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# Enhancing road safety on Tacloban Bypass Road, Philippines: A GIS-based risk assessment

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**ABSTRACT**

The Tigbao-Caibaan Bypass Road in Tacloban City has seen an increase in road crashes, causing property damage, injuries, and fatalities. This study evaluates road safety using the DPWH Risk Assessment Tool, which classified Brgy. Abucay as the highest-risk area based on crash data. Five sections within this barangay were assessed using both the DPWH Risk Assessment Tool and Demasi's Model, yielding consistent results—all sections were classified as low-risk under DPWH's framework. However, Demasi's Model further categorized Sections 3 and 4 as low risk, while Sections 1, 2, and 5 were classified as non-relevant risk due to fewer infrastructure deficiencies. Despite the low-risk classification, Sections 3 and 4 exhibited significant infrastructure deficiencies, including missing pedestrian crossings, inadequate sidewalks, lack of traffic signals, and poor visibility. Spot speed analysis revealed excessive speeding at Station 3 (85th percentile speed of 41.88 km/h), particularly concerning near a school zone. This research suggests traffic calming measures, better signposting, pedestrian crossings, and infrastructure development to reduce risks. These evidence-based interventions, as per DPWH safety standards, can enhance road safety and inform local policy and enforcement initiatives.

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**KEY FINDINGS**

- Specific sections of the 6.4-kilometer Tacloban Bypass Road exhibit heightened crash risks due to poor visibility at intersections, absence of pedestrian crossings, and lack of sidewalks and cycle paths
- Speed analysis revealed significant violations of the 40 kph posted speed limit, with Section 5 recording the calculated speed limit (85$^{th}$ percentile) of 41.875 km/h. Design speed defines road geometry, while speed limits are set based on safety and traffic conditions.
- Excessive speeds, combined with missing pedestrian safety features, significantly contribute to crash frequency.

## INTRODUCTION

Road safety is a prominent issue globally. It is estimated that traffic crashes stand as one of the very causes of mortality and losses in economics worldwide. The World Health Organization has estimated that road traffic crashes claim lives of nearly 1.2 million every year and cause injuries to 20-50 million individuals across the world each year (WHO, 2020). The economic impact is very large, as countries like the Philippines lose 4.1% of their Gross Domestic Product (GDP) annually due to road crashes (WHO, 2016). These statistics indicate the need for improved and effective road safety measures and

**KEYWORDS**

road safety, risk assessment, road inventory, spot speed analysis, DPWH Risk Assessment Tool, Demasi's Model

infrastructure developments to mitigate risks and enhance overall traffic safety.

Road crashes are influenced by different factors such as human factors, vehicle characteristics, road infrastructure, and the environment (Colagrande, 2021). Studies show 80% of road crashes are attributed to human error, vehicle-related factors account for 2%, and the rest are attributed to deficiencies in the road infrastructure (Garber & Hoel, 2010). Therefore, while recognizing these, different international studies have sought to address road safety challenges through technological and analytical methodologies.

One of the major approaches to road safety analysis has been the application of Geographic Information System (GIS) technology. GIS, as cited by Hisam et al. (2022), is used to visualize crash-prone areas in Malaysia, making the area strategic for interventions on road safety improvements. Similarly, although Aghajani et al. (2017) applied GIS-related techniques to determine spatial and temporal patterns of road crashes, a key challenge remains: GIS mainly serves as a mapping tool to show the locations of incidents, rather than providing deeper analysis or directly helping to develop solutions. Demasi et al. (2018) formulated analytical methodology in evaluating urban safety by incorporating road safety inspections data, while Alcaraz et al. (2020) presented an evaluation framework to assess traffic crash risks. These studies indeed give comprehensive safety assessments that integrate both crash mapping and targeted interventions.

Road infrastructure studies reveal the importance of road infrastructure in crash prevention. Road geometry, surface conditions, and roadside hazards significantly affect crash frequency, according to Pembuain et al. (2018). Cheng et al. (2021) also argued this point by saying that road design and maintenance with a user safety-first approach are essential since infrastructure is poor in most cases, which tends to contribute to high crash chances. Romero (2018) also showed how Quantum Geographic Information System (QGIS) can be employed to measure sight distances along highways for the regulation of speeds and possible prevention of crashes.

Another important element for enhancing road safety is geometric road design. Hisam et al. (2022) observed that the geometry of a road is important in distribution of crashes, with T-intersections being especially hazardous.

Crash patterns suggest that crashes along the Tigbao-Caibaan Bypass Road do not happen randomly but indicate some systematic inadequacies in road design or management. Studies in road safety point out that where crashes happen recurrently at a given location, it is more often than not indicative of deep-seated structural or operational inadequacies in the road system rather than the simple occurrence of isolated driver error. For that reason, an in-depth study of the identified accident-prone sections of the Tigbao-Caibaan Bypass Road is warranted to identify factors contributing to the crashes and thus develop appropriate safety measures.

This study aims to analyze crash-prone sections along the Tigbao-Caibaan Bypass Road to determine the key factors contributing to road crashes. Utilizing GIS and the Department of Public Works and Highways (DPWH) Risk Assessment framework, this research seeks to identify road infrastructure deficiencies, evaluate existing speed limits, and propose a comprehensive road safety development plan.

The findings of this study are expected to be instrumental for local government authorities, traffic engineers, and policymakers in developing evidence-based strategies to improve road safety. While road safety studies in the Philippines exist, many focus on national trends or urban traffic management, with limited research specifically examining localized crash-prone areas using GIS-based analysis. This study contributes to the growing body of literature by providing a region-specific assessment of road safety along the Tacloban Bypass Road. Utilizing QGIS as a tool for mapping road crash incidents, this research does not rely solely on GIS for analysis but rather integrates it with the DPWH Risk Assessment framework and Demasi's Model to identify infrastructure deficiencies and develop targeted mitigation measures. By doing so, this study ensures that findings are not only spatially represented but also actionable, offering practical recommendations for improving road safety in localized contexts. By bridging the gap between crash visualization and strategic countermeasure implementation, this research provides a data-driven approach to road safety enhancement, offering insights that are directly applicable to both local policymaking and the broader Philippine road safety context.

## MATERIALS AND METHODS

This study involves mixed methods in examining road safety conditions by utilizing four significant phases to create counter measures in sections that need to be analyzed from Tigbao-Caibaan Bypass Road in Tacloban City (**Fig. 1**).

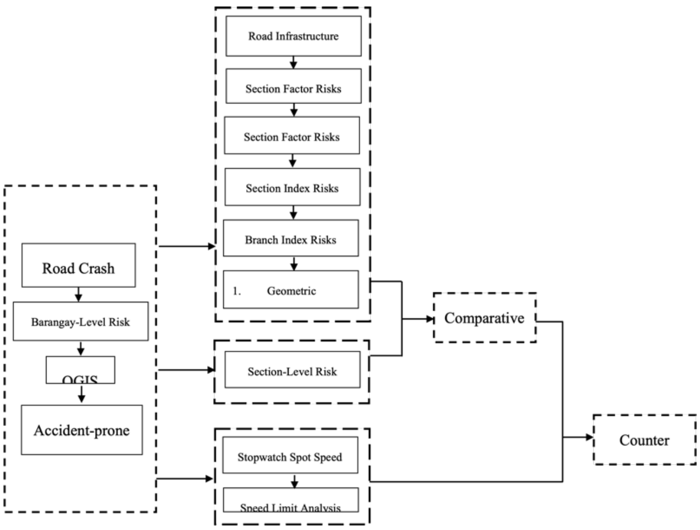


**Figure 1:** Methodological architecture for creating countermeasures

The researchers focused only on the selected sections that will be identified along the Tigbao-Caibaan Bypass Road. The said bypass road is on the east side of Tacloban City. After assessing the road, Quantum Geographic Information System (QGIS) was used exclusively as a tool for pinpointing the locations of crashes within the study area. Following the input of crash data, the researchers employed a risk assessment tool prepared by DPWH to identify sections with high risk enabling the researchers to focus their attention on areas with heightened risk on the Tigbao-Caibaan Bypass Road. This map facilitates the identification of areas with existing defects, enabling researchers to select specific branch/es for further analysis.

Additionally, metal tape measure was used to measure the geometric design of the selected section. They also employed a CCTV camera to capture real-time footage, enabling the analysis of traffic flow and the identification of patterns. A stopwatch with 0.01 accuracy was employed to measure the time it takes for vehicles to pass through points, intersections, or road segments. Furthermore, the researchers relied on police reports documenting traffic crashes, which provided details on crash locations, types, and severity.

**Data Assessment**

**Barangay-Level Risk Assessment**
To initially assess the risk level of the four barangays along the Tigbao-Caibaan Bypass Road and prioritize actions in design decisions with safety implications, the risk assessment conducted by the DPWH was utilized. This assessment, detailed in the DPWH Road Safety Design Manual (Part 1, Chapter 21), categorized road segments based on their respective barangays. The classification was determined solely by the number of recorded crashes and victims from January 1, 2021 to October 30, 2023. The barangay with the highest crash incidence was selected for a more detailed analysis at a granular level.

The probability of a collision occurring can be impacted by various elements like driver conduct (such as distractions, tiredness, and recklessness), road conditions (including surface quality, alignment, etc.), and vehicle health (like inadequately serviced brakes, tires, etc.). Determining the likelihood of a particular kind of collision can be established by referring to the specifications provided in Table 1.

**Table 1:** Likelihood Definition

| Frequency | Description |
|---|---|
| **Frequent** | One of the more times per month |
| **Occasional** | More than once per year (but less than 12) |
| **Infrequent** | Less than once per year |

If a crash occurs, its consequences are determined by factors such as vehicle speed, the severity of roadside hazards, and the vehicle's capacity to safeguard occupants (including seatbelts, airbags, crumple zones, collapsible steering columns, etc.). These consequences can be categorized based on the criteria provided in Table 2.

**Table 2:** Consequence Definition

| Severity of a crash | Description |
|---|---|
| **Very Serious** | Multiple fatalities, severe injuries |
| **Serious** | Single fatality/severe injuries |
| **Minor** | Minor injuries, property damage |

The risk is then estimated from the likelihood and consequences scores per Table 3.

**Table 3:** Risk Category

| | | Consequence | | |
|---|---|---|---|---|
| | | **Very Serious** | **Serious** | **Minor** |
| **Likelihood** | Frequent | HIGH | HIGH | MEDIUM |
| | Occasional | HIGH | MEDIUM | LOW |
| | Infrequent | MEDIUM | LOW | LOW |

**Table 4:** Treatment Priority

| RISK | Suggested Treatment Priority |
|---|---|
| **HIGH** | Must be corrected or the risk significantly reduced at the earliest possible time. |
| **MEDIUM** | Should be corrected or the risk significantly reduced as medium priority |
| **LOW** | Must be corrected or the risk significantly reduced as low priority works. |

**Quantum Geographic Information System (QGIS)**
After assessing the road, Quantum Geographic Information System (QGIS) was used exclusively as a tool for pinpointing the locations of crashes within the study area. Following the input of crash data and corresponding coordinates into the system, researchers were provided with access to a map. This map facilitates the identification of areas with existing defects, enabling researchers to select specific branch/es for further analysis.

**Section-Level Risk Assessment**
Building upon the barangay-level assessment, where the DPWH Risk Assessment Tool was used to classify risk levels across multiple barangays, this study further refined the analysis by focusing on section-level risk evaluation within the highest-risk barangay. The selected barangay was subdivided into five sections, allowing for a more localized assessment of road safety conditions.

Using the same DPWH Risk Assessment Tool, the section-level evaluation was conducted based solely on crash data, including the frequency, severity, and distribution of recorded road crashes from January 1, 2021 to October 30, 2023. By applying the tool at this level, the study aimed to identify specific sections where crash risks were more pronounced, thereby enabling a detailed comparison with Demasi's Model. This comparison helped validate risk classifications and assess whether additional risk factors beyond crash data, such as infrastructure deficiencies or behavioral risks, needed to be considered.

**Road Infrastructure Analysis**
Researchers performing a section-level risk assessment divided the selected barangay into 5 sections. The methodology proposed by Demasi et al. (2018) was applied to evaluate each section quantitatively, specifically assessing the Branch Index Risk (BIR) and Section Index Risk (SIR) along designated segments of the Tacloban Bypass Road. This assessment considers road design, layout, users, and trafficking. The BIR is an overall measure of road crash risk across a network, where a higher BIR indicates less safety characterizing the analyzed infrastructure section. The values of BIR rely on the Section Factor Risk (SFR) related to each uniform section included in the branch, where every homogeneous section is defined by 100 m length with ±20% variance, if needed. The sections measure consistent crash rates, geometric layout, cross-section composition, traffic mix, and average speed across numerous observations. This method makes it possible to estimate the risk density for short sections created based on the specific urban landmark of the city, and in combination with safety performance evaluation of road segments, it is validated by Cafiso et al. (2018). The section risk factor, denoted as $SFR_{j,r}$

incorporates multiple road characteristics, including hazard type and frequency, potential impact on vulnerable road users, and traffic volume. Additionally, it accounts for various contributing factors affecting the section's risk. The computation and planning of $SFR_{j,r}$ follow Equation (1):

$$SFR_{j,r} = \sum_{i=1}^{n} Bi \times K1i \times K2i \times K3 \times K4i \times K5i \quad (1)$$

where Bi represents the base value for defects i located along j, K1i denotes the priority factor associated with the category of element i, K2i accounts for the vulnerability of road users such as pedestrians, cyclists, and motorcyclists, based on their volume, K3 represents the motorized traffic factor for the section, K4i measures the hazardousness factor, reflecting how defect I impacts vulnerable road users, and K5i is the extension factor, which depends on whether defects/elements are continuous or discrete along section j. Using SIR(j,r), the Section Index Risk (SIR) is determined with Equation (2).

$$SIR_{j,r} = SFR_{j,r}/SFR_{max,r} \times 100 \quad (2)$$

where $SIR_{j,r}$ represents the section index risk of the section $j$ in region $r$, and $SFR_{max,r}$ is the maximum section risk factor value, assigned to the most critical defects identified in region $r$.

Therefore, $SFR_{j,r}$ is contingent on the identified road elements and defects, while $SIR_{j,r}$ results from the comparison of actual versus maximum attributed values for $K1i, K2i, K3, K4i$, and $K5i$.

Similarly, the Branch Index Risk $BIR$ for a road branch can be determined using Equation (3).

$$BIRr = Rr/Rmax,r \times 100 \quad (3)$$

where $Rr$ is the summation of all $SIRj,r$ values across m sections comprising branch $r$, computed as:

$$SFR_{j,r} = \sum_{j=1}^{m} SIRj,r \quad (4)$$

where $Rmax,r$ represents the reference risk factor value, calculated using):

$$Rmax,r = m \times SFRmax,r \quad (5)$$

As with $SIR_{j,r}$, the Brach Index Risk (BIR) is influenced by assigned values of K1i, K2i, K3, K4i, and K5i, along with detected defects along the road network. The values of both $SIR_{j,r}$, and BIRr fall within the range of 0 to 1.

To apply this risk assessment framework, road inspections are carried out to identify and classify infrastructure elements and defects that may contribute to crashes. The analysis categorizes these elements into nine groups, geometry (G), cross-section (C), road signs (S), intersections (J), and stopping areas (ST).

The assignment of values for K1i, K2i, K4i, and K5i, as well as Bi, is based on findings from the study titled "Road Safety Analysis of Urban Roads: Case Study of an Italian Municipality" (2018). This research involved technical specialists and academics with expertise in road infrastructure, urban planning, transport management, and public health. Data was collected through consultations with road engineers, urban planners, traffic managers, and trauma specialists. Each variable was assigned a predetermined minimum and maximum value, with individual assessments being combined using a geometric mean.

In total, 55 road elements and defects were identified as potential contributors to crashes. The base values (Bi) of these elements adhere to Equation (6).

$$1 \leq Bi \leq 4 \quad (6)$$

Reference benchmarks were drawn from the DPWH Road Safety Manual (Books 1 & 2, 2012), which outlines national standards for road and intersection design, encompassing geometric and functional considerations, as well as safety guidelines and road lighting specifications. These benchmarks were used to determine non-compliance conditions and to assign corresponding $Bi$ values.

The vulnerability factor $K2i$ is influenced by the traffic conditions of at-risk users (i.e., pedestrians, cyclists, and motorcyclists), reflecting their exposure to defects. According to the Highway Capacity Manual, data collections involve 15-minute interval surveys to estimate traffic volume. Observations were conducted under normal weather conditions and during peak operational hours for work and school activities. $K2i$ is computed as follows:

$$K2i = KPi \times KCi \times KMi \quad (7)$$

where, KPi,KCi, and KMi represent pedestrian, cyclist, and motorcyclist flow, respectively. Their values range as follows:

$$1 \leq \text{KPi} \leq 2.5 \quad (8)$$
$$1 \leq \text{KCi} \leq 2.5 \quad (9)$$
$$1 \leq \text{KMi} \leq 2.5 \quad (10)$$

Average hourly flow values for cyclists (ACF) and motorcyclists (AMF) were determined, along with their standard deviations (DCF and DMF). These were then compared with the observed traffic volumes of the examined road branch rrr to establish KCi and KMi.

The motorized traffic factor K3 depends on vehicle volume within the observed section. It assumes that increased vehicle speeds elevate risks for vulnerable users. The determination of K3 aligns with the approach outlined by Biswas et al. (2016), which assesses urban arterial service levels by defining congested conditions as instances where speed reductions exceed 50% of free-flow speed. The hazardousness factor K4i reflects the likelihood of fatalities resulting from defect i, particularly for vulnerable road users. It is computed using Equation (11):

$$K4i = K4Vi \, x \, K4Pi \quad (11)$$

K4Vi and K4Pi denote expected consequences for motorized vehicle occupants and non-motorized road users, respectively. Their values adhere to the ranges:

$$1 \leq \text{K4Vi} \leq 2.5 \quad (12)$$
$$1 \leq \text{K4Pi} \leq 5.0 \quad (13)$$

These values acknowledge that, at equal speeds, vulnerable road users face significantly higher risks than occupants of motorized vehicles. The probability of fatalities due to collisions with motor vehicles, head-on crashes, or impacts with solid objects follows probability curves presented by Wramborg, which emphasize the increased exposure of unprotected road users.

The extension factor K5i describes the spatial distribution of defects along section j. The classification of SIR levels, along with their chromatic categorization, is summarized in **Table 5**.

**Table 5:** Classes of Risk

| Class | Risk Level | Criterion | SIR (%) Min | SIR (%) Max | Chromatic Categorization |
|---|---|---|---|---|---|
| **I** | Not relevant | $I < \mu - 2\sigma$ | 0 | 14.5 | White |
| **II** | Low | $\mu - 2\sigma < I < \mu - \sigma$ | >14.5 | 21.2 | Green |
| **III** | Moderate | $\mu - \sigma < I < \mu$ | >21.2 | 28.0 | Yellow |
| **IV** | High | $\mu < I < \mu + 2\sigma$ | >28.0 | 34.8 | Orange |
| **V** | Very High | $\mu + 2\sigma < I < \mu + 2\sigma$ | >34.8 | 41.5 | Red |
| **VI** | Critical | $I > \mu - 2\sigma$ | >41.5 | 100 | Burgundy |

*Source: Demasi, et. al. (2018)*

**Speed Limit Analysis**

**Obtain Appropriate Study Length**

The duration of the study is a critical factor as it directly impacts the calculation of vehicle speeds. Table 6 offers suggested study lengths, which are determined based on the average speed of the traffic flow. These recommended study lengths simplify calculating speeds and reduce potential confusion. However, if these specified lengths are not suitable for a particular situation, an alternative length can be employed, provided it is sufficiently long to accommodate reliable observer reaction times (Smith et al 2002).

**Table 6:** Recommended Spot Speed Study Lengths

| Posted Speed Limit | Recommended Study Length (m) |
|---|---|
| **Below 40 kph** | 26.823 |
| **40-64 kph** | 53.645 |
| **Above 64 kph** | 80.467 |

*Source: Handbook of Simplified Practice for Traffic Studies. (2002, November)*

**Proper Location**

To conduct a spot speed study with a stopwatch, it's essential to follow a specific layout. Care should be taken when selecting the study location and layout to ensure that the observer has a clear line of sight to any vertical reference posts. Ideally, the observer should be positioned at a point overlooking the study area. To collect the elapsed time, it takes a vehicle to traverse the study area, reference points should be used. The starting reference point might be a brightly colored vertical post, while the endpoint reference point could be a tree or a signpost in the observer's line of sight. It's important to document the site accurately, noting details such as the number of lanes, the observer's position, and descriptions of the reference points (Smith et al 2002).

**Field Data**

The selected section for data collection was deliberately situated at a considerable distance from any intersection or access point to ensure an uninterrupted flow of traffic. One considered factor of choosing the stations is based on the sections where there are most number of recorded crashes. A longitudinal segment, measuring feet in length that depends on the posted speed limit, is marked on the highway toward traffic movement using white self-adhesive cloth tape or any brightly colored reference. Video recording of the sections was conducted. Subsequently, the recorded video was played back on a monitor in the laboratory, and information on classified volume counts was deciphered and compiled (Mehar et al., 2014). A minimum sample size of 100 vehicles was used in most circumstances. (Ewing 1999).

**Calculate Vehicle Speed**

To ascertain a vehicle's speed, the predetermined length was utilized specified in the study and the recorded time it took for the vehicle to cover that distance, as documented on the stopwatch data form. This calculation follows the formula outlined by Robertson (1994). This method enables a good evaluation of the vehicle's speed, providing valuable data for the comprehensive analysis of factors influencing traffic flow and contributing to a deeper understanding of road safety dynamics. (Smith et al 2002).

**RESULTS**

**Barangay-Level Risk Assessment**

Using the DPWH Risk Assessment Tool, **Fig. 2** indicates that all four barangays fall under the high-risk category. Among them, Brgy. Abucay recorded the highest number of crashes and victims.

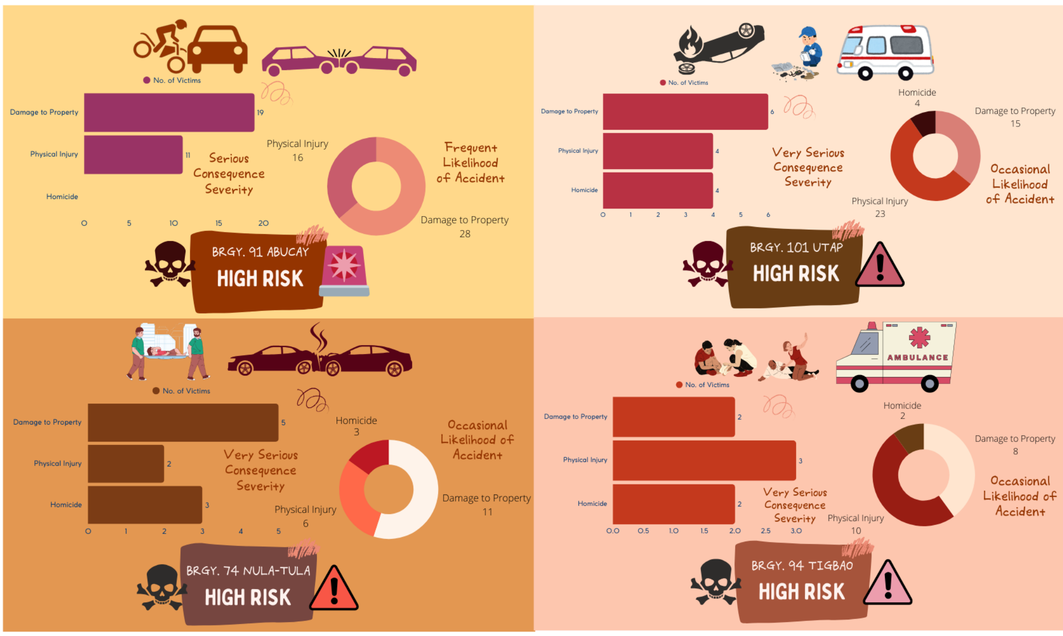


**Figure 2:** Barangay- Level Risk Category based on DPWH Risk Assessment Tool

**Generate Frequency Distribution Table and Determine Speed Percentiles**

To determine the 50th (median) and 85th speed percentiles, the study employs a frequency distribution table coupled with meticulous calculations. This statistical analysis provides insights into the central tendency and upper percentile of vehicle speeds, contributing to a more nuanced understanding of the speed distribution within the dataset. The 50th percentile represents the median speed, indicating the value below which 50% of the recorded speeds fall. On the other hand, the 85th percentile offers a higher threshold, illustrating the speed at or below 85% of the observed data lies. These percentiles serve as valuable metrics for characterizing the speed profile of the studied vehicles, aiding in the identification of critical points for traffic management and safety interventions. (Smith et al 2002).

**(Fig. 3)** delineates the chosen branch from the Tacloban City Bypass Road within the purview of the research. This branch was selected based on the comprehensive data set provided by Tacloban City Police Station 1 and Police Station 2 from January 1, 2021 to October 30, 2023.

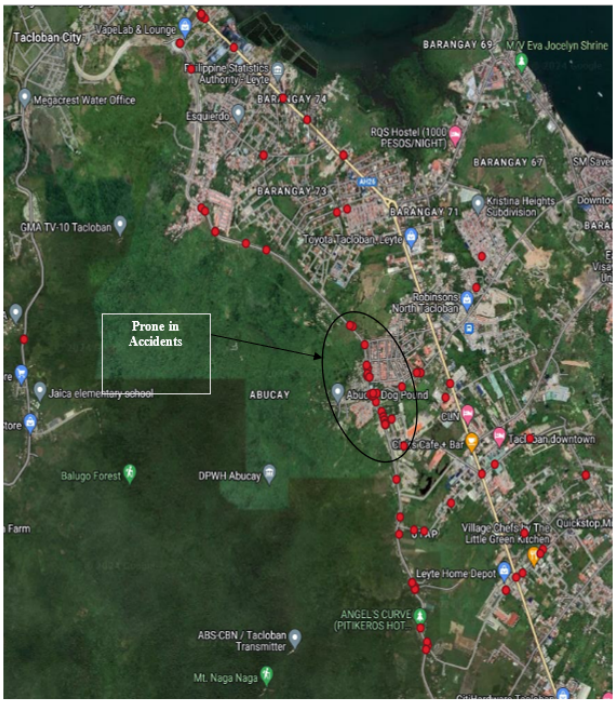


**Figure 3:** Overall Geographical Location of Tacloban City Bypass Road with the accident data, Google Earth (2024) (QGIS)

**Road Infrastructure Inventory Analysis**

A road inventory was conducted by the researchers on selected sections of Brgy. Abucay spanning 500 meters within the chosen branch of the study area. **(Fig. 4)** on the other hand shows the cumulative number of recorded crashes transpiring within the delineated stretch amounts to 16 incidents spanning the period from 2021 to 2023. This stretch of road is subdivided into five distinct segments having 100 meters in length per section.

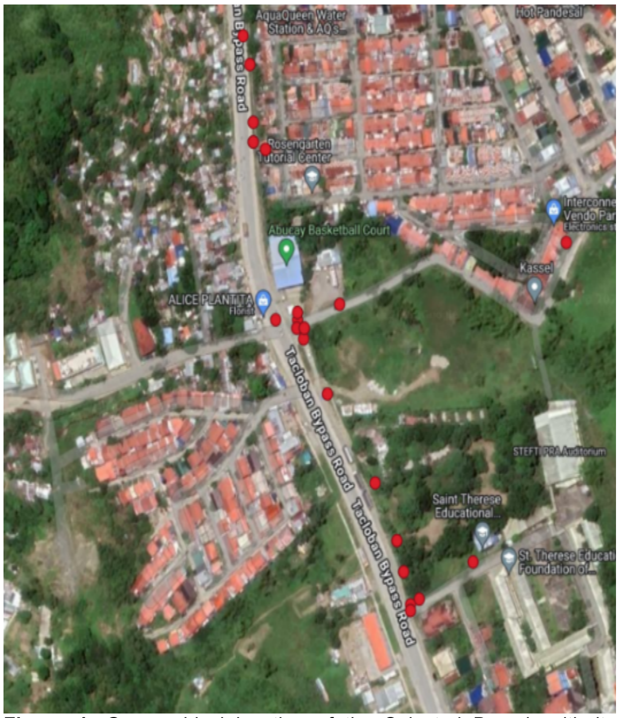


**Figure 4:** Geographical location of the Selected Branch with its accident data, Google Earth (2024) (QGIS)

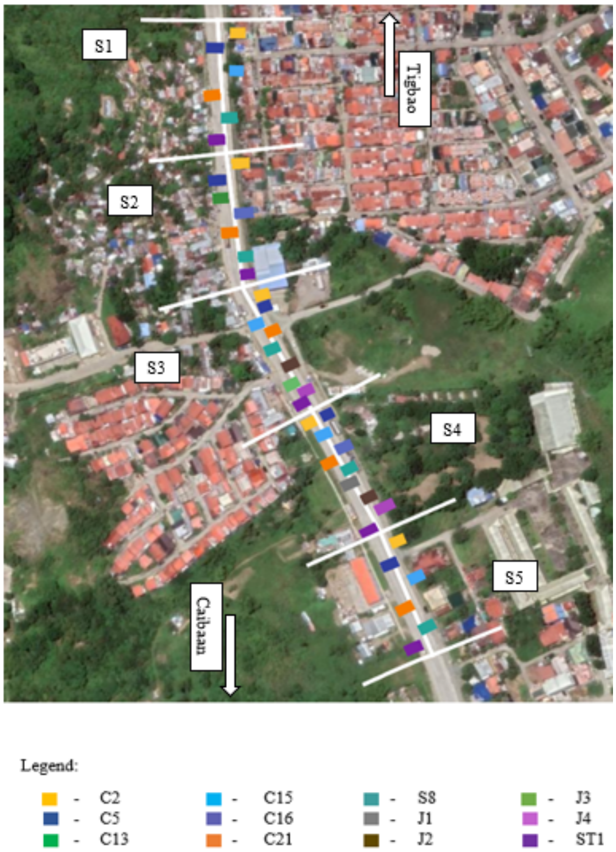


**Figure 5:** Defects Found in Every Section, Google Earth (2024) (QGIS)

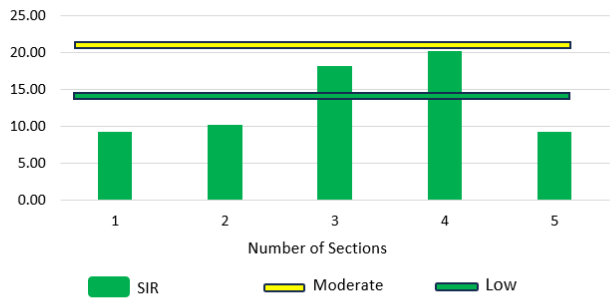


**Figure 6:** SIRj of Selected Road Section


**Figure 7:** Street View Images of Five Sections via Google Earth Satellite (2024)

**Fig. 7** shows the street view of the actual site showcasing the defects (see **Fig.5**) that were calculated in **Table 7**.

**Table 7:** The calculation for the Value of *SFR* and *SIR* of every Section

| **Section 1** | **Defects** | **Bi** | **K1i** | **K2i** | **K3** | **K4i** | **K5i** | **SFRj,r** | $SIR_{1,1}$ |
|---|---|---|---|---|---|---|---|---|---|
| **C2** | missing shoulder | 2 | 1 | 1.5 | 2.5 | 1 | 2 | 15 | 9.284267 |
| **C5** | missing sidewalk | 4 | 1 | 1.5 | 2.5 | 4.5 | 2 | 135 | |
| **C15** | missing pedestrian crossing | 4 | 1 | 1.5 | 2.5 | 3 | 2 | 90 | |
| **C21** | missing cycle path | 3 | 1 | 2 | 2.5 | 2 | 2 | 60 | |
| **S8** | missing traffic light | 4 | 0.7 | 1 | 2.5 | 4 | 1 | 28 | |
| **ST1** | Illegal parking | 1 | 0.4 | 4 | 2.5 | 2 | 1.5 | 12 | |
| **Section 2** | Defects | Bi | K1i | K2i | K3 | K4i | K5i | **SFRj,r** | $SIR_{2,1}$ |
| **C2** | missing shoulder | 2 | 1 | 1.5 | 2.5 | 1 | 2 | 15 | 10.24 |
| **C5** | missing sidewalk | 4 | 1 | 1.5 | 2.5 | 4.5 | 2 | 135 | |
| **C13** | a pedestrian crossing without ramps | 2 | 1 | 1.5 | 2.5 | 3 | 2 | 45 | |
| **C16** | more than 12 m-long crossing | 4 | 1 | 1.5 | 2.5 | 4 | 2 | 80 | |
| **C21** | missing cycle path | 3 | 1 | 2 | 2.5 | 2 | 2 | 60 | |
| **S8** | missing traffic light | 4 | 0.7 | 1 | 2.5 | 4 | 1 | 28 | |
| **ST1** | Illegal parking | 1 | 0.4 | 4 | 2.5 | 2 | 1.5 | 12 | |
| **Section 3** | Defects | Bi | K1i | K2i | K3 | K4i | K5i | **SFRj,r** | $SIR_{3,1}$ |
| **C2** | missing shoulder | 2 | 1 | 2 | 2.5 | 1 | 2 | 20 | 18.22037 |
| **C5** | missing sidewalk | 4 | 1 | 2 | 2.5 | 4.5 | 2 | 180 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **C15** | missing pedestrian crossing | 4 | 1 | 2 | 2.5 | 3 | 2 | 120 | |
| **C21** | missing cycle path | 3 | 1 | 1.5 | 2.5 | 2 | 2 | 45 | |
| **S8** | missing traffic light | 4 | 0.7 | 2.25 | 2.5 | 4 | 1.5 | 63 | |
| **J2** | missing reserved lane | 3 | 1 | 2.25 | 2.5 | 4 | 2 | 135 | |
| **J3** | hazardous maneuvers | 3 | 1 | 2.25 | 2.5 | 4 | 1.5 | 67.5 | |
| **J4** | missing weaving section | 3 | 1 | 1 | 2.5 | 4 | 1.5 | 30 | |
| **ST1** | Illegal parking | 1 | 0.4 | 2.25 | 2.5 | 2 | 1.5 | 6.75 | |
| **Section 4** | Defects | Bi | K1i | K2i | K3 | K4i | K5i | **SFRj,r** | $SIR_{4,1}$ |
| **C2** | missing shoulder | 2 | 1 | 1.5 | 2.5 | 1 | 2 | 15 | 20.17963 |
| **C5** | missing sidewalk | 4 | 1 | 1.5 | 2.5 | 4.5 | 2 | 135 | |
| **C15** | missing pedestrian crossing | 4 | 1 | 1.5 | 2.5 | 3 | 2 | 90 | |
| **C21** | missing cycle path | 3 | 1 | 2 | 2.5 | 2 | 2 | 60 | |
| **S8** | missing traffic light | 4 | 0.7 | 4 | 2.5 | 4 | 1 | 112 | |
| **J1** | lack of visibility | 4 | 1 | 1.5 | 2.5 | 2 | 1.5 | 45 | |
| **J2** | missing reserved lane | 3 | 1 | 4 | 2.5 | 4 | 2 | 420 | |
| **J4** | missing weaving section | 3 | 1 | 1 | 2.5 | 4 | 1.5 | 30 | |
| **ST1** | Illegal parking | 1 | 0.4 | 4 | 2.5 | 2 | 1.5 | 12 | |
| **Section 5** | Defects | Bi | K1i | K2i | K3 | K4i | K5i | **SFRj,r** | $SIR_{5,1}$ |
| **C2** | missing shoulder | 2 | 1 | 1.5 | 2.5 | 1 | 2 | 15 | 9.284267 |
| **C5** | missing sidewalk | 4 | 1 | 1.5 | 2.5 | 4.5 | 2 | 135 | |
| **C15** | missing pedestrian crossing | 4 | 1 | 1.5 | 2.5 | 3 | 2 | 90 | |
| **C21** | missing cycle path | 3 | 1 | 2 | 2.5 | 2 | 2 | 60 | |
| **S8** | missing traffic light | 4 | 0.7 | 1 | 2.5 | 4 | 1 | 28 | |
| **ST1** | Illegal parking | 1 | 0.4 | 4 | 2.5 | 2 | 1.5 | 12 | |

Using the defects found in the five selected sections, the calculation for the Section Factor Risk ($SFR_{j,r}$) of every section and their Section Index Risk ($SIR_{j,r}$) are shown in **Table 7**. Each defect has its value in the following factors:

> *Bi* which represents the base value associated with defects i located along j, *K1i* which is the priority factor for the category to which element i belong, *K2i* is the vulnerability factor of users, such as pedestrians, cyclists, and motorcyclists, along route r, which depends on their volume, *K3* represents the motorized traffic factor for route r, *K4i* is the hazardousness factor, reflecting the impact of defect i on the most vulnerable road users, and *K5i* is the extension factor, influenced by weather elements/defects i along j are continuous or discrete.

Upon inputting the corresponding values of these factors, the SFR of each defect will be obtained by multiplying the values of all the factors. Then the researchers can calculate the value of SFRj,r of every section by summing up all its respective defect's SFR.

Meanwhile, SFRmax is calculated by finding the highest value of SFRj,r among all the five selected sections. After identifying the defect with the highest value, the product of the maximum value of each factor becomes the value of $SFR_{max}$. Finally, The $SIR_{j,r}$ for each section can be calculated by dividing $SFR_{j,r}$ by SFRmax.

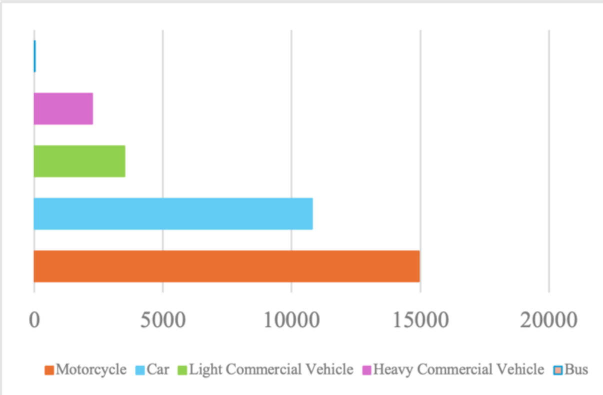


**Figure 8:** Average Traffic Volume Based on Vehicle Type passing through Tigbao-Caibaan Bypass Road

The traffic volume and composition data (**Fig. 8**) reveal that motorcycles (14,948) dominate the Tigbao-Caibaan Bypass Road, followed by cars (10,800), LCVs (3,494), HCVs (2,253), and buses (20). The high presence of motorcycle highlights the need for dedicated lanes and safety measures. The mix of vehicle types suggests varying road safety risks, particularly for smaller vehicles sharing space with larger commercial trucks. These findings emphasize the need for infrastructure improvements, speed control measures, and proper traffic management to enhance road safety.

### Section-Level Risk Assessment

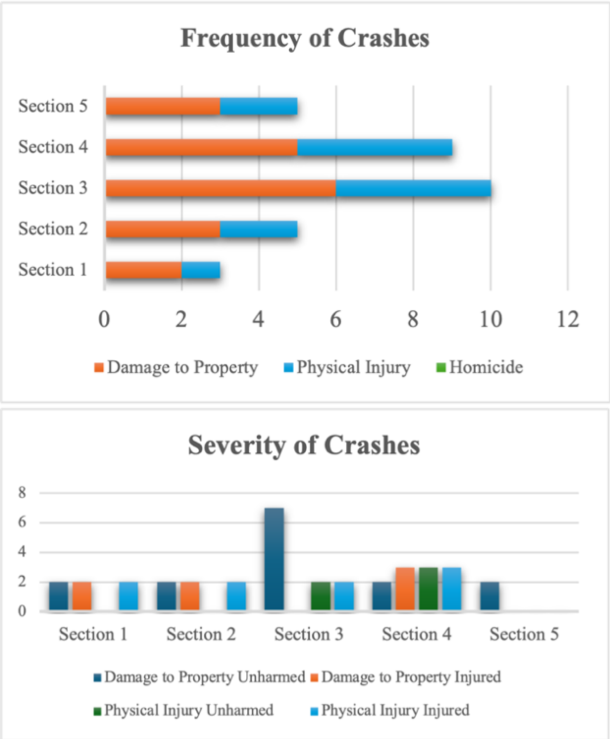


**Figure 9:** Crash Data in Section Level Risk Assessment

The DPWH Risk Assessment Tool was used to evaluate crash data at the section level, focusing on crash frequency (likelihood) and crash severity (refer to **Fig.9**). The findings indicate that all five sections fall under the "Occasional Likelihood" category, meaning crashes occur more than once per year in each section. However, the severity of crashes in all sections is classified as "Minor Severity", as the recorded incidents primarily resulted in minor injuries and property damage, with no significant fatalities or life-threatening injuries reported. Given this classification, the overall risk level for all sections is categorized as "Low-Risk" according to the DPWH framework.

### Speed Limit Analysis

The researchers conducted speed analysis across three designated stations which had the highest recorded crashes (refer to **Fig. 10**), as depicted in (**Fig. 9**).


**Figure 10:** Stations for Spot Speed Limit Analysis

**Table 8:** Summary of Observed Operational Speeds

| | 85$^{th}$ Percentile Speed (km/h) | Mean Speed (km/h) | Standard Deviation (km/h) | Minimum Speed (km/h) | Maximum Speed (km/h) |
|---|---|---|---|---|---|
| Station 1 | 26 | 22.03 | 4.918 | 12 | 39 |
| Station 2 | 38.625 | 32.485 | 7.116 | 14 | 64 |
| Station 3 | 41.875 | 33.78 | 7.882 | 17 | 59 |

The values in **Table 8** represent observed operational speeds rather than posted speed limits. The 85th percentile speed, which reflects the speed at or below which 85% of vehicles travel, is commonly used to assess prevailing traffic behavior and guide speed limit adjustments. The mean speed provides the average vehicle speed within each section, while the standard deviation indicates variability.

## DISCUSSION

### Barangay-Level Risk Assessment

In line with the findings of the DPWH Risk Assessment, all barangays are classified as High Risk as shown in **Fig. 2**. Among the four barangays, Brgy. Abucay had the highest recorded number of crashes and victims (refer to **Fig.4**). To better understand crash probability and severity, this study further examines its sections, offering a quantitative basis for risk evaluation. This outcome aligns with several previous studies investigating the correlation between road conditions and traffic crash frequency. The spatial analysis of crash locations in this study identified intersections and curved road segments as areas of heightened risk. These findings emphasize the necessity of prioritizing interventions in these sections to enhance safety and mitigate crash occurrences.

### Road Infrastructure Inventory Analysis

After the initial assessment using the DPWH Risk Assessment tool, the selected branch was divided into five (5) equal sections. To scale down the risk assessment in each section, a road infrastructure inventory analysis was conducted, following Demasi's methodology.

The said analysis conducted revealed a significant correlation between risk and defects present in sections 3 and 4 shown in **Fig. 5**. It was found during the inventory that sections 1 and 5 have the same number and kind of defects, which are (C2, C5, C15, C21, S8, ST1), while section 2 recorded a total of seven defects (C2, C5, C13, C16, C21, S8, ST1). Additionally, sections 3 and 4 have the same number of defects, totaling eight, which are the same as the other sections (C2, C5, C15, C21, S8, J2, J4, ST1), but each has one unique defect: J3 for section 3 and J1 for section 4. This data provides insight into the specific defects found in each selected road section (**Fig.7**), aiding in assessing countermeasures and overall road conditions.

These defects, including missing shoulders, sidewalks, pedestrian crossings, cycle paths, traffic lights, visibility issues, reserved lanes, illegal parking, and hazardous maneuvers, were found to contribute significantly to the overall risk. Moreover, the above-mentioned findings were used to calculate the Section Index Rate (SIR) for each section shown in **Table 7**, indicating the risk level associated with the identified defects. Sections 1, 2, and 5 were classified as "non-relevant" risk, while sections 3 and 4 were labeled as "low" risk. The results were visualized in **Fig. 6**, highlighting the impact of defects on road safety within the studied sections.
The findings suggest that infrastructure deficiencies play a

crucial role in influencing crash occurrences. The prevalence of missing pedestrian facilities, visibility obstructions, and improper traffic control measures in certain sections underscores the necessity for targeted road improvements to enhance overall safety. Addressing these deficiencies through engineering interventions and improved enforcement strategies can significantly reduce crash risks and enhance road user safety.

Moreover, understanding the traffic volume and composition (refer to **Fig. 8**) along the Tigbao-Caibaan Bypass Road is essential for assessing road safety risks across the five sections. Motorcycles account for the highest traffic volume, with 14,948 recorded movements, highlighting their significant presence on the road and the need for motorcycle-friendly infrastructure such as designated lanes, improved road markings, and increased visibility measures. Cars, the second-largest category with 10,800 recorded vehicles, contribute to traffic congestion and speeding-related risks, requiring proper lane markings, speed control measures, and intersection improvements. Light Commercial Vehicles (LCVs) and Heavy Commercial Vehicles (HCVs), totaling 3,494 and 2,253 vehicles, respectively, create mixed traffic conditions, increasing risks of rear-end collisions and lane-changing conflicts, which may be mitigated through wider road shoulders, dedicated truck lanes, and regulated speed limits. Buses, with only 20 recorded movements, indicate minimal public transport use; however, strategically placed bus stops and pedestrian crossings should still be considered to ensure safe access for passengers. The diverse mix of vehicle types underscores the need for well-planned road infrastructure that accommodates all users safely.

**Section-Level Risk Assessment**

The DPWH Risk Assessment Tool classified all five sections as having "Occasional Likelihood" (crashes occurring more than once per year) and "Minor Severity" (resulting in minor injuries and property damage, with no fatalities or severe injuries).

Based on this classification, all sections are designated as "Low-Risk" under the DPWH framework. This suggests that while crashes occur periodically, they are generally not severe enough to warrant immediate high-priority interventions from an infrastructure perspective. However, this does not eliminate the need for preventive measures, as minor crashes can still contribute to financial costs, traffic congestion, and potential escalation into more severe incidents over time.

**Comparative Analysis**

At the section level, both DPWH Risk Assessment Tool and Demasi's Model were used to identify the risk levels on various evaluation criteria. The best evaluation was found between all five sections as low-risk areas categorized by the DPWH Risk Assessment Tool into the "Occasional Likelihood" classification (crashes occurring at least twice a year) and "Minor Severity" (minor injuries and property damage). Meanwhile, Demasi's Model, in contrast, assessed each section regarding potential risk using a structured road inventory on its deficiencies in infrastructure, traffic conditions, and user-exposure factors. The results of Demasi's Model categorized Sections 3 and 4 as low risk, while Sections 1, 2, and 5 were classified as non-relevant risk areas, emphasizing different approaches between the two tools on risk factor assessment.

Both models indicate the same classifications in sections; however, their approaches to getting there differ. DPWH assessments are retrospective and thus rely on occurrences of past crashes to ascertain the levels of risk, while Demasi's Model provides pre-emptive risk identification based on conditions of the roads and vulnerability components of users. This difference shows that a section's historical risk level, as indicated by crash data, would not imply that comprehensive assessment since infrastructure deficiencies identified through Demasi's Model can point out latent hazards that might occur because of future crashes if left unaddressed.

Correlatively, between crash and infrastructure conditions as indicated by both models, there are incidences or factors that would suggest areas with potential risks. Sections 3 and 4, categorized low risk by Demasi's Model, have deficiencies that include missing pedestrian crossings, inadequate signing, lack of road shoulders, and absence of dedicated lanes for vulnerable users. These deficiencies can therefore become potential factors for an increased probability and severity of crashes, even at the low-risk categorization levels currently attached to them. In contrast, Sections 1, 2, and 5, classified under Demasi's Model as irrelevant risk, would have less shown infrastructure deficiencies and, in that sense, correlate to a lower recorded crash frequency historical in tool usage by DPWH.

Thus, the comparison between the two models confirms that crash data and infrastructure assessment are crucial for complete road safety evaluation. The consistency in some results strengthens the validity of the low-risk classification while differences underscore the need for considering infrastructure-based evaluations to describe potential hazards. Findings reveal that reliance on historical crash data may ignore emerging aspects related to infrastructure deficiencies. A balanced approach toward using both retrospective crash data and proactive risk assessment methodologies is therefore very important for data-driven, infrastructure-informed and proactive road safety interventions, as emerged from this study.

**Speed Limit Analysis**

The speed analysis across three stations (**Fig. 10**) the sections where the most crashes occur (**Fig. 4**) highlights critical safety concerns. Station 3, near a school, recorded the highest 85th percentile speed, mean speed, and standard deviation, indicating significant speed variability in a high-risk pedestrian area. Station 2 had the highest maximum speed, while Section 1 recorded the lowest minimum speed.

**Table 8** shows that Station 3 exceeded the 40 kph posted speed limit, presenting a compliance issue that requires immediate intervention. Targeted measures such as stricter enforcement, traffic calming strategies, and awareness campaigns are necessary to mitigate speed-related risks.

The 85th percentile speed, representing the speed at or below which 85% of vehicles travel, is commonly used to assess traffic behavior and guide speed limit adjustments. With Station 3 registering an 85th percentile speed of 41.88 km/h, exceeding the posted limit, speed management strategies are essential.

While Section 5, where Station 3 lies, is classified as 'non-relevant risk' based on SIR calculations, the speed analysis at Station 3—located near a school—reveals a significant compliance issue, with recorded speeds exceeding the posted limit. This highlights the need to integrate behavioral risk assessments with infrastructure-based evaluations. Although the SIR framework focuses on road conditions, it does not fully capture risks associated with driver behavior, such as excessive speeding near pedestrian zones. Given these findings, targeted interventions, including stricter enforcement, speed calming measures, and enhanced pedestrian safety infrastructure, are necessary to mitigate speed-related hazards in this area. This underscores the importance of using a comprehensive risk assessment approach that incorporates both physical road conditions and dynamic traffic behaviors to ensure road safety.

These findings emphasize the need for proactive speed control measures to enhance road safety, particularly in areas with high pedestrian activity. By addressing speeding issues, stakeholders can help reduce crash risks and create safer roads for all users.

**Study Strengths and Limitations**

A major strength in this research is the fact that it is data driven in road safety assessment, employing both the DPWH Risk Assessment Tool and Demasi's Risk Assessment Model to determine systematically road safety risk alongside the Tigbao-Caibaan Bypass Road.

In fact, crash data from the DPWH Risk Assessment Tool were used to analyze and categorize high-risk barangays by crash history from January 1, 2021 to October 30, 2023, thus focusing safety intervention on areas with the most recorded crashes, creating more directed evaluation of road hazards. GIS technology was used only to geocode the exact locations of crash incidents and assist in visualizing accident-prone areas, without providing further analysis.

In addition, this study also implemented Demasi Risk Assessment Model for quantitative analysis of the risk levels across five specific sections within the highest-risk branch that was identified from crash data. Using Section Factor Risk (SFR) and Section Index Risk (SIR) calculations, this study ranked risk numerically, so that safety measures could be prioritized objectively in terms of risk. This combination strengthened the evidence-based road safety recommendations with crash history (DPWH tool) and infrastructure-based quantification of risk (Demasi's Model).

Another advantageous feature of this study was the detailed road infrastructure inventory that included assessment of critical safety elements such as missing pedestrian crossings, lack sidewalks, poor visibility, absence of traffic control devices, and so on. This allowed the team to make identifications among infrastructure deficiencies contributing to road hazards and thereby reinforce engineering-based intervention.

Spot speed analysis was also used in the study, which found out that Station 3 had excessive speed violations above the posted limit, justifying the need for speed control measures and stricter enforcement. It also relates speed data against crash-prone sections in its analysis of road conditions and driver behavior, further strengthening its recommendations.

Moreover, the study is empirical and evidence-based: it uses police crash reports and field surveys, not theoretical models by themselves. The advantage is that the results become much more easily digestible for policymakers, engineers and urban planners. The study also finds cost-effective, high-impact road safety measures like speed limit devices, enhanced pedestrian crossings and better signage, which are in keeping with the DPWH Road Safety Manual, to be very feasible for implementation.

This study has, nonetheless, a few limitations. Firstly, the DPWH Risk Assessment Tool generally classifies high-risk areas based on crash data; however, it neglects infrastructure conditions and variations in traffic volume and near-miss incidents. Therefore, while crash history provides some insight into past incidents, the tool cannot necessarily be used to predict current or future safety risks, which may change with traffic patterns.

In addition, although Demasi's Model yields a numerical risk classification for some sections of road, it is about road infrastructure deficiencies, putting human behavioral factors like driver habits, vehicle maintenance, or law enforcement effectiveness, outside its sphere of influence. A more holistic model incorporating a behavioral and socio-economic rationale would lead to a wider conception of road safety risks.

Geographical limits determine another limitation. Investigation was done in a 6.4-km section of the Tigbao-Caibaan Bypass Road, indicating that the major findings are not directly applicable to any other road networks within or around Tacloban City. Road safety conditions may strongly depend on land use, traffic density, and the intensity of enforcement, making it difficult to generalize the conclusions from this study.

Crash data reported by police in Tacloban City Police Stations 1 and 2 were used in this study, which may be affected by underreporting or inconsistencies in data, or other missing information. This could have implications for the estimation of crash frequencies. Future studies should be enhanced by using hospital reports or insurance claims, or actual assessment of traffic situation, which would provide more comprehensive datasets.

The study is limited to the time frame of January 2021 to October 2023, limiting the ability to look at long-term crash trends or to measure the sustained effectiveness of road safety interventions. A longer-term study would thus provide more understanding of how crash patterns might change and how effective interventions are over time.

Notwithstanding these limitations, this study therefore becomes a good platform for an analysis on road safety for the Tigbao-Caibaan Bypass. It combines qualitative risk assessment with quantitative crash analysis for insight into infrastructure-related crash risks and provides a firm reference for road safety enhancement initiatives in Tacloban City and similar urban settings.

## CONCLUSION

The persistent occurrence of road crashes along the Tigbao-Caibaan Bypass Road, despite existing traffic infrastructure, highlights the need for targeted road safety interventions. This study employed the DPWH Risk Assessment Tool to classify all four barangays as high-risk areas, with Brgy. Abucay recording the highest number of crashes and victims. A section-level risk assessment using Demasi’s Model identified Sections 3 and 4 as having the highest infrastructure-related risks, with deficiencies such as missing pedestrian crossings, inadequate sidewalks, lack of traffic signals, and poor visibility contributing to road hazards.

While both DPWH and Demasi’s assessments classified all sections as low risk, the findings suggest that infrastructure deficiencies remain a significant concern. The presence of hazardous road conditions including missing pedestrian crossings, inadequate sidewalks, lack of traffic signals, and poor visibility, and high motorcycle traffic volume underscores the need for dedicated lanes, improved markings, and enhanced visibility measures.

Speed analysis further identified Station 3, near a school zone, as a critical safety concern, with an 85th percentile speed of 41.88 km/h, exceeding the posted limit. Although classified as "non-relevant risk" under the SIR framework, excessive speeding in pedestrian-heavy areas presents a behavioral risk, emphasizing the need for stricter speed enforcement, traffic calming measures, and enhanced pedestrian infrastructure.

These findings indicate that road safety concerns along the Tigbao-Caibaan Bypass Road are multifaceted, requiring a combination of infrastructure improvements, speed management, and behavioral interventions. By implementing strategic enhancements such as traffic calming measures, signage improvements, pedestrian crossings, and traffic enforcement measures, the risk of crashes can be significantly reduced. A comprehensive, proactive approach to integrating crash data, infrastructure assessment, and behavioral analysis will be essential to improving overall traffic safety for all road users.

## RECOMMENDATIONS

Based on the study findings, the following countermeasures are recommended to enhance road safety on the Tigbao-Caibaan Bypass Road:

**Table 9:** Defects & their Corresponding Countermeasures

| Sections | Defects | Counter Measures |
|---|---|---|
| **3 and 4** | Missing Shoulder | Application of Road Shoulder<br>Road Widening |
| **3 and 4** | Missing Sidewalk | Application of Sidewalk/ pedestrian path |
| **3 and 4** | Missing pedestrian crossing | Speed limiting device<br>Slow Down Signage<br>Reduce Speed Signage |
| **3 and 4** | Missing cycle path | Application of cycle path |
| **3 and 4** | Missing traffic light | Installation of road signage |
| **3 only** | Lack of Visibility | Horizontal directions<br>Vertical directions |
| **3 and 4** | Missing reserved lane | Application of Road Shoulder |
| **3 and 4** | Illegal Parking | Installation of road signage |
| **4 only** | Hazardous maneuvers | Installation of median barriers |
| **1,2, and 5** | Missing Shoulder | Installation of paved shoulders to reduce vehicle drift and improve safety |
| **1,2, and 5** | Missing Sidewalk | Construction of sidewalks to improve pedestrian safety |
| **1,2, and 5** | Missing Traffic Light | Installation of Traffic signals at key intersections |
| **1,2, and 5** | Illegal Parking | Implementation of parking restrictions, enforcement of no-parking zones |
| **2 only** | Pedestrian Crossing without Ramps | Installation of pedestrian ramps for better accessibility |
| **2 only** | More than 12m-long pedestrian crossing | Installation of mid-crossing islands or pedestrian refuge areas |

While this study focused on road infrastructure and speed limits, road safety is influenced by multiple factors, including human behavior, enforcement, and vehicle safety. The Safe System Approach emphasizes that roads should be designed to reduce the likelihood of serious injuries and deaths, even when mistakes happen. Studies show that 18% of crashes are due to infrastructure deficiencies, while 70% result from human error. Because of this, improving road safety requires a more holistic approach that considers how road design interacts with driver behavior, enforcement, and vehicle conditions.

To align with the Safe System Approach, future studies should explore how drivers and pedestrians respond to road improvements, such as pedestrian crossings, speed bumps, or traffic signals. If road users do not follow traffic rules, additional measures like driver education programs or stricter enforcement may be needed. Traffic law enforcement should also be assessed, as the effectiveness of speed limits and parking rules depends on how well they are monitored and enforced. Additionally, vehicle conditions should be considered, as well-maintained vehicles play a role in reducing accident risks.

Future research should also examine other sections of the bypass road to identify additional safety risks. Factors such as drainage systems, weather conditions, and driver behavior should be analyzed alongside infrastructure deficiencies to provide a deeper understanding of road safety issues. Alternative methodologies, such as the Conditional Visual Inventory (CVI), can help refine road safety assessments and intervention planning. Addressing these areas will contribute to more effective, data-driven road safety improvements.

By considering infrastructure, law enforcement, road user behavior, and vehicle safety, future research can develop more effective safety measures that address the root causes of accidents. Methods such as real-time traffic monitoring, accident pattern analysis, and driver behavior studies can further enhance risk assessments. Collaborating with traffic authorities, law enforcement, and road safety experts will help ensure that interventions are both practical and impactful.

A comprehensive strategy that includes safe infrastructure, strong enforcement, and informed road users will help prevent serious injuries and fatalities on the Tigbao-Caibaan Bypass Road and improve road safety for all.

## DATA AVAILABILITY STATEMENT

The data and materials used in this study are available upon request from the corresponding author. Due to confidentiality agreements and ethical considerations, access to certain datasets may be restricted. However, relevant portions of the data supporting the findings of this study can be provided for academic and research purposes. Any protocols used in the study are also available upon request.


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## CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper. No financial, personal, or professional interests have influenced the research or its outcomes, and all work has been conducted with transparency and integrity.

## CONTRIBUTIONS OF INDIVIDUAL AUTHORS

All authors contributed to the study, including research design, data collection, analysis, and manuscript preparation. HMCE, as the corresponding author, played a leading role in conceptualizing the study, overseeing the methodology, and finalizing the manuscript. The other authors provided significant contributions to data interpretation, literature review, and revisions. All authors reviewed and approved the final version of the paper.

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