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Research Paper

Estimating of Critical Gaps at Uncontrolled Intersections under Heterogeneous Traffic Conditions

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Abstract

Pedestrian crossing behavior can be studied by estimating critical gap, which is determined by analyzing accepted and rejected gaps by pedestrians. This can provide insight into safety levels at pedestrian facilities. The aim of this study is to determine critical gaps using various methods such as Logit method, Raff's method and Wu's Method. These methods are then compared to identify the most appropriate one. Three locations in Malaysia were selected for data collection based on their land use, number of lanes, and carriage way width. Video cameras were used to capture mixed traffic flow and pedestrian crossing movements simultaneously at the selected sections. The results indicate that the critical gap values obtained from the three methods are highly comparable. Specifically, the Logit Method yielded a critical gap value of 8.4s, while Raff's Method and Wu's Method produced critical gap values of 7.7s and 7.12s, respectively. The study concludes that the Logit method is the most suitable for estimating critical gap as it takes into account both pedestrian behavior and vehicular characteristics concurrently. The findings of this study have the potential to contribute towards the review of design parameters for pedestrian crossing facilities, leading to the improvement of existing facilities and the enhancement of pedestrian safety.

Keywords: Pedestrian behaviour; Vehicular characteristics; Critical gap; Uncontrolled mid-block crossings; Heterogeneous traffic

1. Introduction

Unsignalized Mid-block crosswalk's locations serve as a means of connecting adjacent land-use activities that share a common type. However, in un-signalized conditions at mid-blocks, there is an increased likelihood of conflicts occurring between pedestrians crossing the street and oncoming vehicles. The findings of Gobalarajah [1] study highlight that mid-block locations are a significant site of pedestrian fatalities. The rapid increase in the number of vehicles in recent decades has resulted in heavy traffic volumes across all types of urban roads, which poses a risk of accidents not only for pedestrians but also for vehicles. Due to its high population and diverse traffic composition, Malaysia poses a significant safety challenge regarding mid-block crossings. The increased interaction between pedestrians and vehicles in such situations results in a heightened risk of accidents and safety issues [2], [3]. In Malaysia, pedestrians are at high risk when crossing un-signalized mid-block areas with mixed traffic flow conditions. Because pedestrians are among the most vulnerable road users in such scenarios, crossing the street poses a major risk to their safety.

Unsignalized Mid-block crosswalk's locations serve as a means of connecting adjacent land-use activities that share a common type. However, in un-signalized conditions at mid-blocks, there is an increased likelihood of conflicts occurring between pedestrians crossing the street and oncoming vehicles. The findings of Gobalarajah [1] study highlight that mid-block locations are a significant site of pedestrian fatalities. The rapid increase in the number of vehicles in recent decades has resulted in heavy traffic volumes across all types of urban roads, which poses a risk of accidents not only for pedestrians but also for vehicles. Due to its high population and diverse traffic composition, Malaysia poses a significant safety challenge regarding mid-block crossings. The increased interaction between pedestrians and vehicles in such situations results in a heightened risk of accidents and safety issues [2], [3]. When crossing unsignalized mid-block areas with mixed traffic flow conditions in Malaysia, pedestrians face a high risk of injury. Because pedestrians are among the most vulnerable road users in these circumstances, pedestrian road crossings pose a major threat to their safety.

Pedestrian gap acceptance refers to the calculation of the minimum time-based distance from the adjacent vehicle's speed. The smaller the gap, the higher the risk of accidents for pedestrians [4]. As a result, the critical gap is crucial to the gap-acceptance process since it influences safety and makes it easier to evaluate the probability of pedestrian accidents. One approach to analyze pedestrian crossing behavior is to observe the gaps that pedestrians accept or reject to estimate the critical gap, which can provide insight into the safety levels at pedestrian infrastructures [5]. Given the low likelihood of discovering greater gaps in traffic streams, pedestrians must adjust their behavior to take advantage of smaller openings. Pedestrians engage in a premeditated behavior upon reaching a crosswalk, where they perceive the size of the gap and decide whether to accept or reject it based on their perception of its size relative to the critical gap. In case the previous gap is rejected, the pedestrian must continue looking for another suitable gap. This sequential decision-making process continues until the pedestrian identifies an appropriate gap to cross the road. Typically, pedestrians will accept smaller gaps as their waiting time increases. The critical gap refers to the shortest duration, in seconds, between approaching vehicles that allows pedestrians to safely cross the road. The critical gap is the smallest amount of time (measured in seconds) required for a pedestrian to cross the road safely, according to the highway capacity manual (HCM 2010) recommendations. Nevertheless, some pedestrians may decide to cross with a gap duration that is less than the essential gap, displaying a variety of behavioral patterns include walking more quickly, changing their direction when crossing, rolling, attempting to cross more than once, or crossing in a group. Age, gender, and other induced characteristics, among others, can have an impact on the crucial gap, or the amount of time needed for a pedestrian to cross the road safely. This factor is crucial in ensuring pedestrian safety at un-signalized mid-block crosswalks. Additionally, driver behavior in yielding to pedestrians can affect the size of the gap that pedestrians accept, particularly in scenarios where there is mixed traffic. There has been limited research on how human factors impact critical gap analysis, which is vital for ensuring pedestrian safety. Moreover, there is a scarcity of studies that investigate critical gap analysis at un-signalized mid-block crosswalks, especially in situations with mixed traffic. Hence, it is essential to explore the suitability of critical gap estimation techniques by taking into account the influence of human factors on critical gap duration at unsignalized mid-block crosswalks.

2. Literature Review

There are several approaches for figuring out the crucial gap, and many of them presuppose that drivers are reliable and consistent. The crucial gap has been calculated using a variety of techniques, such as Raff's method, as well as methods proposed by Jain & Rastogi [4] and Brilon et al. [6]. These techniques entail calculating the critical gap based on variables like the volume of traffic in the main stream, the standard deviation, and the average of the permitted gap. Tian et al. [7] used the Maximum Likelihood Method (MLM) to determine the driver's critical gap, while logit and probit models were used by Jain & Rastogi [4] and Mohamed et al. [8]. In addition, Bargi [9], [10] suggested models for simulating pedestrian gap acceptance and driver yielding, which revealed that a pedestrian's decision to cross depends on the distance between the vehicle and the crosswalk as well as the speed of the vehicle. Hamed [11] and Bargi and Daniel [12] observed that female pedestrians take longer to cross the street than male pedestrians. Oxley et al. [13] discovered in their investigation that many crossing cases involving elderly pedestrians accept more time gap. A study was conducted by Naser et al. [14] and Kadali & Vedagiri [15] to investigate changes in pedestrian speed while crossing the road. Rastogi et al [16] conducted research on pedestrian crossing speed and observed that the crossing speed of male and female pedestrians is similar regardless of the road type and land-use.

The gap acceptance theory, as explained by Naser et al. [14], sheds light on the behavior of pedestrians while crossing the road. Rather than waiting for larger gaps, most pedestrians prefer to use rolling gaps (crossing over small vehicular gaps) [17]. In a study conducted by Kadali and Vedagiri [15], they found that pedestrian behavioral traits, such as rolling gaps, driver yielding behavior, and frequency of attempts, play a significant role in uncontrolled pedestrian road crossing. Other studies, including Bargi et al. [18] and Yannis et al. [19], developed binary logistic regression models to examine the impact of traffic gaps on the decision to cross the street, using a lognormal regression model. The results suggested that pedestrian waiting time and the size of the vehicle are the primary factors influencing the decision-making process. In a study on pedestrian accepted gaps at several mid-block crosswalk locations in mixed traffic, Koh et al, [20] discovered that the quantity of lanes, volume of vehicles, and pedestrian characteristics have a substantial impact on the pedestrian accepted gap values. Additionally, Serag [21] discovered that individual pedestrian characteristics had no discernible influence on crossing decision, only the age and frequency of pedestrian attempts were found to affect gap acceptability. Yang et al. [22] and Koh [23] utilized a discrete choice approach to create and validate a pedestrian gap acceptance model.

According to Mohan and Chandra [24], pedestrian walking speed is influenced by environmental and traffic flow conditions. Meanwhile, the critical gap is the smallest window of time a minor street driver is prepared to accept for crossing or entering a major stream conflict zone [10]. Then, utilizing vehicle clearing behavior and gap acceptance data, Weinstein et al. [25] suggested a new method for calculating crucial gaps. Chandra et al. [26] found that critical gap decreases when smaller gaps are available in high volume traffic streams. Jain and Rastogi [4] noted that critical gap values are generally higher in developed countries compared to India, due to more aggressive driver behavior. Tian et al. [7] introduced the Probability Equilibrium Method (PEM), which establishes macroscopic equilibrium between rejected and accepted gaps using cumulative gap distributions. Kadali et al. [27] used various techniques to estimate critical gap and found that pedestrian behavioral characteristics significantly affect critical gap values.

In previous studies [6], [7], [28], [29], it has been noted that the gap acceptance behavior of pedestrians is influenced by various factors such as the surroundings, traffic flow, location, and personal characteristics. Therefore, research and strategies developed in developed countries may not be directly applicable to developing countries. This study focuses on examining pedestrian behavior at uncontrolled mid-block crosswalks by estimating the critical gaps for crossing pedestrians from approaching vehicles and the curb-side. The study aims to compare and determine the most appropriate method among three methods, including Raff's method, logit, and Wu's method, for estimating critical gaps for pedestrians at unprotected mid-block crosswalks in mixed traffic scenarios. The study's primary goal is to identify the most effective critical gap estimation method for ensuring pedestrian safety.

3. Investigation Area

Three locations in Malaysia were chosen and observed for the study: Kuala Lumpur, Johor, and Selangor. Sites for data collection were chosen based on the kind of land use, the number of lanes, the width of the carriageway, and the behavioral traits of pedestrians with a variety of available gaps. Two high-resolution video cameras were mounted on nearby high-rise buildings, and video graphic surveys were conducted from 07.00 am - 08.00 am and 04.00 am - 05.00 pm, as well as during non-peak hour at 11.00 am -12.00 pm. At certain intersections, the cameras simultaneously recorded mixed traffic flow and pedestrian crossing actions. The recorded data was examined for factors such pedestrian flow, vehicular traffic flow, demographics of pedestrians, movement at crossings, and acceptance of vehicular gaps by pedestrians. During the survey at each site, vehicular traffic flow, pedestrian flow rates and mean vehicular speed was observed. **Figure 1** illustrates the data recording and extraction process.

4. Results and Discussion

The three approaches represented below were used to determine the critical gap for through movement from a minor road at uncontrolled locations.

4.1. Analysis of Critical Gaps

According to the Highway Capacity Manual (HCM 2010), the crucial gap is the amount of time, measured in seconds, that is deemed insufficient for pedestrians to start crossing the roadway. This is important to the gap acceptance procedure for crossing roads. The pedestrian critical gap, which is measured in seconds, is the bare minimum amount of time between two oncoming cars that permits safe crossing. While it cannot be measured in the field directly, accepted and rejected gap data can be used to estimate it.. This estimation is particularly important in countries such as Malaysia that have varying conditions and a lack of lane discipline. However, existing critical gap determination methods assume that drivers are consistent and homogeneous in their behavior, which may not be the case. This study aimed to calculate the critical gap value using Logit, Raff's, and Wu's methods based on observed accepted and rejected gap data from three locations in Malaysia. When calculating the critical gap, pedestrian gender, age, and group size behavior were taken into account. The pooled data sets from each location were used in the Logit approach to calculate the critical gap based on different explanatory variables.

4.2. Critical Gap Estimation Methods

4.2.1. Logit Model

To analyze a pedestrian's decision-making process when crossing a road, the Binary Logistic (BL) technique can be employed. Discrete choice theory [30] is used to represent this procedure, where a pedestrian makes a decision regarding whether to accept or reject a vehicular gap. In this context, the gap's dimensions serve as the key factor in the utility equation for accepting the gap, while the decision to accept or reject the gap is employed as the predictive variable. Using a linear combination function (utility function), Eq. (1) is used to construct the likelihood of opting for one of the alternatives (acceptance or rejection).

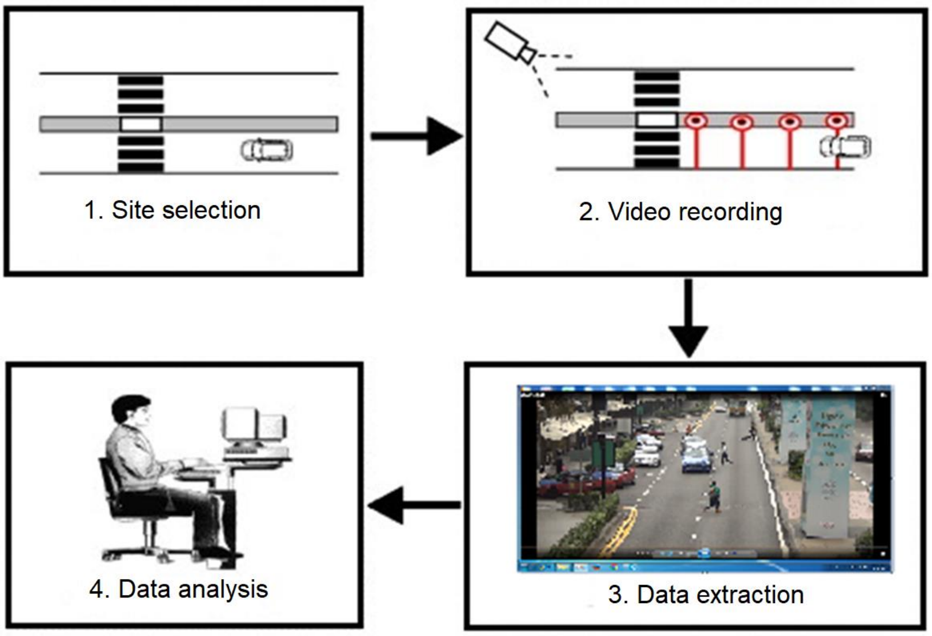

Figure 1. Data recording and extraction process

$$Ui = a_0 + a_1x_1 + a_2x_2 + \ldots + a_kx_k \quad (1)$$

where; Ui= the utility of choosing the alternative i, a_k-n= explanatory variables, a_1-n= are estimated parameters from the model, a_0 = coefficients of corresponding variables.

To calibrate this model, the SPSS software platform is utilized. The logit model is used to estimate the critical gap, with the pedestrian choice based on gap acceptance or rejection as the response variable and gap size as the independent variable. The key gap is defined as the point when the acceptance probability is 0.50 in the model, which forecasts the likelihood of accepting or rejecting a gap. Figure 2 displays the cumulative probability plot of the acceptance probability for observed gaps. The critical gap for pedestrians, which corresponds to the 50th percentile of gaps, is determined to be 8.4 seconds. The critical gap value is calculated based on the utility equation and critical gap outcomes.

4.2.2. Raff's Method

Overall, a total of 300 pedestrians were observed, and from this, 73 rejected gaps and 227 accepted gaps were obtained and used for analysis. The Raff method was chosen due to its small sample requirements, non-robust calculations, and popularity in past research. The simplicity of this method also makes it frequently used in transportation engineering. The critical gap value is defined as the point where the CDFs of accepted gaps intersect with the CDF of rejected gaps. At this point of intersection, the probability of a pedestrian rejecting a gap becomes less than accepting it, indicating the critical gap value. Based on the plotted CDF graph, the critical gap size was approximately 9.5 seconds as shown in Figure 3. It was also noted that the critical gap value obtained in this study was higher than the value reported by Pawar and Patil [31] in China but lies within the range suggested by Brewer et al. [32]

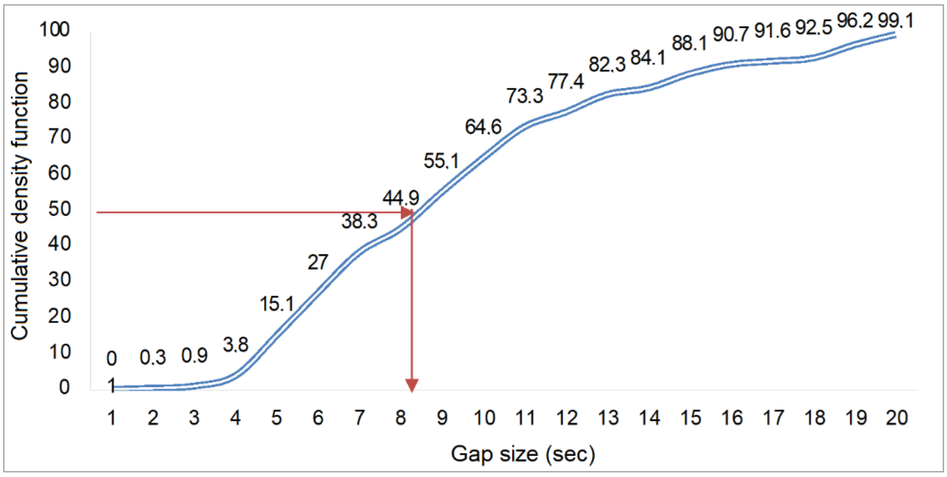

Figure 2. Critical gap estimation by logit method

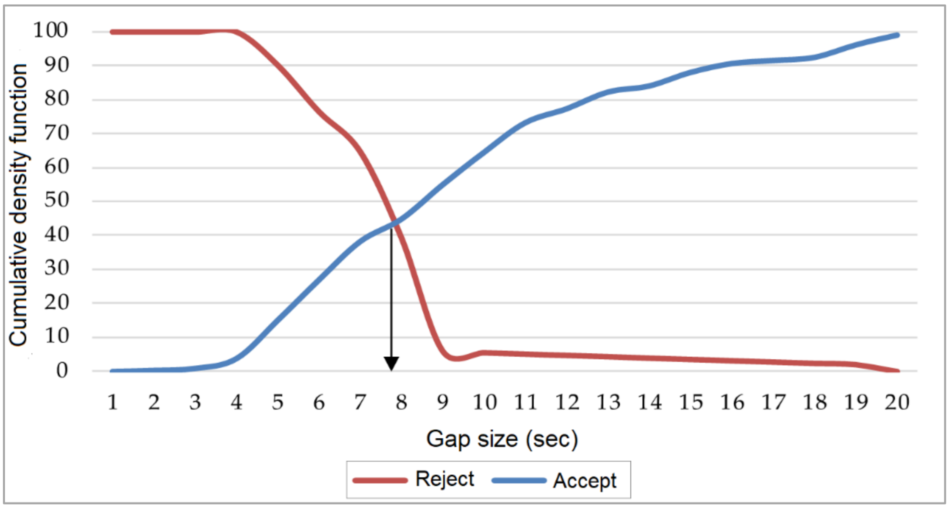

Figure 3. CDF of gap size rejection and acceptance

in the United States of America, indicating that the different pedestrian behaviors and vehicular characteristics in Malaysia led to the different critical gap value obtained.

4.2.3. *Wu's Model*

Wu's method is an approach that determines the average critical headway based on the probability balance between accepted and rejected gaps, eliminating the need for predefined distribution functions or assumptions about driver consistency and homogeneity. This technique provides an empirical distribution of critical gaps that can be useful for microscopic simulation. Using the maximum rejected gap instead of all rejected gaps in Wu's method produces results similar to those obtained in Johor for the average critical gap. However, considering all rejected gaps results in a shorter average critical gap than previous findings. A limitation of Wu's method is that the maximum rejected gap should be greater than the minimum accepted gap in the observation data, which may only occur in small sample sizes. The critical gap value is calculated by taking the product of the average gap value for a class and the frequency at which critical gap estimation is performed, and then adding up the outcomes. Based on Wu's method, the critical gap value computed is 7.122 seconds.

5. Discussions

Figure 4 illustrates a variety of critical gap values that have been estimated using various approaches, underscoring the significance of selecting the right critical gap value when planning pedestrian infrastructure. The default value of 8.9 seconds in the HCM 2010 is considered sufficient for an average pedestrian to cross the street safely. Interestingly, the estimated gap values in Malaysia are comparable to the HCM default value. Critical gaps were estimated at various locations, and their values are presented in **Figure 4**. The critical gap size obtained from Raff's method is approximately 7.7 seconds, while logit and Wu's methods result in critical gap sizes of 8.4 and 7.12 seconds, respectively. **Figure 4** summarizes the critical gap sizes for pedestrians in Malaysia derived from these methods.

Table 1 comparing the critical gap results obtained in this research to those estimated in other countries, it is noteworthy that the average critical gap in Malaysia is higher than the values reported by Guo et al. [28] in China (5.79 s) and by Jain & Rastogi [4] in India (3.1 s). However, critical gap sizes in Malaysia were found to range between 5.79 s to 9.40 s, consistent with the findings of Guo et al. [28] and Brewer et al [32] in China the United States of America respectively . Thus, it can be argued that differences in pedestrian behavior and vehicular characteristics from which the gap data was derived in Malaysia may have contributed to the variation in critical gap values obtained.

A notable observation between these experiments is that Raff and Wu methods provided accurate and consistent outcomes [33]. Notably, Wu's method offers advantages that address the limitations of the Raff's method, particularly in dealing with pedestrians who exhibit inconsistent crossing behaviors as stated by Mithun [33] this approach consistently delivers reliable and precise outcomes in real-world conditions. However, it requires the least accepted

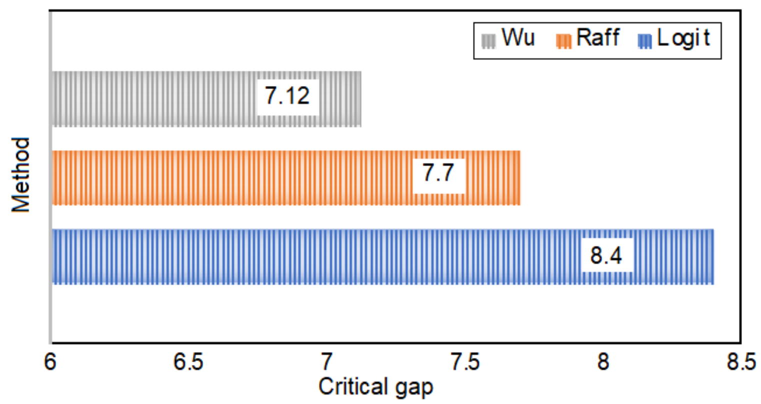

Figure 4. Critical gap of pedestrians in Malaysia

Table 1. Comparison critical gap of pedestrian with different countries

Author's name	Year	Critical gap in sec	Country
DiPietro and King [34]	1970	10	USA
Guo *et al.*, [28]	2014	5.79	China
Brewer *et al.*, [32]	2006	9.40	USA
Jain & Rastogi [4]	2017	3.1	India
Al Bargi *et al.*, (this research)	2023	7.74 (Avg)	Malaysia

gap value to be smaller than the largest rejected gap. The critical gaps estimated by logit method results in higher values than the Raff's as well as Wu method. In logit method, every rejected gap circumstance is taken into account, and pedestrian behavior with all rejected gap values can accurately depict the field's true state. Without any presumptions, unlike the HCM technique, the logit model's pedestrian safety threshold has a realistic value. In contrast to the HCM technique, which is "entirely based on pedestrian speed," the logit method contains numerous pedestrian behavioral and vehicular characteristics associated with metrics that may represent the actual field situation of pedestrian road crossing behavior.

6. Conclusion

The research aimed to estimate critical gap values on various roadways in Malaysia utilizing three different methods. The findings indicate that the average critical gap value is approximately 7.74 seconds, which aligns with the range of values reported in earlier studies conducted in the United States of America and India by Jain & Rastogi [4], as depicted in **Table 1**. Based on the obtained critical gap values, it can be inferred that pedestrians in Malaysia exhibit less aggressive behavior compared to those in India, as the estimated critical gap value in India was 3.1 seconds. This observation suggests that Malaysian pedestrians prioritize safety and demonstrate a tendency to avoid unnecessary risks, ensuring they cross roads only when there are sufficient gaps available. These findings also highlighted that the logit approach is the most suitable for estimating the critical gap because it takes into account both pedestrian behavior and vehicle characteristics. Additionally, it provides an accurate portrayal of how pedestrians cross streets at crosswalks in mixed traffic situations.

7. Recommendation

- Increase sample size: Future studies should aim to include larger and more diverse samples to improve the representativeness of the findings. This would enhance the generalizability of the results and provide a more comprehensive understanding of critical gaps.
- Employ multiple methodologies: Utilize a combination of quantitative and qualitative methodologies to triangulate the findings. By employing different methods, researchers can validate and strengthen the robustness of the results.
- Conduct comparative studies: Conduct comparative studies across different regions or countries to understand the variations in critical gaps. This would provide insights into the contextual factors influencing the gaps and facilitate knowledge sharing and best practices.
- Improve data collection: Enhance the quality and availability of data used in critical gap assessments. This may involve ensuring data completeness, accuracy, and reliability. Collaborating with relevant stakeholders or utilizing alternative data sources can help address data limitations.

By implementing these recommendations, future studies can advance the knowledge and understanding of critical gaps, leading to more effective policies and interventions to address these gaps and promote inclusive development.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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