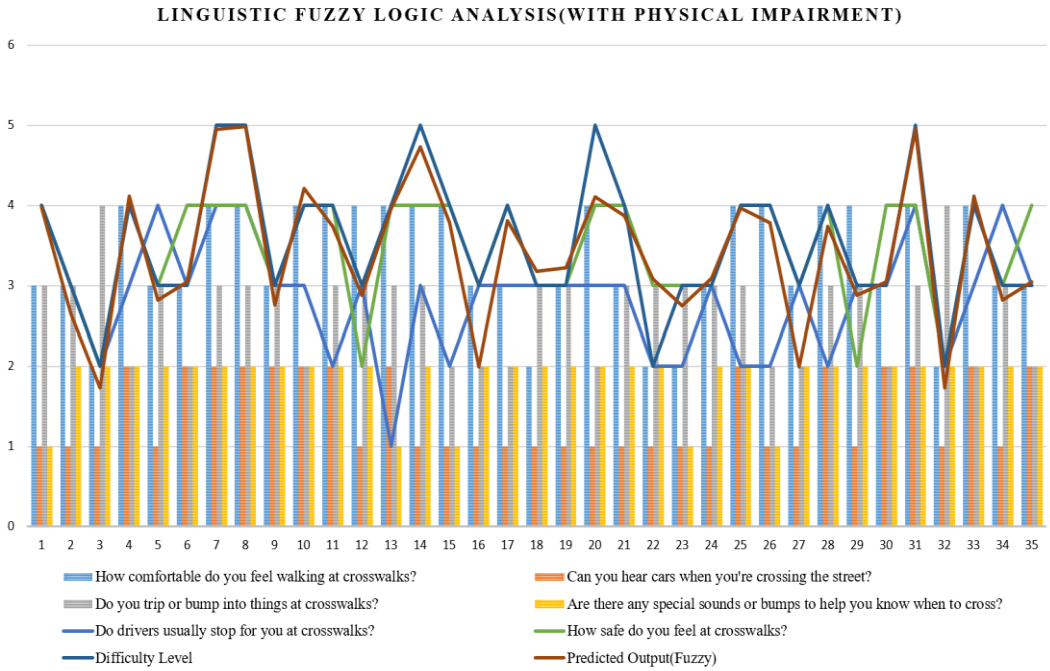


Fig. 15 Linguistic fuzzy logic analysis (With physical impairment)

Figure 15 illustrates the results of the fuzzy logic analysis done on pedestrian with physical impairment in terms of their perception and challenges when crossing at the crosswalk facility. The input parameters considered in this study are gathered via the predefined questionnaire survey. These include comfort while walking at a crossroad, the ability to hear the vehicle approaching sound, driver yelling behaviour, and the number of times a person has bumped into or tripped over something.

The graph shows a change in the perception of pedestrians around 35 times. The blue and green lines in the plot indicate the level of safety and difficulty based on the FIS output. A lower output derived from fuzzy logic represents a safe condition for the pedestrians, and higher output represents poor safety.

From the figure, many participants reported medium or high levels of difficulty. This is due to the existing crossing facilities, inconsistent driver behaviour, and a missing sound guidance system. On the other hand, some people gave high scores because drivers may have stopped at the crossing and provided safe passage to the pedestrians.

This fuzzy logic approach is indeed able to encapsulate all the uncertainties and subjective nature that are inherent in the situation of physical disability among the pedestrian population. Through incorporation of various qualitative variables in one evaluation process, the study gives a true portrayal of how the situation of pedestrian crossings is and what measures should be taken to improve it.

A figure illustrating LOS ratings per respondent (Figure 15) has been shown. The mean value of these ratings is determined to be 3.50, which means LOS C. It highlights the pedestrian experience and perception that prevails in the urban area under study.

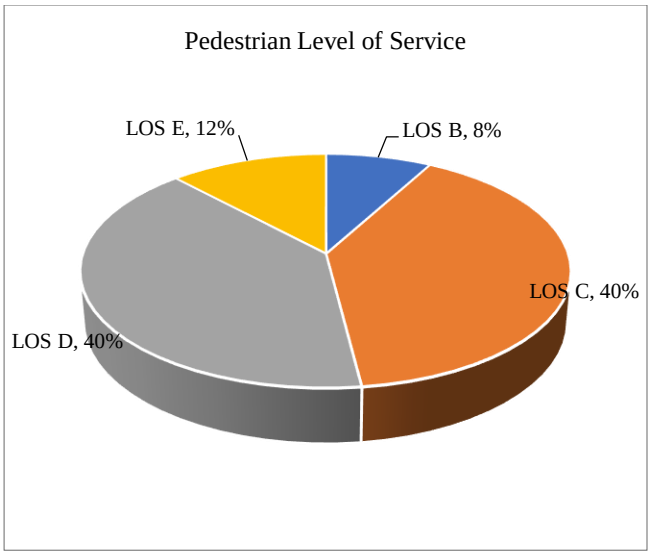


Fig. 16 LOS percentage pie chart (With physical impairment)

Figure 16 shows the percentage distribution of PLOS according to the fuzzy analysis of physical impairment pedestrians. The results showed that 40% of the respondents fall under the category of LOS D, while 40% were found to be in the category of LOS C. Further, 8% of the results have shown LOS B, and 12% of the respondents fall under the category of LOS E.

5.3.3. Analysis of LOS using Fuzzy Logic for Pedestrian without Impairment

Fuzzy Logic analysis was performed for pedestrians without any physical disability using the user perception survey carried out at the chosen crosswalks. Figure 17 shows the answers of 100 pedestrians concerning various parameters affecting pedestrian crossing behaviour and comfort. These factors include driver behaviour, use of gadgets while crossing, level of efficiency, safety awareness, accessibility level, talking while crossing, difficulty level, and the fuzzy output generated by the fuzzy interpretation system.

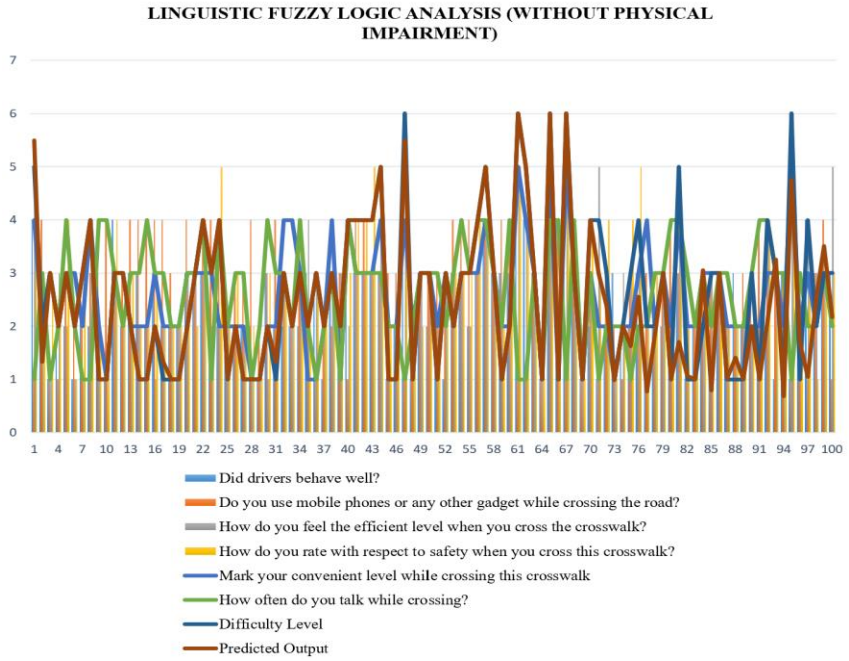


Fig. 17 Linguistic fuzzy logic analysis (Without physical impairment)

The displayed line in the graph shows how a pedestrian feels while crossing the road. Most of the replies are between 1 and 4; this means that pedestrians feel a moderate level of safety, comfort, and convenience at crossings.

Even in some of the cases, ratings reached the 5 and 6 levels due to unsafe acts like using mobile phones, lack of crossing facilities, or some unsafe act from the vehicle drivers.The FIS combines various input factors in the single output levels by considering the ‘difficulty level’ and ‘predicted output.' Mainly, the output depends on the input parameters and shows the Pedestrian Level of Service (PLOS), where higher values show the crossing environment is less comfortable and feels challenging.

The analysis shows that even without any disability, pedestrians feel different levels of discomfort while crossing the roads. Fuzzy logic can capture the responses and convert them into numerical levels. This makes the results easier and more practical. An average score of 2.40 was obtained from the level of services LOS taken from the individuals, which is shown in Figure 18. This shows that the study area falls under the LOS B category. Which means that crossing conditions are good, but still some improvement is required in a few areas.

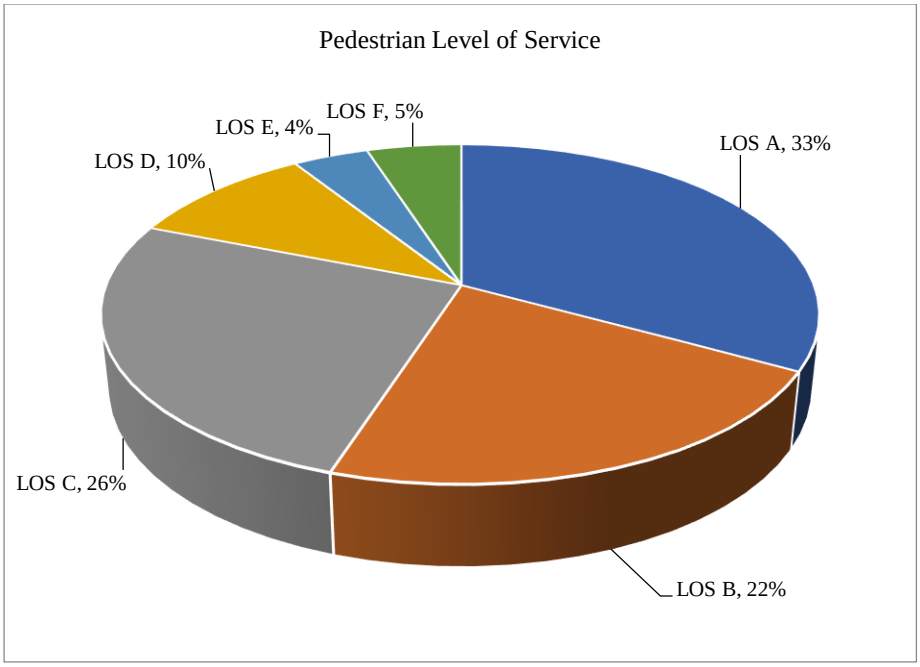


Fig. 18 LOS percentage pie chart (Pedestrians without physical impairment)

The pie chart represents the distribution of PLOS for pedestrians without physical impairment. The results demonstrate that the highest proportion of pedestrians experienced LOS A (33%), which reflects excellent pedestrian conditions with high comfort, safety, and convenience.

This is followed by LOS C (26%) and LOS B (22%), showing that a considerable percentage of pedestrian facilities provide moderate to good service quality.

A smaller proportion of locations fall under LOS D (10%), indicating noticeable pedestrian discomfort and operational issues. Very few locations were categorized as LOS E (4%) and LOS F (5%), which represent poor and highly unsatisfactory pedestrian conditions, respectively. Overall, the chart suggests that most pedestrian facilities provide acceptable to good levels of service for pedestrians without physical impairment, while only a limited number of locations require significant improvement in pedestrian infrastructure and safety conditions.

Table 10. PLOS based on average delay

Location	Observed Delay (s)	Observed Average Delay (s)	FIS LOS Values (Fuzzy)
Andhjan Mandal BRTS	Morning-13.91 Evening-24.42	19.16	3.1862
Chandkheda BRTS	Morning-20.20 Evening-19.53	19.86	2.8197
GU-LD Crossroad	Morning-6.56 Evening-6.04	6.30	2.8197
Swastik Crossroad	Morning-9.06 Evening-9.14	9.04	3.4181
Suma Crossroad	Morning-7.54 Evening-7.8	7.67	2.9658

To evaluate the factors affecting PLOS, each input variable had been analysed with respect to the output using different approaches.

Regression analysis is performed to identify the input variables. The input parameters for the FIS is pedestrian characteristics in correlation with the relationship between variables.

5.4. Regression Analysis

Regression analysis helps to identify how different road and traffic impacts pedestrian comfort. By analysing the data, it can predict the level of pedestrian service in various conditions.The data collected from the survey are considered independent variables, and data obtained from fuzzy logic are taken as dependent variables. Correlation of the same can be specified in Table 11.

Table 11. Correlation matrix (Pedestrian with impairment)

	PLOS (Fuzzy)	Total time (s)	Crossing Time (s)	Waiting Time (s)	crossing speed (m/s)	Crossing Delay (s)	Pedestrian Delay (s)
Pedestrian LOS (Fuzzy)	1.000						
Total time(s)	0.587	1.000					
Crossing Time(s)	-0.788	-0.268	1.000				
Waiting Time(s)	0.612	0.7670	-0.503	1.000			
Crossing speed(m/sec)	-0.200	-0.706	-0.157	-0.278	1.000		
Crossing Delay(s)	-0.197	0.258	0.235	0.111	-0.667	1.000	
Pedestrian Delay(s)	0.841	0.854	-0.729	0.816	-0.424	0.071	1.000

From Table 11, it is observed that Pedestrian delay, waiting time, and total travel time are the most influential factors affecting pedestrian LOS. Higher delays and waiting times reduce pedestrian comfort and operational performance. Improved pedestrian movement efficiency and higher crossing speed generally lead to better service conditions. Strong correlations states that these parameters are suitable inputs for developing regression- or fuzzy-based PLOS analysis for urban crosswalk evaluation. By considering the parameters, i.e. total time, crossing time, waiting time and crossing speed are considered for development. Table 12 shows regression analysis.

Table 12. Regression analysis of pedestrians with physical impairments

Multiple R	R Square	Adjusted R Square	Standard Error	Observations
0.88171	0.777412	0.755871	0.121655	35

Table 13. ANOVA test for pedestrian LOS (Pedestrian with physical impairment)

	df	SS	MS	F	Significance F
Regression	3	1.6024	0.53413	36.0901	3.11E-10
Residual	31	0.4588	0.0148		
Total	34	2.0612			

Table 14. Coefficient table for pedestrian LOS (Pedestrian with physical impairment)

	Coeff.	Std. error	t Stat	P value	Lower 95%	Upper 95%
Intercept	2.178	0.74	2.944	0.026	0.368	3.989
Crossing Time(s)	-0.046	0.039	-1.204	0.274	-0.141	0.048
Pedestrian Delay(s)	0.05	0.031	1.594	0.162	-0.027	0.126
Waiting Time(s)	-0.003	0.008	-0.367	0.726	-0.024	0.017

During the regression analysis, the selected parameters had impact on the output variable. The coefficient (R2) is calculated to be 0.777412, showing a firm connection between the selected parameters and the output.

The combined correlation value produced a result of 0.88171, supporting the significance of the identified factors in affecting the outcome, for Linguistic regression analysis constructed for the individuals without any physical impairment. The parameter correlation for linguistic is shown in Table 15.

5.5. Linguistic Regression Analysis

A Linguistic Regression helps to identify situations where data is not exact. The use of human language terms like "low," "moderate," and "very high" instead of exact numbers. Table 15 shows the correlation between the input variables used in the linguistic regression approach. The correlation matrix for the Linguistic-Fuzzy analysis identified four main parameters positively influencing the Predicted Output for pedestrians without physical impairments: Safety Rating (0.807)-strongest influencing factor, Convenience Level (0.744)-strong positive relationship, Efficiency Perception (0.674) - shows positive corelation, Driver Behaviour (0.467)

- moderate positive influence. These variables have been selected for further regression analysis. Distraction-related factors revealed very weak negative relation and were excluded: Mobile Phone/Gadget Use (-0.140), Talking While Crossing (-0.052). Additionally, pedestrians perceiving higher safety also reported better convenience and efficiency, while distracted behaviours such as phone use and talking while crossing were strongly related (0.635). Based on the correlation matrix, four variables have been selected for the regression analysis.

Table 15. Correlation matrix for linguistic regression analysis (Without physical impairment pedestrian)

	Predicted Output	Did drivers behave well?	Do you use mobile phones or any other gadget while crossing the crosswalk?	How efficient do you find crossing the crosswalk?	How would you rate the safety and convenience of this crosswalk while crossing it	Rate your level of convenience while crossing this crosswalk.	How often you talk while crossing the crosswalk?
Predicted Output	1.000						
Did drivers behave well?	**0.467**	1.000					
Do you use mobile phones or any other gadget while crossing the crosswalk?	-0.140	0.035	1.000				
How efficient do you find crossing the crosswalk?	**0.674**	0.404	-0.240	1.000			
How would you rate the safety and convenience of this crosswalk while crossing it	**0.807**	0.441	-0.029	0.660	1.000		
Rate your level of convenience while crossing this crosswalk.	**0.744**	0.347	-0.111	0.636	0.652	1.000	
How often you talk while crossing the crosswalk?	-0.052	0.192	0.635	-0.132	0.042	0.027	1.000

Table 16. Regression statistics for pedestrian without physical impairment

Multiple R	R Square	Adjusted R Square	Standard Error	Observations
0.865507	0.749103	0.738539	0.6988373	100

Table 17. ANOVA test for pedestrian without physical impairment

	df	SS	MS	F	Significance F
Regression	4	138.523	34.63076	70.9104	1.10E-27
Residual	95	46.39549	0.488374		
Total	99	184.9185			

Table 18. Coefficient table of linguistic regression analysis for pedestrian LOS

	Coeff.	Std. Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-1.241	0.247	-5.034	0.001	-1.73	-0.752
Did drivers behave well?	0.15	0.089	1.682	0.0096	-0.027	0.328
How efficient do you find crossing the crosswalk?	0.144	0.095	1.51	0.0134	-0.045	0.333
How would you rate the safety and convenience of this crosswalk while crossing it	0.608	0.098	6.214	0.001	0.413	0.802
Rate your level of convenience while crossing this crosswalk.	0.465	0.103	4.515	0.001	0.261	0.67

The regression diagnostics shows that the analysis is statistically significant proof of pedestrian LOS for pedestrians without physical impairment. The multiple correlation coefficient (R = 0.8655) shows strong relationship between variables, and the coefficient of determination (R^2 = 0.7491) shows around 74.91% variation in pedestrian LOS is explained by the selected predictor variables. The standard error 0.6988 indicates an acceptable error of prediction. The ANOVA results confirm that the regression model is highly significant overall (F = 70.910, p = 1.10×10^{-27}), indicating that the selected variables collectively have a significant influence on pedestrian LOS. In the course of regression analysis, it became evident that the chosen parameters exerted a considerable influence on the output variable. With a Coefficient of Determination (R^2) of 0.7491031, the analysis revealed a robust relationship between the selected parameters and the output. Moreover, the combined correlation value, which amounted to 0.8655074, underscored the significance of the identified parameters in shaping the outcome. Linguistic regression analysis carried out for individuals with physical impairments. The correlation matrix indicates the relationship between variables.

Table 19. Correlation matrix for linguistic regression analysis (Pedestrians with physical impairment)

	Predicted Output (Fuzzy)	How comfortable you feel walking at crosswalks?	Can you hear cars when you're crossing the street?	Do you trip or bump into things at crosswalks?	Are there any special sounds or bumps to help you know when to cross?	Do drivers usually stop for you at crosswalks?	How safe you feel at crosswalks?
Predicted Output (Fuzzy)	1.000						
How comfortable you feel walking at crosswalks?	**0.688**	1.000					
Can you hear cars when you're crossing the street?	**0.433**	0.517	1.000				
Do you trip or bump into things at crosswalks?	-0.224	-0.359	-0.137	1.000			
Are there any special sounds or bumps to help you know when to cross?	-0.064	0.018	0.100	0.009	1.000		
Do drivers usually stop for you at crosswalks?	0.250	0.085	-0.064	-0.103	0.352	1.000	
How safe you feel at crosswalks?	**0.812**	0.575	0.479	-0.503	-0.184	0.079	1.000

Based on the correlation matrix, three parameters were selected for the regression analysis for this analysis.

Table 20. Linguistic regression statistics for pedestrian LOS with physical impairment

Multiple R	R Square	Adjusted R Square	Standard Error	Observations
0.85691	0.73429	0.69633	0.46308	35

Table 21. ANOVA test for pedestrian LOS with physical impairment

	df	SS	MS	F	Significance F
Regression	3	12.4447	4.14823	19.3443	2.98E-06
Residual	31	4.50328	0.21444		
Total	34	16.9479			

Table 22. Coefficient table of linguistic analysis for pedestrian LOS with physical impairment

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-0.536	0.538	-0.997	0.033	-1.654	0.582
How comfortable do you feel walking at crosswalks?	0.398	0.166	2.39	0.026	0.052	0.744

Can you hear cars when you're crossing the street?	-0.09	0.233	-0.385	0.0704	-0.575	0.396
How safe do you feel at crosswalks?	0.819	0.183	4.474	0.0001	0.438	1.200

The regression diagnostics shows the analysis provides a strong and statistically significant representation of pedestrian LOS for individuals with physical impairment. The multiple correlation coefficient (R = 0.8569) clarifies a strong relationship between the variables, while the R^2 = 0.7343 shows that approximately 73.43% of the variation in pedestrian LOS is explained by the selected predictor variables. The ANOVA results revealed a significant overall model fit (F = 19.344, p = 2.98×10^{-6}), indicating that the selected variables collectively have a significant influence on pedestrian LOS.

During the regression analysis, it became apparent that the selected parameters wielded a significant influence on the output variable. The coefficient of determination (R^2), standing at 0.734289, highlighted a strong relation among the chosen parameters and the output. Furthermore, the combined correlation value, totalling 0.856906, emphasized the importance of the identified parameters in shaping the outcome.

6. Results and Discussion

- The Indo-HCM was used to evaluate pedestrian delay at signalized intersections. The overall PLOS value obtained from the Indo-HCM PLOS table showed LOS C.
- In the same way, the Fuzzy Logic analysis gave an overall LOS value of 2.85 at the selected location of Ahmedabad city, which also falls under LOS C. This shows that both methods gave similar results for pedestrian experience and satisfaction.
- In Linguistic Fuzzy Analysis, pedestrian (without physical impairment) characteristic parameters were added for a more detailed analysis. This analysis helped to estimate the pedestrian delay at all study locations and identify the features involving pedestrian experience. The values of PLOS obtained from this analysis is 2.4. Which is LOS B based on the PLOS table of Indo-HCM. This indicates satisfactory pedestrian environment.
- The Linguistic Fuzzy Analysis was also carried out for the pedestrian (with physical impairment). It produced an overall LOS value of 2.16, which also belongs to LOS B. These results support the findings of the Indo-HCM.
- From the correlation and regression analysis, three factors were found to have the highest impact on PLOS. The Crossing Time(s), Waiting Time(s), and Pedestrian Delay(s).
- In view of regression analysis, the PLOS equation is created as follows:

$$PLOS = 2.178 - 0.046CT + 0.050PD - 0.003WT \quad (7)$$

Where:
CT = Crossing Time (s) represents the time taken to cross the road, PD = Pedestrian Delay (s) indicates the delay experienced by pedestrians, WT = Waiting Time (s) is the time pedestrians spend waiting to cross.

- From the correlation and regression analysis conducted based on the linguistic variables in questionnaires (pedestrian without physical impairment), it was revealed that factors such as Driver's behaviour, Efficiency Level, Safety Level, and Convenience Level had an impact on the PLOS.
- After analysing the regression results, the equation representing the Pedestrian Level of Service (PLOS) can be expressed as follows:

$$PLOS = -1.241 + 0.150DB + 0.144EL + 0.608SL + 0.465CL \quad (8)$$

Where:
DB = Drivers behaving well is the rating for driver behaviour, EL = Efficient level when crossing represents the efficiency level felt when crossing the crosswalk, SL= Feeling of safety when crossing indicates the perceived safety level when crossing the crosswalk, CL = Convenient level when crossing is the rating for convenience when crossing the crosswalk.

- From the correlation and regression analysis carried out for pedestrian (with physical impairment), it was observed that factors such as Comfortability, Safety, and Hear of vehicles while or before crossing had a impact on the PLOS.
- After analysing the regression results, the equation representing PLOS can be expressed as follows:

$$PLOS = -0.536 + 0.398CL - 0.090HV + 0.819SL \quad (9)$$

Where:
PLOS be the Pedestrian Level of Service, CL represent Comfort walking at crosswalks, HV denote Ability to hear Vehicles while crossing, SL stand for Feeling of safety at crosswalks.

- The Indo-HCM analysis resulted in a LOS C for the pedestrian at selected locations, which is in line with the PLOS score of 2.85 from the Mamdani Fuzzy Inference System. It indicates consistency in regardless of the different input variables and approaches. The linguistic fuzzy analysis resulted in higher PLOS values (2.40 and

2.16) for pedestrians without and with physical impairments (classified as LOS B), which shows the importance of perception-based variables over delay. PLOS was linked with key operational variables such as crossing and waiting times, and individual effects had to be interpreted with caution. The study indicated that comfort and safety are more important for both the groups, highlighting the need for improvements in signal timing, infrastructure, and driver compliance for better pedestrian conditions.

7. Novelty of the Study

- In this study, qualitative and quantitative data are collectively used, considering videographic observations, traffic data, and questionnaire responses.
- This research is based on three techniques, namely Indo-HCM, multiple linear regression, and Mamdani FIS. Indo-HCM provides LOS classification based on delay, regression provides quantification of statistical relations, and FIS provides the nonlinear and linguistic relations among the selected variables.
- The study also analyses the safety, comfort, convenience, and accessibility between pedestrians with and without physical impairment.
- It also explores PLOS in mixed traffic conditions such as pedestrian behaviour, safety, traffic conditions, driver behaviour, and crosswalk qualities.
- The joint analysis allows an evaluation of traditional delay-based classification, statistical relations, and rule-based fuzzy assessment, showing consistency.

8. Conclusion and Recommendations

- The study shows the detailed assessment of how factors affect pedestrians in urban areas. The approaches used in the study are Indo-HCM, FIS, and Regression Analysis, with the complex relationships between different variables that affect pedestrian safety, convenience, and variables at the crosswalks.
- The data is collected using videography at crossroad with different set of questionnaires on 135 numbers of pedestrians with and without disabilities. The output results show mixed approaches from the pedestrians by different aspects, from safety to comfort. There was also mixed approach based on gender as well as generations, which clearly visualizes in the results.
- The important factor that is contributing to the PLOS is obtained from correlations and the regression analysis. In FIS analysis, PLOS is mainly affected by behaviour of drivers, safety level on crossing, and convenience level of individuals.
- The study also examined the aspects of the experience of pedestrian with physical impairment. Comfortability was found to vary depending on auditory abilities and interactions with drivers. Although 56% of participants felt comfortable while crossing, it is evident that there were others who completely lacked any comfort while crossing roads.
- In conclusion, this study provides an in-depth understanding of the experience and perception of pedestrians that can be very helpful for urban planners, policymakers, and transportation engineers. The developed equations of PLOS estimation considering the main variables provide a practical solution for assessing the pedestrian facilities. In the future, further research and implementation of interventions would be needed in order to ensure a safe and efficient environment for pedestrians in urban areas.

8.1. Suggestions and Recommendation

- Enhance Crosswalk Infrastructure and Pedestrian Safety: Well-marked crosswalks, proper lighting, pedestrian refuge islands, properly maintained walkways, and traffic calming measures such as elevated crossings and speed control devices can enhance pedestrian facilities.
- Pedestrian Perception in Design and Planning: In order to make the design of pedestrian facilities more user-centred, it is imperative that the perception of pedestrians related to safety, comfort, and convenience be considered along with traffic and geometric elements by transport planners.
- Application of PLOS Evaluation Tools: To conduct a comprehensive evaluation of pedestrian level of service, advanced techniques such as Fuzzy Inference, Linear Regression need to be applied in combination with the Indo-HCM model.
- Conduct further studies and develop policies: Although policymakers might strengthen laws related to pedestrian safety and conduct awareness campaigns to inspire safer road-user behaviour, further research should focus on diverse metropolitan areas and different data sets.

Limitations

The PLOS is evaluated using the available dataset and the regression analysis technique. Future studies may validate the framework by considering independent datasets using RMSE, MAE, and MAPE to verify its predictive robustness.

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Author Contributions

Jitendra Kumar: Conceptualization, methodology, investigation, data curation, formal analysis, writing - original draft preparation.

Toral Vyas: Conceptualization, methodology, validation, formal analysis, supervision, manuscript review & editing.

Sahista Kazi: Visualization, investigation, writing-reviewing and editing

Jalpa Modi: Statistical Analysis, visualization, and validation.

Ghanshyam Savaliya: Literature review, data interpretation, and writing - review & editing.

Anjum Mirza: Technical guidance and critical review of the manuscript.

Soham Vyas: Software support, computational analysis.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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