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Evaluating the Effect of Pothole Severity on Traffic Safety in Urban Arterials Using Time-to-Collision Analysis

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Abstract

This study quantitatively evaluates the impact of pothole severity on traffic safety using the Time-to-Collision (TTC) metric as a surrogate safety indicator. Field data were collected from four urban arterial road segments in Jiroft, Iran: three sections with low-, moderate-, and high-severity potholes, and a control section. High-resolution video footage was analyzed using Kinovea to extract trajectories and compute TTC values, with conflicts defined below a 2-second threshold. A total of 779, 790, 715, and 783 vehicles were observed across the four sections, respectively. Conflict rates were calculated as 9.02% (no pothole), 8.95% (low severity), 12.27% (moderate), and 24.39% (high severity). Statistical analysis using z-tests revealed that only high-severity potholes significantly increased conflict occurrence compared to the control ($z = 5.84$, $p < 0.001$, Cohen's $h = 0.42$). Low- and moderate-severity potholes did not yield statistically significant differences ($p > 0.05$). These results highlight the substantially greater safety risk associated with severe potholes and underscore the critical need for prioritizing their repair. The findings also demonstrate that TTC analysis is a reliable and proactive tool for assessing traffic safety on roads with deteriorating pavement, offering a quantitative, data-driven alternative to reactive, crash-based safety assessments.

Keywords: Safety, Road & Highways, Pavements, Pothole, Time to Collision

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1. Introduction

Globally, approximately 1.19 million people are killed in road traffic crashes each year. A disproportionate 92% of these fatalities occur in low- and middle-income countries, despite these countries possessing only 60% of the world's roads (Organization, 2023). Research indicates that, without targeted interventions, road collisions are projected to become the seventh leading cause of death worldwide by 2030 (Ihueze & Onwurah, 2018). Road accidents result from complex interactions between environmental factors, road design and maintenance, driver behavior, and vehicle condition (Manion & Tighe, 2007). However, studies often consolidate the factors contributing to accidents into three main categories: driver behavior, vehicle condition, and road characteristics, encompassing both pavement quality and geometric design (Katrakazas et al., 2026; Michelaraki et al., 2024; Shahin, 1994).

Historically, conventional safety assessments have heavily relied on historical crash data, requiring a substantial record of accidents, fatalities, or economic losses to evaluate a road segment's safety profile (Behboudi et al., 2024). This reactive approach, however, falls short in assessing safety during the design phase or early operational periods. To address this limitation, contemporary research has shifted toward proactive safety evaluations (Jalal Kamali & Pedram, 2026; Jalalkamali et al., 2026). Methodologies and predictive models, such as those outlined in the Highway Safety Manual (HSM) and its associated software tools, have been developed to forecast safety performance. These advancements enable engineers to simulate and analyze roadway safety during the planning and design phases without relying on observed crash data (Haghani et al., 2021; Manual & Manual, 2010).

Pavement condition is a critical determinant of road safety, yet its causal pathways to crash risk remain less thoroughly examined compared to human behavior and vehicle factors (Amani et al., 2024; Mkwata & Chong, 2022). While general pavement characteristics (such as roughness, rutting, surface texture abrasion, and skid resistance) are known to compromise vehicle stability and increase driver distraction (Al-Masaeid, 2025; Mohammad Hossain Jalal Kamali, 2024; Sadeghi & Goli, 2024), potholes represent a particularly severe, localized form of distress with immediate safety implications.

Given these safety implications, effective maintenance prioritization requires a clear and quantitative understanding of how different levels of pavement distress influence traffic safety. Although the general relationship between poor pavement condition and compromised safety is well recognized, limited empirical evidence is available on whether low-, moderate-, and high-severity potholes produce measurably different levels of traffic conflict under real urban traffic conditions (Bhatia & Greer, 2023). To address this gap, the present study quantitatively examines how different pothole severity levels affect traffic conflict occurrence on urban arterial roads. Unlike previous studies that typically evaluate pavement condition or pothole presence in aggregate, this research distinguishes between low-, moderate-, and high-severity

potholes and compares their safety effects with a no-pothole control section. By applying Time-to-Collision (TTC) analysis to vehicle trajectory data extracted from field video observations, the study provides a proactive, conflict-based assessment of pothole-related safety risk and identifies the severity level at which potholes significantly increase traffic conflict rates.

2. Literature Review

Recent scholarship in transportation safety has demonstrated a paradigm shift from reactive, crash-based safety evaluations toward proactive safety assessment approaches, including predictive modeling, risk-based evaluation, and surrogate safety measures (Ahmadinejad et al., 2018; Behboudi et al., 2024; Hayward, 1972; Jalal Kamali & Pedram, 2026; Jalalkamali et al., 2026). Within this broader framework, predictive software tools such as the Interactive Highway Safety Design Model (IHSDM) have been used to evaluate roadway safety performance based on geometric and traffic variables during the design phase (Jalal Kamali et al., 2013; Tola et al., 2022). In addition, when empirical data are limited, expert judgment and multi-criteria decision-making frameworks, including the Analytic Hierarchy Process (AHP) and Fuzzy Logic, have been employed to assess safety risks under uncertainty (Jalal Kamali & Pedram, 2026; Sepahvand et al., 2026). Parallel to these approaches, Surrogate Safety Measures (SSMs) provide a dynamic, field-based framework by using variables such as acceleration, deceleration, speed, and derived kinematic indicators to evaluate safety without waiting for actual crashes to occur (Ahmadinejad et al., 2018; Jalalkamali et al., 2026). Within this proactive framework, conflict-based indicators such as Time-to-Collision (TTC) have gained particular attention because they allow hazardous interactions to be evaluated before actual crashes occur (Roșu et al., 2023; Vogel, 2003).

2.1. Impacts of Pavement Distress on Traffic Flow and Safety

Potholes and other forms of pavement distress are widely recognized as roadway hazards that can disrupt vehicle stability, alter driver behavior, and increase the likelihood of unsafe traffic interactions (Haghighat & Jalal Kamali, 2026; Jongga Jihanny, 2022). Unlike general pavement roughness, potholes represent localized and unexpected surface defects that may require immediate driver response. Previous studies have shown that such defects can prompt sudden braking, abrupt steering, lateral displacement, and evasive lane-changing maneuvers, all of which may increase the probability of traffic conflicts and collision risk (Ali et al., 2023; Khan et al., 2024; YALEW et al., 2023). Beyond behavioral changes, potholes impose direct mechanical hazards; impact with severe depressions can lead to tire blowouts, rim damage, and suspension misalignment, which further impair vehicle handling and increase the likelihood of losing control (Zimmer & Ivey, 1984).

Empirical and simulation-based studies have further demonstrated that pothole geometry can significantly influence traffic performance. Larger or deeper pavement defects tend to produce stronger behavioral responses, including greater speed reductions and more aggressive

avoidance maneuvers (Khan et al., 2024). Microscopic traffic simulation studies have indicated that the presence of potholes can substantially reduce vehicle speeds, with the magnitude of speed reduction depending on pothole dimensions, vehicle type, traffic density, and driver sensitivity (Ali et al., 2023; Tarnini et al., 2026). Empirical evidence suggests that while highway-speed hazards often involve larger depressions, on urban streets, potholes exceeding 30 inches in length and 3 inches in depth are sufficient to cause significant structural vehicle damage and immediate traffic disturbances (Zimmer & Ivey, 1984). These findings suggest that potholes do not merely affect ride quality but can also disturb traffic stream stability by generating speed differentials, sudden deceleration events, and unexpected lateral movements.

An important issue in evaluating pothole-related safety risk is the severity level of the pavement defect. Although technical standards such as ASTM D6433 classify pothole severity based on physical characteristics such as depth and diameter (International, 2018), many safety-oriented studies have treated potholes primarily as binary conditions, distinguishing only between their presence and absence. For example, previous studies have modeled pothole occurrence as a dichotomous outcome (presence vs. absence) in detection algorithms (Bruwer & Andersen, 2025) or as a binary independent variable in crash prediction models (Al-Zubaidi et al., 2023). This simplified approach may obscure meaningful differences in driver response across severity levels. Low-severity potholes may lead to minor speed adjustments or limited trajectory deviations, whereas moderate- and high-severity potholes may trigger sudden evasive maneuvers, sharp braking, or lane encroachment into adjacent traffic streams (Jongga Jihanny, 2022; Yang et al., 2021). Therefore, differentiating potholes by severity is essential for identifying the threshold at which pavement distress shifts from a comfort-related issue to a critical traffic safety hazard.

Despite the growing body of research on pavement condition and road safety, existing studies remain limited in several respects. Some studies rely on crash records, which are often sparse, reactive, and unable to capture near-miss events associated with localized pavement defects. As noted by Amani et al., crash data frequently lack detailed information on road deterioration, whereas surrogate safety measures focusing on driver behavior can help identify the specific pavement defects that contribute to unsafe conditions (Amani et al., 2025).

Others use driver surveys or simulation models, which provide valuable insights but may not fully reflect real-world driver behavior under actual traffic conditions (Fares et al., 2025; Himmels et al., 2024). Moreover, relatively few studies have directly compared the safety effects of low-, moderate-, and high-severity potholes using field-observed vehicle trajectories and conflict-based safety indicators. This gap is particularly important for urban arterials, where dense traffic conditions and frequent lane-changing behavior may amplify the safety consequences of pothole-induced evasive maneuvers. Accordingly, a severity-specific and observation-based assessment is needed to better understand how different pothole conditions influence traffic conflict occurrence.

2.2. Application of Time-to-Collision (TTC) in Proactive Safety Assessment

The Time-to-Collision (TTC), originally introduced by Hayward as Time Measured to Collision (TMTC), is defined as the time remaining until two vehicles would collide if they continue at their current speeds and trajectories (Hayward, 1972). As a continuous and physically interpretable measure, TTC can be calculated at any instant during a traffic interaction and has become one of the most widely used surrogate measures in proactive safety assessment (Arun et al., 2021; Nadimi et al., 2020). For longitudinal interactions, TTC is computed according to Eq. (1) (Vogel, 2003):

$$TTC_i = \frac{X_{i-1}(t) - X_i(t) - l_i}{\dot{X}_i(t) - \dot{X}_{i-1}(t)} \qquad \forall \dot{X}_i(t) > \dot{X}_{i-1}(t) \qquad (1)$$

where X_i and $\dot{X}_i$ denote the position and speed of vehicle i, respectively, X_{i-1} and $\dot{X}_{i-1}$ denote the position and speed of the leading vehicle, and l_i is the length of vehicle i.

The introduction of TMTC provided an objective and physically measurable criterion for evaluating the degree of danger in traffic interactions, thereby reducing the subjectivity that had previously limited the use of near-miss events as reliable safety indicators (Hayward, 1972). In this respect, TTC has been widely adopted in proactive safety studies because it enables the identification of hazardous interactions before an actual crash occurs (Arun et al., 2021; Nadimi et al., 2020).

The applicability of TTC extends beyond conventional rear-end conflicts. In pedestrian protection systems, TTC has been used as a reliable indicator for distinguishing between avoidable and unavoidable vehicle–pedestrian conflicts based on radar sensor data (Li et al., 2025; Roșu et al., 2023). In such applications, lower TTC values indicate higher collision risk and can be used to trigger warning or emergency responses aimed at mitigating crash severity (Roșu et al., 2023).

Recent studies have further demonstrated that TTC can also be applied to more complex traffic conflicts, including intersection and angular conflicts as well as interactions between vehicles and pedestrians (Hula et al., 2025; Li et al., 2023). By supporting the analysis of multidirectional traffic situations, TTC offers a broader framework for safety assessment in mixed and complex traffic environments, rather than being limited to simple car-following conditions (Bai et al., 2026; He et al., 2025).

In addition, advanced monitoring technologies have strengthened the practical use of TTC in field-based traffic safety analysis (Park et al., 2025). For example, a geo-referenced stereo vision system integrating stereo cameras and GPS can automatically collect synchronized image, depth, and location data in urban environments and use them to identify and track potential traffic conflicts through TTC (Battiato et al., 2013). Such systems make it possible to

perform frame-by-frame analyses of driver behavior and near-miss events, providing valuable insight into how road users respond to surrounding hazards.

This capability is particularly relevant to the present study, where pavement defects may induce sudden braking, lateral shifts, or evasive maneuvers that do not necessarily lead to crashes but still reflect elevated conflict risk. Therefore, TTC provides an appropriate surrogate safety measure for examining how pothole severity influences traffic safety on urban arterials.

3. Methodology and Data Collection

This study was conducted in Jiroft, a developing urban center in Kerman Province, Iran, selected for its representative road conditions and development patterns. The research methodology, consisted of site selection, field data collection, pothole assessment, and trajectory analysis, and statistical modelling.

To begin, two-way arterial roads with similar geometric characteristics, including width, lane configuration, and traffic volumes, were identified for analysis. Data collection was carried out during optimal daylight conditions, between 10:30 and 11:30 AM, under sunny weather. This specific time window was selected to ensure consistent lighting for video analysis, standardized visibility, and off-peak traffic conditions to minimize congestion effects. High-resolution traffic footage was obtained from fixed rooftop vantage points of adjacent buildings. The camera positioning was carefully established to guarantee complete coverage of the study sections, clear visibility of vehicle movements, and a consistent angle and scale for trajectory extraction.

Prior to the traffic analysis, all potholes within the selected study sections were geotagged, measured in terms of diameter and depth, and classified into Low, Moderate, and High severity levels using standardized criteria [6]. The specific dimensional thresholds for this classification are detailed in Table 1.

Table 1. Classification of Potholes by Severity Level Based on Diameter and Depth [6]

Maximum depth of pothole (mm)	Average pothole diameter (mm)		
	102 – 203 mm	203 – 457 mm	457 – 762 mm
12.7 – 24.4 mm	Low	Low	Moderate
24.4 – 50.8 mm	Low	Moderate	High
More than 50.8 mm	Moderate	Moderate	High

Based on typical driver perception-reaction times and vehicle maneuvering requirements, a 70-meter approach distance was established as the critical reaction zone. Subsequently, vehicle paths were extracted from the video footage using Kinovea motion analysis software. This

frame-by-frame analysis enabled the precise tracking of lane positioning variations, speed profiles, and evasive maneuvers relative to the pothole locations.

Overall, this methodology was designed to systematically evaluate driver responses to pavement potholes while controlling for environmental and traffic variables. The combination of field measurements and video analysis provides objective data for Time-to-Collision (TTC) calculations and safety assessments, for which a threshold of 2 seconds was considered in this study.

Following the extraction of trajectory and TTC data, traffic conflict occurrences were modelled using a binary random variable X. Specifically, a conflict was recorded (X=1) if a vehicle's TTC fell below the critical 2-second threshold, and no conflict (X=0) otherwise. This Bernoulli-distributed variable has an expected value E[X]=p and variance Var(X)=p(1−p), where p represents the probability of conflict occurrence. Given our large sample size (n>30), we invoke the Central Limit Theorem to justify using normal approximation for our z-test statistics.

The primary objective of this statistical analysis is to test whether the probability of conflict (p) varies significantly across different pothole severity levels (low, Moderate, high) compared to the baseline (No Pothole). Formally, we test:

H_0: $P_{low}=P_{moderate}=P_{high}$

H_1: At least one probability differs

To evaluate this, a Chi-square test was initially employed to assess whether the differences in conflict rates across all four groups are statistically significant. For specific pairwise comparisons between each severity level and the baseline (non-damaged road), z-tests using normal approximation were conducted. To account for multiple comparisons and mitigate the risk of Type I error, a Bonferroni correction was applied to the p-values. Furthermore, Cohen's h was calculated to evaluate the practical significance (effect size) of the differences in conflict proportions. All statistical tests were evaluated at a 95% confidence level ($\alpha=0.05$).

4. Results

As explained earlier, for safety evaluation using the TTC method, we required parameters such as vehicle speed and the position/distance between vehicles at each moment. These data were obtained through video analysis using Kinovea software. Data were collected from street sections each containing potholes with low, moderate, and high severity levels. Additionally, data from a similar section with no pavement damage were also collected. Fig. 1 and 2 show one of these traffic conflicts.

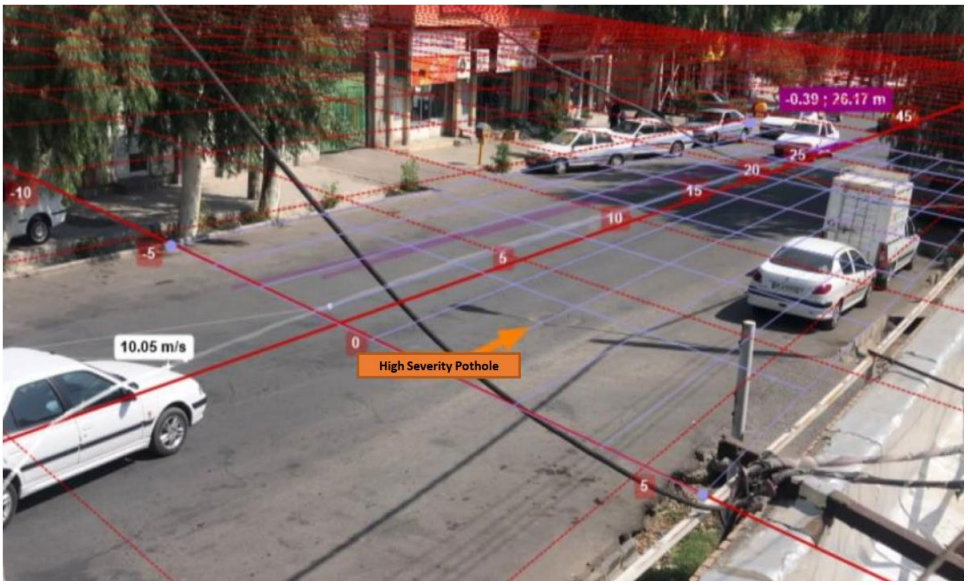

Figure. 1. Vehicle Trajectory Extraction Using Kinovea Software (Pre-Pothole Approach Phase)

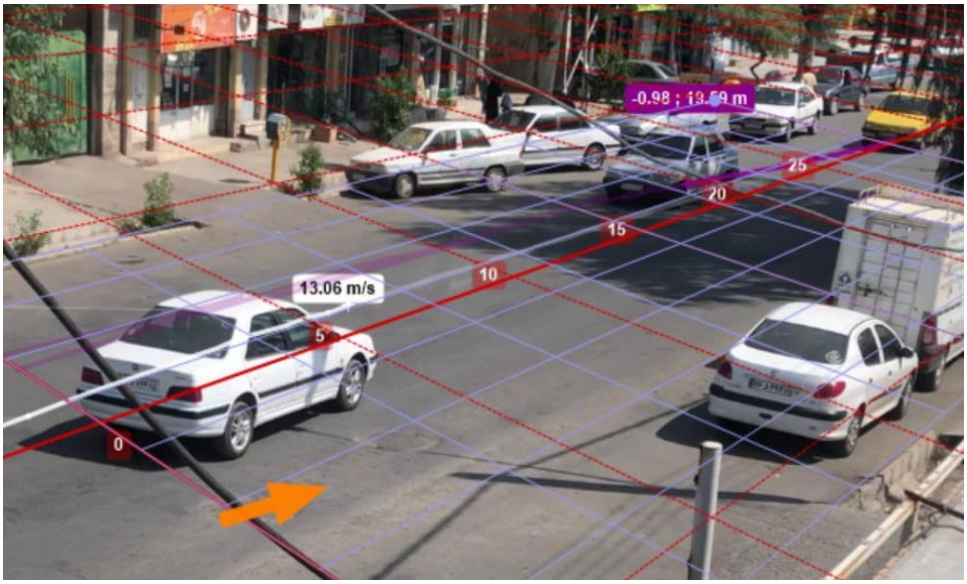

Figure. 2. Vehicle Trajectory Extraction Using Kinovea Software (Pothole Traversal Phase)

As evident in Figure. 1, a vehicle encountering a pothole ahead swerves into the opposing lane to avoid collision. At this moment, the position of the oncoming vehicle is recorded. The data captured in Figure. 2 show that the vehicle in the opposing lane moves toward the roadside to prevent a crash. Ultimately, while the opposing-lane vehicle continues along the roadside, the encroaching vehicle returns to its original lane without reducing speed.

The white line indicates the trajectory of the encroaching vehicle, while the purple line represents the path of the other vehicle. Based on this data, the movement patterns of both vehicles are plotted in Figure 3. In this figure:

- The horizontal axis represents longitudinal displacement (distance along the road).

- The vertical axis indicates lateral displacement (lane positioning).

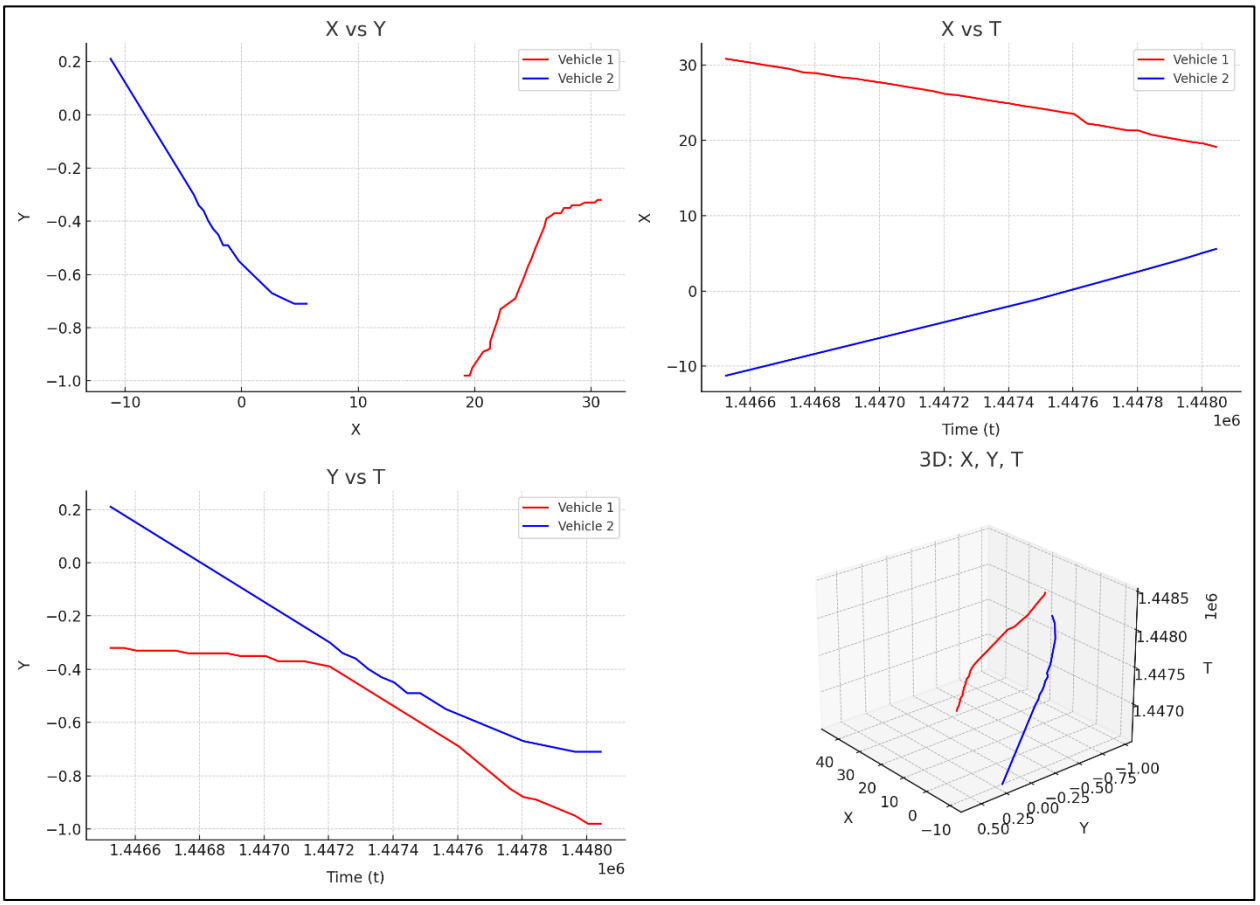

Figure 3. Spatial Positioning of Vehicles Adjacent to Pothole

Table 2. Collected Field Measurement Data

	Without pothole	Low severity pothole	Moderate severity pothole	High severity pothole
Conflicts	36	36	46	100
interacting vehicles	72	70	91	196
Pothole-lane traffic	399	402	375	410
Non-pothole lane traffic	380	388	340	373
Total traffic volume (both directions)	779	790	715	783
Conflict ratio per vehicle in the pothole-affected lane	9.02%	8.95%	12.27%	24.39%

4.1. Impact of Pothole Severity on Traffic Conflict Rates

This section evaluates the impact of pothole severity (low, moderate, and high) on the occurrence of traffic conflicts. The conflict rates for each severity level were calculated and statistically analyzed to determine whether the severity of potholes significantly alters driver behavior and safety. The summary of these statistical comparisons is presented in Table 3.

For low-severity potholes, the observed conflict rate was 0.0896. The statistical analysis indicated no significant difference ($z=-0.03$, $p=0.947$), with a negligible effect size (Cohen's $h=-0.00$). Similarly, moderate-severity potholes resulted in a conflict rate of 0.1227, which also did not reach statistical significance at the 5% level ($z=1.47$, $p=0.286$, Cohen's $h=0.11$). In stark contrast, high-severity potholes demonstrated a substantial impact on traffic safety, yielding a conflict rate of 0.2439. This increase was highly significant ($z=5.84$, $p<0.001$) and exhibited a moderate-to-large effect size (Cohen's $h=0.42$). The Bonferroni-corrected p-values further confirm that only the high-severity condition significantly increases the likelihood of traffic conflicts compared to the baseline.

Table 3. Statistical Summary of Traffic Conflicts by Pothole Severity

Pothole Severity	Conflict Rate	95% CI	z-score	p-value	Cohen's h	Bonferroni-corrected p	Significant at 5%
Low	0.0896	0.0616 to 0.1175	-0.03	0.947	-0.0	1.0	No
Moderate	0.1227	0.0895 to 0.1559	1.47	0.286	0.11	0.86	No
High	0.2439	0.2023 to 0.2855	5.84	P<0.001	0.42	<0.001	Yes

5. Discussion

This study examined how the severity of potholes affects traffic safety on urban two-lane roads, using Time-to-Collision (TTC) as a measure of driver safety. Video recordings were systematically collected from multiple arterial road segments that shared similar geometric features—such as lane width—and traffic volumes. These segments varied in terms of pothole severity, which we categorized as low, Moderate, or high. This controlled setup allowed us to specifically isolate the impact of pothole severity on driver behavior. The results indicate that drivers exhibit different behavioural patterns depending on the severity level of the potholes, as discussed below.

The findings indicate no significant effect on driver behavior in the case of low-severity potholes. The majority of vehicles maintained their intended trajectories without the need for evasive actions, implying that these Low pavement irregularities do not substantially influence normal driving patterns or pose safety concerns. The lack of notable lane deviations or speed changes suggests that drivers tend to perceive low-severity potholes as non-threatening hazards.

In contrast, Moderate- and high-severity potholes provoke noticeable behavioral changes. A proportion of drivers (9% and 24% respectively) elect to change lanes to avoid traversing these substantial pavement defects, even when this requires encroaching into opposing traffic lanes. This evasive behavior introduces new collision risks that were not present in the original lane configuration, effectively trading one hazard for another.

The escalation in driver response correlates strongly with increasing pothole severity. While only a minority of drivers risk opposing-lane incursions for Moderate-severity potholes, this behavior becomes markedly more common with high-severity defects. The progressive nature of this response suggests drivers conduct an implicit risk assessment, tolerating greater traffic violations to avoid more severe pavement damage.

Although moderate potholes may suggest increased risk, only high-severity potholes show both statistically and practically significant safety implications.

This graduated behavioural response underscores the importance of severity-based maintenance prioritization. Given that municipalities and road authorities frequently operate under strict financial constraints, allocating resources efficiently is a critical challenge. The findings of this study provide a data-driven framework for such decision-making. By demonstrating that potholes transition from negligible safety concerns to significant hazards primarily at higher severity levels, agencies can confidently deprioritize low-severity defects. Consequently, they can direct limited maintenance budgets toward the immediate repair of high-severity potholes, thereby maximizing overall traffic safety and resource efficiency.

While this study successfully demonstrates the link between pothole severity and driver behavior, the findings are context-specific and may vary with cultural, infrastructural, or traffic enforcement differences. Future research should validate these results across different urban environments and explore the integration of TTC-based assessments in real-time road maintenance decision-making. Additionally, coupling TTC data with in-vehicle sensing technologies could enhance proactive safety interventions.

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