RESEARCH PAPER

# Examining The Direct Relationships Between Human, Environmental, Vehicle, And Road Infrastructure Factors On Road Safety Factor

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**Abstract**
Road safety remains a global challenge, with accident risks shaped by the interplay of human, environmental, vehicle, and infrastructure factors. This study investigates the direct effects of these four dimensions on road safety outcomes using Partial Least Squares Structural Equation Modeling (PLS-SEM). Guided by the Theory of Planned Behaviour, Systems Theory, and the Haddon Matrix, the research integrates behavioral and systemic perspectives into a unified framework. The findings indicate that systemic determinants particularly road infrastructure, vehicle safety, and environmental conditions exert stronger direct influence on road safety outcomes compared to human factors, which show limited explanatory power. This highlights the importance of shifting emphasis from behavior-centric approaches toward structural and institutional determinants of safety. The study contributes theoretically by advancing a multidimensional perspective of road safety and methodologically by demonstrating the utility of PLS-SEM in modeling complex relationships. Practically, it provides evidence-based guidance for policymakers to prioritize infrastructure investment, strengthen vehicle standards, and integrate environmental management into sustainable safety strategies.

**Keyword:** Road Safety, PLS-SEM, Human Factor, Environment Factor, Vehicle Factor, Road Infrastructure Factor
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## 1.Introduction

Road safety remains a pressing global concern, with traffic accidents ranking among the leading causes of death and injury worldwide (WHO, 2023). The complexity of road safety lies in its multidimensional nature, where human, environmental, vehicle, and infrastructure factors interact to shape accident risks and outcomes. According to the United Nations Economic Commission for Europe (UNECE)(NATIONS, 2021), human factors including cognitive, emotional, and behavioural aspects play a critical role in crash causation, often surpassing the influence of mechanical or infrastructural elements (Harith & Mahmud, 2018; Trung et al., 2023; Zhang et al., 2019).

At the same time, environmental factor such as weather, visibility, rainy, fogy, climate change and night time significantly effect on driving performance and accident likelihood (Gupta & Kaur, 2021; Omranian et al., 2018). Additionally, vehicle-related aspects including design, safety features, and maintenance are equally vital, as deficiencies in these areas can exacerbate the severity of crashes (Adanu et al., 2024; Montero-Salgado et al., 2022). Furthermore, road infrastructure design and management from road geometry to traffic control systems directly shape driver behaviour and safety outcomes (Opoku, 2019; Wahyudi & Indrastuti, 2025).Research highlights that integrating infrastructure safety assessments during planning and construction phases is essential to reducing accident risks (Taylor & Francis, 2023).

Globally, the World Road Association (PIARC) emphasizes that over 90% of traffic fatalities occur in low- and middle-income countries, underscoring the urgent need for comprehensive strategies that address all four dimensions of road safety (Technical et al., 2023). This is particularly relevant in Malaysia, where rapid motorization and expanding road networks demand systemic approaches to safety management. By examining the direct relationships between human, environmental, vehicle, and infrastructure factors, this study seeks to provide evidence-based insights that can inform sustainable safety strategies and policy interventions.

Despite extensive research on road safety, much of the existing literature tends to examine human, environmental, vehicle, and road infrastructure factors in isolation rather than exploring their direct and systemic relationships. This fragmented approach limits our understanding of how these dimensions interact to influence accident risks and safety outcomes. For instance, while human behaviour is often cited as the leading contributor to crashes (Harith & Mahmud, 2018; KheirAbadi & Bolhari, 2012), environmental conditions such as weather and visibility (Mondal et al., 2011), vehicle safety features (Hudec & Šarkan, 2022; Law, 2023), and road infrastructure factor also exert significant influence (Ahmed, 2013; Opoku, 2019). However, few empirical studies have systematically compared these factors within a unified framework to determine which exerts the strongest direct effect on road safety. This gap is particularly critical in developing contexts such as Malaysia, where rapid motorization, diverse road conditions, and evolving infrastructure demand evidence-based strategies that integrate all four dimensions. Addressing this gap, the present study investigates the direct effects of human, environmental, vehicle, and infrastructure factors on road safety outcomes, while also identifying which systemic factor

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contributes most significantly to accident reduction and safety improvement. Building on the preceding discussion, the present study sets the following research question and objectives.

**Resarch Question**

RQ1: What are the direct effects of human, environmental, vehicle, and road infrastructure factors on road safety?

RQ2:Which systemic factor exerts the strongest influence on road safety outcomes?

## 2.Litrature Review & Hypothesis Development

### 2.1 Theoretical Background

This study draws upon three theoretical frameworks that provide critical foundations for understanding the multidimensional nature of road safety: the Theory of Planned Behaviour (TPB) (Ajzen, 1991), Systems Theory (Bertalanffy, 1972), and the Haddon Matrix (Haddon, 1980). The TPB is employed to examine the human dimension of road safety, particularly how attitudes, subjective norms, and perceived behavioural control influence driver behaviour and accident risk. Systems Theory, with its emphasis on interdependence and holistic analysis, is applied to conceptualize the environmental factors that shape road safety outcomes, highlighting the dynamic interactions between ecological conditions and human activity. Finally, the Haddon Matrix provides a structured framework for analysing the role of road infrastructure across pre-crash, crash, and post-crash phases, thereby underscoring its direct influence on accident prevention, crash severity, and post-crash survivability (Bocage et al., 2020). Collectively, these theories offer a comprehensive lens through which the study investigates the direct effects of human, environmental, vehicle, and infrastructure factors on road safety outcomes (Arnold et al., 2024; Chen, 2024; Haddon, 1980).

### 2.2 Factor Impacting Road Safety

#### 2.2.1 Human Factor and Theire Effects on Road Safety

Road safety is shaped by multiple complex causes, yet human factors consistently emerge as the most critical determinant of accident risk. Empirical evidence indicates that driver behavior accounts for the majority of road crashes worldwide. For example, Bucsuházy et al., (2020), highlight human error as the dominant contributor to road accidents, while (McCarty & Kim, 2024), similarly emphasize human behavioral influences as the primary source of crash occurrence. Supporting this, the National Highway Traffic Safety Administration (NHTSA) reports that human error is implicated in the vast majority of road crashes in the United States (NHTSA, 2020). The World Health Organization (WHO, 2018, 2023), further underscores the importance of addressing human behavior through education, enforcement, and engineering interventions. Academic research consistently demonstrates that psychological, social, and behavioral dimensions significantly amplify accident risk. Wang, (2019), for instance, found that human factors including driver cognition, physical condition, and behavioral tendencies accounted for approximately 93% of traffic accidents in Belgium. Similarly, Alecu, (2019) and Elslande & Naing, (2019), identify inappropriate driver behavior as a central determinant of road crashes. Such behaviors include fatigue, distraction, speeding, aggressive driving, alcohol or drug impairment, and violations of traffic regulations. Collectively, these actions critically undermine road safety, reinforcing the conclusion that human factors remain the most critical influential element in accident causation. Collectively, these actions critically undermine road safety, reinforcing the conclusion that human factors exert the strongest and most direct influence on road safety outcomes compared to other systemic elements (Dangisso, 2023; McCarty & Kim, 2024). Based on the empirical evidence, the following hypothesis is developed.

***$H_1$: Human Factors Have a Significant Direct Effect on Road Safety***

#### 2.2.2 Enviromental Factor and Theire Effects on Road Safety

Environmental factors encompass the specific conditions within the road setting that directly influence driver performance and elevate the likelihood of collisions. Road surface quality, weather, climate variability, and lighting conditions are consistently identified as substantial contributors to accident causation (Hammad et al., 2019; Mondal et al., 2011). Adverse weather events such as fog, rain, snow, and sun glare compromise visibility and road surface integrity, while night-time driving and inadequate lighting further impair drivers' ability to detect hazards, thereby increasing road accident risk (Cai et al., 2013; González Collazo et al., 2022; Gyimah, 2023). Rainfall, in particular, has been highlighted as a critical environmental determinant. Hammad et al., (2019; Sangkharat et al., (2021) demonstrated that accident fatalities rise significantly in regions experiencing heavy rainfall, as wet conditions reduce headlight effectiveness, obscure road markings, and distort distance perception.

Additionally, night driving represents another major environmental challenge. Reduced visibility during darkness delays hazard recognition and impairs reaction times, often resulting in unsafe driving performance. Fleyeh & Mohammed, (2012; Khan et al., (2020), emphasize that inadequate or excessive lighting exacerbates these risks, while Åkerstedt et al., (2001) confirm that darkness consistently impairs visual capacity and compromises on road safety outcomes. Beyond immediate weather and lighting conditions, climate change has emerged as an escalating threat on road safety sustainability (Shahid & Minhans, 2016).

Nazif-Munoz et al., (2021), found that extreme temperatures and prolonged rainy seasons contribute to higher crash fatalities in the United States. Similarly, Akorli et al., (2024) reported that rainfall trends in Ghana significantly increase crash severity, with accidents rising by 3.59% during the wet season. Islam et al., (2019), further demonstrated that rainfall and sandstorms in Saudi Arabia correlate positively with accident frequency, leading to substantial fatalities and injuries. Collectively, these findings underscore that environmental and climate-related conditions directly degrade driving performance, visibility, and road surface quality. Consequently, environmental factors exert a highly significant and direct influence on road safety outcomes, making them a critical element in accident causation.

*$H_2$: Environmental factors have a significant direct effect on road safety.*

### 2.2.3 Vehicle Factor and Theire Effects on Road Safety

Vehicle-related factors play a critical role in shaping road safety outcomes, with mechanical defects consistently identified as major contributors to accident causation. Hoque & Hasan, (2006); Hudec & Šarkan, (2022), emphasize that essential safety features including brakes, lighting systems, steering mechanisms, tires, seatbelts, and airbags are fundamental to safe vehicle operation. Malfunction or failure of these components significantly compromises safety by reducing drivers' ability to prevent or mitigate collisions.

Recent empirical evidence reinforces this view by Adanu et al., (2024), analysing crash data from 2016 to 2020, found that brake and tire defects independently accounted for approximately 65% of road accidents, underscoring their disproportionate influence on crash occurrence. Similarly, Gorzelańczyk et al., (2023), using inspection station data, reported that tire and steering defects each contributed to nearly 40% of accidents, highlighting the strong correlation between technical condition and accident risk. Furthermore, earlier studies also confirm the severity of vehicle defects in developing contexts. Oduro, (2012) revealed that brake failure was the leading cause of road accidents in Ghana, with 83% of surveyed drivers identifying it as the primary factor. The study further noted that brake failure (40%), overheating (33%), and poor servicing (14%) were recurrent contributors to crashes. More recently, Alonso et al., (2013; Case, (2024) identified faulty brakes, defective electrical systems, steering malfunctions, wiper failures, accelerator issues, and lighting defects as significant predictors of accident occurrence. These findings align with broader literature that consistently associates poor vehicle maintenance and technical defects with elevated accident risk (Adanu et al., 2024; VLAKVELD & Institute for Road Safety Research, 2005). Collectively, these studies demonstrate that vehicle defects particularly those involving braking, tires, and steering substantially undermine road safety by impairing drivers' ability to control their vehicles and respond effectively to hazards (Hudec & Šarkan, 2022; Moodley & Allopi, 2008; Solah et al., 2021). Consequently, vehicle factors exert a major and direct influence on road safety outcomes, representing one of the most critical elements in accident causation and prevention strategies.

*$H_3$: Vehicle factors have a significant direct effect on road safety.*

### 2.2.4 Road Infrastructure Factor and Theire Effects on Road Safety

Road infrastructure plays a decisive role in shaping traffic safety outcomes, with deficiencies in design, maintenance, and management consistently linked to accident causation. Poorly designed roads, inadequate guardrails, potholes, uneven surfaces, insufficient signage, poor lighting, and inadequate drainage collectively compromise safe mobility and hinder efficient transportation (Gautam et al., 2021; Gutierrez & Mohan, 2020). Moreover, properly designed infrastructure, including traffic signals, road markings, and signage, is essential for guiding vehicle movement and ensuring sustainable safety (Babić et al., 2022).Street lighting, for instance, has been shown to enhance visibility, reduce collision risk, and improve traffic flow during night-time driving (Ackaah et al., 2020; Kepa, 2020). Furthermore, the growing number of vehicles and motorcycles necessitates infrastructure separation, such as pedestrian pathways, sidewalks, and dedicated lanes, which provide safer and more accessible routes for diverse road users (Griffith, 2022; Lugtigheid et al., 2024; UNIndia, 2024).

Empirical studies reinforce the critical role of road infrastructure in accident prevention. Dumitrascu, (2024); Yang & Han, (2025) demonstrated that inadequate road design, including unsafe roadside elements such as ditches parallel to the roadway, significantly increases the likelihood of run-off accidents, particularly under adverse weather conditions. Poor road geometry, limited visibility, and complex traffic scenarios can overload drivers cognitively, leading to errors and heightened accident risk. Similarly Elvik et al., (2019); Gutiérrez-Rodríguez et al., (2025); Huang et al., (2025), emphasize that infrastructure deficiencies such as inadequate markings, poor lane separation, and insufficient safety barriers are strongly correlated with accident frequency and severity. More recent findings by Faizan & Guibas, (2024); Zahidy et al., (2024), highlight that sustainable infrastructure planning, including proper drainage and resilient road surfaces, is vital for mitigating risks associated with climate variability and heavy rainfall. Collectively, these studies underscore that road infrastructure is not merely a supporting element but a fundamental determinant of road safety. Deficiencies in design, maintenance, and separation facilities directly impair driver performance, increase accident likelihood, and compromise sustainable mobility. Consequently, infrastructure factors exert a substantial and highly significant effect on road safety outcomes, making them a critical focus for accident prevention and policy intervention.

*$H_4$: Road infrastructure factors have a significant direct effect on road safety.*

## 3. Framework of Study

Based on the reviewed literature, a conceptual framework has been developed to examine the direct relationships between human, environmental, vehicle, and road infrastructure factors on road safety outcomes (Figure 1). Human factors, encompassing driver behaviour, cognition, and physical condition, have consistently been identified as the leading contributors to traffic accidents (Bucsuházy et al., 2020). Environmental conditions, including weather variability, visibility, and climate change, further exacerbate accident risks by impairing driver performance and road surface quality (Harith et al., 2019; Mondal et al., 2011). Vehicle-related elements, such as mechanical defects in braking, tires, and steering systems, directly compromise operational safety and have been shown to account for a substantial proportion of crashes (Adanu et al., 2024; Gorzelańczyk et al., 2023). Finally, road infrastructure including design, geometry, signage, lighting, and maintenance plays a decisive role in shaping driver behaviour and accident severity, with deficiencies consistently linked to higher crash rates (Gautam et al., 2021; Gutierrez & Mohan, 2020).

This framework integrates these four systemic dimensions to provide a holistic understanding of road safety determinants. By analysing their direct effects, the study seeks to identify which factor exerts the strongest influence on safety outcomes, thereby offering evidence-based insights for targeted interventions and sustainable policy development. Collectively, the framework underscores that road safety is not the product of a single determinant but rather the outcome of complex interactions among human, environmental, vehicle, and infrastructure factors.

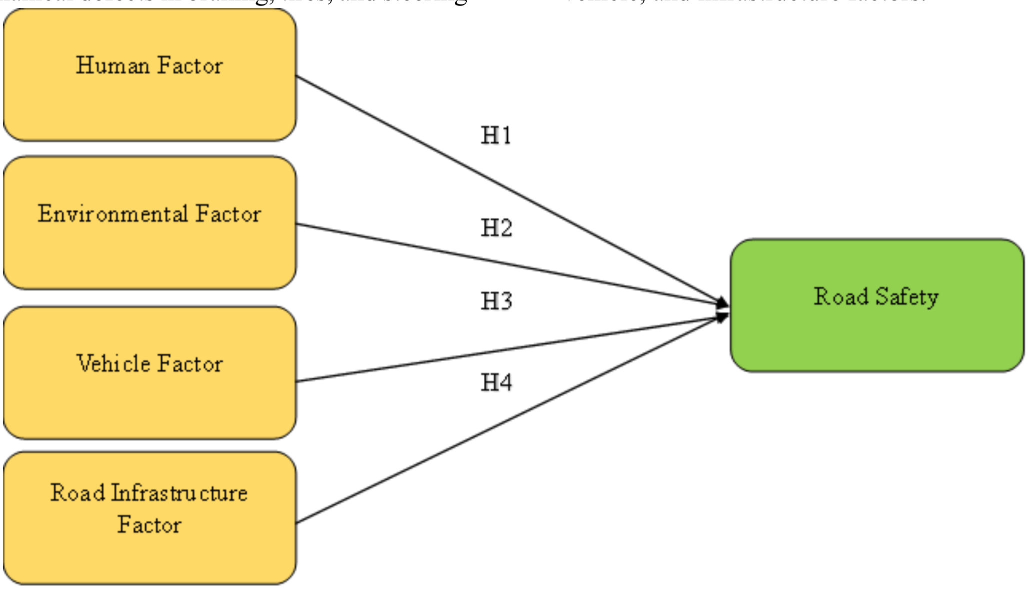


Figure.1: *Conceptual Framework*

### 3.1 Research Design

This study employed a quantitative research design to investigate the direct effects of human, environmental, vehicle, and road infrastructure factors on road safety outcomes. Data were collected through a structured survey administered to undergraduate and postgraduate students at Universiti Utara Malaysia (UUM) who possessed valid driving licenses. The choice of participants was justified on the basis that licensed drivers have direct experience with road safety issues and can provide reliable insights into the influence of systemic factors on driving performance and accident risk.

A total of 363 respondents were randomly selected, ensuring diversity across gender, age groups, and driving experience. This sample size was deemed sufficient to achieve statistical power for Structural Equation Modelling (SEM) analysis, with SmartPLS utilized to test the hypothesized relationships and assess the relative strength of direct effects. The demographic distribution of respondents is presented in Table 2.

The demographic profile demonstrates a balanced representation of young and experienced drivers, with nearly half of the respondents aged between 18 and 25 years. This distribution reflects the student population while also capturing a range of driving experiences, thereby enhancing the generalizability of findings. The response rate was satisfactory, and the diversity of participants ensured that the dataset was robust for SEM analysis.

By employing SmartPLS, the study conducted Confirmatory Factor Analysis (CFA) to validate measurement constructs, to test the hypothesized direct effects (H1–H4). This methodological approach allowed for a comprehensive examination of the conceptual framework and provided empirical evidence on the relative impact of human, environmental, vehicle, and infrastructure factors on road safety outcomes.

### 3.2 Operational Definition and Measurement

In this study, the variables of human factor, environmental factor, vehicle factor, road infrastructure factor, and road safety are operationally defined as measurable constructs that directly influence road accident risk and safety outcomes. Human factor refers to driver-related behavioural, cognitive, and physiological attributes; environmental factor encompasses external conditions such as weather, visibility, and climate; vehicle factor includes mechanical and technical conditions of vehicles; and road infrastructure factor represents the physical and structural elements of the road system. Road safety is defined as the measurable condition in which road users are protected from accidents, injuries, and fatalities. Each construct was measured using a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree, a widely established approach for capturing attitudes, perceptions, and opinions in research (Armstrong, 1987; Roselidyawaty & Mohd Rokeman, 2024). This numerical scale provides a reliable and valid method for quantifying respondents' evaluations of the factors influencing road safety outcomes. Table 1, presents the operational definitions of the study variables, providing a clear description of each construct.

**Table 1:*Operational Defamation***

| Construct | Operational Defination | Source |
|---|---|---|
| **Human Factor** | Human factor refers to the behavioral, cognitive, and physiological attributes of drivers that directly influence road safety outcomes. It includes compliance with traffic rules, attentiveness, decision-making, fatigue, distraction, and impairment. | (Bastos et al., 2020; Bucsuházy et al., 2020) |
| **Environmental Factor** | Environmental factor refers to external road and weather conditions that directly affect driver performance and accident risk. It includes night-time driving, poor visibility, rainfall, fog, and broader climate variations such as extreme weather events. These conditions impair visibility, reduce vehicle control, and increase collision likelihood. | (Mondal et al., 2011) |
| **Vehicle Factor** | Ehicle factor refers to mechanical and technical conditions of vehicles that directly influence accident risk and safety outcomes. It includes poor maintenance and defects in critical components such as brakes, tires, steering, lighting, and electrical systems. Malfunction or failure of these elements reduces vehicle control and increases collision likelihood, making vehicle factors a measurable determinant of road safety | (Hudec & Šarkan, 2022; Moodley & Allopi, 2008; Solah et al., 2021) |
| **Road Infrastructure Factor** | Road infrastructure factor refers to the physical and structural elements of the road system that affect safety outcomes. It includes road design, geometry, signage, traffic lights, street lighting, drainage systems, guardrails, and overall maintenance. Deficiencies such as potholes, poor markings, inadequate lighting, and weak safety barriers increase accident risk, while well-maintained infrastructure enhances visibility, traffic flow, and driver performance | (Gautam et al., 2021; Gutierrez & Mohan, 2020) |
| **Road Safety** | Road safety is defined as the set of measures aimed at preventing accidents, serious injuries, and fatalities among road users. It involves adherence to traffic regulations, the use of safety technologies, and the development of safer road | (Du et al., 2023; Salmon et al., 2019) |

| Construct | Operational Defination | Source |
|---|---|---|
| | environments. As a critical component of sustainable development, road safety seeks to reduce the burden of traffic-related injuries, particularly among vulnerable groups such as pedestrians, cyclists, and motorcyclists. | |

### 3.3 Data Collection & Sampling

The respondents for this study consisted of 363 licensed drivers from Universiti Utara Malaysia (UUM), including both students and staff, selected to provide insights into the influence of human, environmental, vehicle, and infrastructure factors on road safety outcomes. Random sampling was employed to capture diversity across demographic categories such as gender, age, and driving experience, thereby enhancing the representativeness and analytical robustness of the data.

The gender distribution shows that 56.5% of respondents were male and 27.5% female, reflecting the predominance of male drivers within the student population (Table 2). This imbalance highlights the broader gender dynamics in driving participation, where male students are more likely to hold vehicle licenses compared to their female counterparts.

The age profile of respondents indicates that 49.9% were between 18–25 years, representing the majority of young drivers who are at the early stages of their driving experience. Meanwhile, 22% were aged 26–35, and smaller proportions belonged to the 36–45 (13.5%), 46–55 (7.7%), and above 55 (6.9%) categories. This distribution captures both novice and experienced drivers, offering a balanced perspective on how age influences driving behavior and safety perceptions.

Driving experience was also diverse: 28.1% had more than 10 years of driving experience, while 18.5% had less than one year. The remaining respondents fell into intermediate categories (1–3 years = 28.1%; 4–7 years = 18.5%; 8–10 years = 6.9%). This variation is significant because it allows the study to examine how experience levels shape attitudes toward road safety and accident risk.

In summary, the demographic composition of the sample provides a comprehensive view of licensed student drivers at UUM. The inclusion of respondents across gender, age, and driving experience ensures that the findings are both representative and analytically robust, offering valuable insights into the multifactorial determinants of road safety. Table 2 provides a comprehensive summary of the respondents' demographic characteristics, including gender, age groups, and driving experience, offering a clear profile of the study sample.

**Table 2:** ***Demographics Information of The Respondent***

| Demographics | No of Respondent | Percentage (%) |
|---|---|---|
| **Gender** | | |
| Male | 205 | 56.5% |
| Female | 100 | 27.5% |
| **Age group** | | |
| 18-25 | 181 | 49.9% |
| 26-35 | 80 | 22.0% |
| 36-45 | 49 | 13.5% |
| 46-55 | 28 | 7.70% |
| 56> | 25 | 6.90% |
| **Driving experience** | | |
| 1< year | 67 | 18.5% |
| 1-3year | 102 | 28.1% |
| 4-7 year | 67 | 18.5% |
| 8-10 year | 25 | 6.90% |
| 10> | 102 | 28.1% |

## 4. Measurment Model

The internal consistency reliability of all constructs in this study was found to be high, with Cronbach's alpha values ranging between 0.853 and 0.878, exceeding the recommended threshold of 0.70 (Hair et al., 2019). Among the constructs, Environmental Factor demonstrated the highest reliability (α = 0.878), followed closely by Road Infrastructure Factor (α = 0.875), Human Factor (α = 0.871), Vehicle Factor (α = 0.862), and Road Safety (α = 0.853). These results confirm that the measurement scales used in this study are internally consistent.

Composite reliability (CR) values ranged from 0.895 to 0.911, all surpassing the minimum benchmark of 0.70, further supporting the robustness of the measurement model. Similarly, the average variance extracted (AVE) values ranged between 0.630 and 0.672, exceeding the critical value of 0.50 (Fornell & Larcker, 1981), thereby establishing convergent validity. Although some individual item loadings were slightly below the ideal threshold of 0.70, all remained above 0.50, indicating acceptable indicator reliability.

Factor loadings across constructs ranged between 0.722 and 0.849, with the majority surpassing the 0.70 benchmark. For instance, Human Factor items loaded between 0.781 and 0.849, while Environmental Factor items ranged from 0.803 to 0.840. Road Infrastructure Factor demonstrated strong loadings between 0.776 and 0.841, and Road Safety items ranged from 0.762 to 0.817. Vehicle Factor showed slightly more variability (0.722–0.844), yet all items remained within acceptable limits.

Taken together, these results confirm that the measurement model demonstrates strong internal consistency, composite reliability, and convergent validity, ensuring that the constructs are both reliable and valid for assessing the influence of human, environmental, vehicle, and infrastructure factors on road safety outcomes.

The measurement model demonstrates adequate convergent validity, thereby providing empirical support for the conceptual framework employed in the structural equation modelling analysis. Discriminant validity was subsequently assessed using both the HTMT ratio and the Fornell–Larcker criterion. Table 3 presents the item loadings, Cronbach's alpha, composite reliability (CR), and average variance extracted (AVE) for the constructs examined in this study.

Additionally, Figure 2 below, offers a graphical representation of the measurement model, illustrating that the observed indicators load appropriately onto their respective constructs. This visual depiction reinforces the statistical evidence reported in Table 3, highlighting how each construct is operationalized through its indicators and thereby confirming the reliability and convergent validity of the model.

**Table 1:Convergent Validity Result**

| Constructs | Items | Loadings | Cronbach Alpha | CR | AVE |
|---|---|---|---|---|---|
| Environmental Factor | EF1 | 0.803 | 0.878 | 0.911 | 0.672 |
| | EF2 | 0.827 | | | |
| | EF3 | 0.806 | | | |
| | EF4 | 0.822 | | | |
| | EF5 | 0.840 | | | |
| Human Factor | HF1 | 0.849 | 0.871 | 0.906 | 0.659 |
| | HF2 | 0.818 | | | |
| | HF3 | 0.781 | | | |
| | HF4 | 0.804 | | | |
| | HF5 | 0.804 | | | |
| Road Safety | RDS1 | 0.792 | 0.853 | 0.895 | 0.630 |
| | RDS2 | 0.817 | | | |
| | RDS3 | 0.762 | | | |
| | RDS4 | 0.802 | | | |
| | RDS5 | 0.795 | | | |
| Road Infrastructure Factor | RI1 | 0.776 | 0.875 | 0.909 | 0.667 |
| | RI2 | 0.821 | | | |
| | RI3 | 0.811 | | | |
| | RI4 | 0.841 | | | |
| | RI5 | 0.834 | | | |
| | VF1 | 0.794 | 0.862 | 0.901 | 0.646 |
| | VF2 | 0.808 | | | |
| | VF3 | 0.844 | | | |
| | VF4 | 0.844 | | | |
| | VF5 | 0.722 | | | |

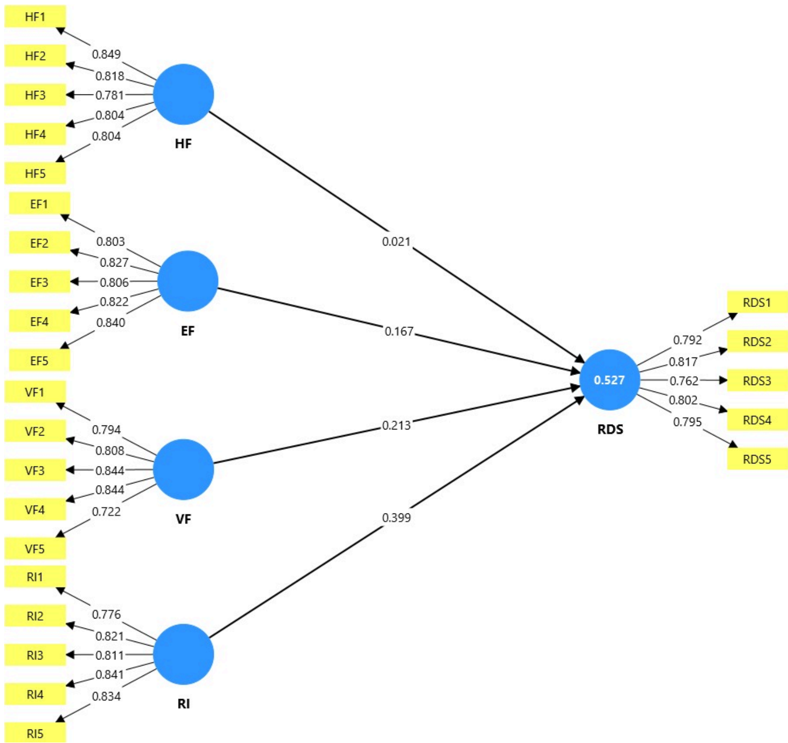


**Figure 2:** ***SEM Analysis Result by Measurement Model***

*Note: HF; Human factor, EF; Environment factor, VF; Vehicle factor, RI; Road Infrastructure factor, RDS; Sustainable road safety*

**4.1 Collinearity Statistics (VIF)**

Multicollinearity was assessed using the variance inflation factor (VIF), which provides an indication of the degree of correlation among predictor variables. Following the guidelines of (Midi et al., 2013; Upendra et al., 2023), a cut-off value of 3.3 was applied, while (Hair et al., 2019), suggest values below 5.0 as acceptable. The results, presented in Table 4, demonstrate that all VIF values fall within the recommended thresholds, confirming the absence of multicollinearity issues. Specifically, the VIF values were 2.553 for environmental factor, 1.773 for human factor, 2.815 for road infrastructure factor, and 3.609 for vehicle factor. Although the vehicle factor recorded the highest VIF, it remains below the critical cut-off, indicating that collinearity does not compromise the stability of the model. These findings confirm that the predictor variables are sufficiently independent, and the path coefficient estimates are stable and reliable

Table 2: *Collinearity Statistics (VIF)*

| | **RS** |
|---|---|
| **Environmental Factor (EF)** | 2.553 |
| **Human Factor (HF)** | 1.773 |
| **Road Infrastructure (RI)** | 2.815 |
| **Vehicle Factor (VF)** | 3.609 |

**4.2 Discriminant Validity**

Discriminant validity was assessed using both the Heterotrait-Monotrait (HTMT) ratio and the Fornell–Larcker criterion. According to (Voorhees et al., 2015), discriminant validity ensures that each construct is statistically distinct from the others. The HTMT analysis (Table 5) revealed that all values were below the conservative threshold of 0.85 (Henseler et al., 2015; Rhayha & Alaoui Ismaili, 2024), thereby confirming satisfactory discriminant validity across all construct pairs. For example, the HTMT values ranged from 0.524 (Human Factor–Road Safety) to 0.843 (Environmental Factor–Vehicle Factor), while Road Infrastructure Factor also demonstrated acceptable values, such as 0.794 (Road Infrastructure–Road Safety) and 0.841 (Road Infrastructure–Vehicle Factor). These results indicate that each construct captures unique variance without excessive overlap.

The Fornell–Larcker criterion (Table 6) further supported these findings. The square root of the AVE for each construct was greater than its correlations with other constructs, thereby satisfying the criterion proposed by (Fornell & Larcker, 1981). For example, environmental factor (0.820) was higher than its correlations with human factor (0.629), road safety (0.600), road infrastructure (0.659), and vehicle factor (0.736). Similarly, human factor (0.812), road safety (0.794), road infrastructure (0.817), and vehicle factor (0.804) each exceeded their respective inter-construct correlations. These results confirm that the constructs are empirically distinct, thereby establishing strong discriminant validity within the measurement model.

Taken together, the HTMT ratios and Fornell–Larcker results provide strong evidence of discriminant validity. These findings confirm that environmental factor, human factor, road safety, road infrastructure factor, and vehicle factor are empirically distinct, ensuring that the structural relationships tested in this study are both reliable and valid.

**Table 3:** ***Heterotrait - Monotrait Ratio (HTMT)***

| Variables | EF | HF | RDS | RI | VF |
|---|---|---|---|---|---|
| Environment factor (EF) | | | | | |
| Human factor (HF) | 0.722 | | | | |
| Road safety (RDS) | 0.687 | 0.524 | | | |
| Road infrastructure (RI) | 0.748 | 0.584 | 0.794 | | |
| Vehicle factor (VF) | 0.843 | 0.690 | 0.776 | 0.841 | |

Table 6: *Fornell-Larcker Criterion*

| Variables | EF | HF | RDS | RI | VF |
|---|---|---|---|---|---|
| Environment Factor (EF) | **0.820** | | | | |
| Human Factor (HF) | 0.629 | **0.812** | | | |
| Road Safety (RDS) | 0.600 | 0.459 | **0.794** | | |
| Road Infrastructure (RI) | 0.659 | 0.515 | 0.689 | **0.817** | |
| Vehicle Factor (VF) | 0.736 | 0.598 | 0.666 | 0.795 | **0.804** |

**5. Structure Model**

The structural model demonstrates that Road Safety has a moderate coefficient of determination ($R^2 = 0.527$), indicating that approximately 52.7% of its variance is explained by the four antecedent factors: Human Factor, Environmental Factor, Vehicle Factor, and Road Infrastructure. This suggests that road safety outcomes are substantially shaped by the hypothesized predictors.

Path analysis reveals several important relationships. Road infrastructure factor exerts the strongest positive and significant influence on road safety ($\beta = 0.399$, $p < 0.001$), highlighting the critical role of road design, quality, and maintenance in reducing accident risks. Vehicle factor also shows a significant positive effect ($\beta = 0.213$, $p = 0.006$), underscoring the importance of vehicle condition and safety technologies. Similarly, environmental factor contributes positively ($\beta = 0.167$, $p = 0.006$), reflecting the influence of external conditions such as weather and surroundings on safety outcomes. In contrast, human factor demonstrates a weak and statistically insignificant effect ($\beta = 0.021$, $p = 0.705$), suggesting that within this sample, driver-related variables did not substantially predict road safety compared to infrastructure and vehicle-related factors.

Taken together, these findings confirm that the proposed model explains a meaningful proportion of variance in road safety, with infrastructure and vehicle-related factors emerging as the most influential determinants. This provides strong empirical support for the multidimensional framework of road safety, emphasizing the need for integrated strategies that combine infrastructure improvements, vehicle safety measures, and environmental management. The information provided in Figure 3 offers strong empirical support for the multidimensional framework of road safety, emphasizing the need for integrated strategies that combine infrastructure improvements, vehicle safety measures, and environmental management.

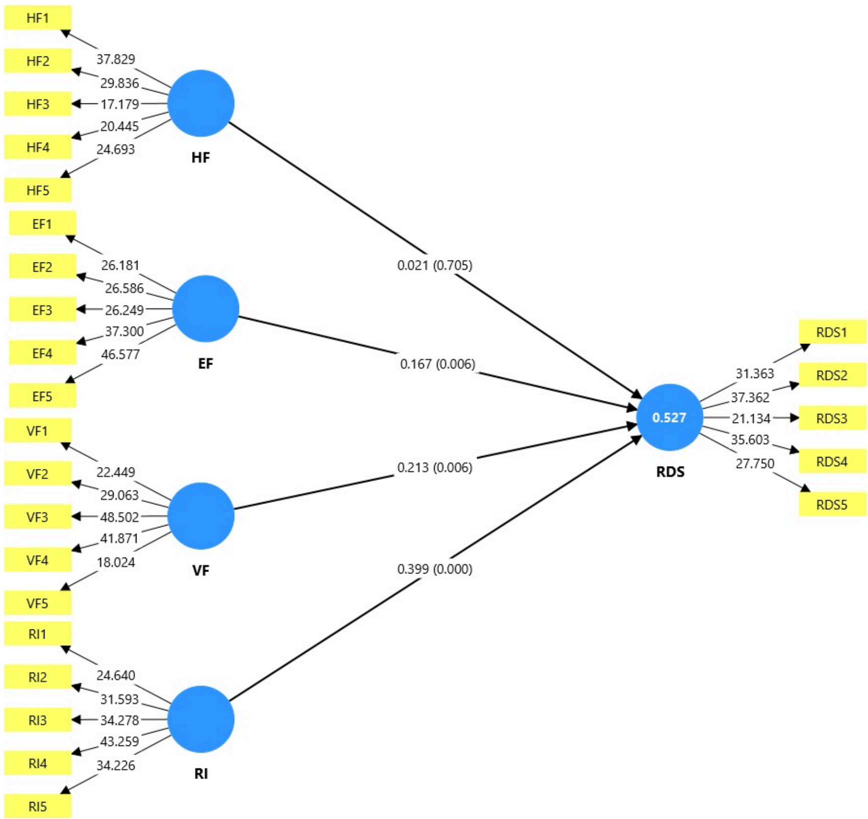


**Figure 3:** ***SEM Analysis Result by Structure Model***

*Note: HF; Human factor, EF; Environment factor, VF; Vehicle factor, RI; Road Infrastructure factor, RDS: Road Safety*

### 5.1 Path Coefficients and Hypothesis Testing

The Table 7, presents the empirical support for the proposed hypotheses in the structural model. The t-values for the hypothesized paths ranged from 0.378 to 5.880, with three of the four relationships found to be statistically significant at $p < 0.05$.

Hypothesis 1, which posited a positive effect of human factor on road safety, was not supported ($\beta = 0.021$, $t = 0.378$, $p = 0.705$). This suggests that driver-related variables in this sample did not exert a meaningful influence on road safety outcomes. In contrast, Hypothesis 2 received strong support, with environmental factor showing a significant positive effect on road safety ($\beta = 0.167$, $t = 2.768$, $p = 0.006$). This highlights the importance of external conditions such as weather and surrounding environment in shaping safety outcomes.

Similarly, Hypothesis 3 was supported, as vehicle factor demonstrated a significant positive relationship with Road Safety ($\beta = 0.213$, $t = 2.748$, $p = 0.006$). This finding underscores the role of vehicle condition and safety features in reducing accident risks. Finally, Hypothesis 4 received the strongest empirical support, with road infrastructure factor exerting a substantial positive effect on Road Safety ($\beta = 0.399$, $t = 5.880$, $p < 0.001$). This result emphasizes the critical role of road design, quality, and maintenance in ensuring safe transportation systems.

Taken together, the results confirm that environmental, vehicle, and infrastructure factors significantly contribute to road safety, while human factors did not emerge as a significant predictor in this context. These findings provide robust empirical support for the multidimensional framework of road safety proposed in this study.

**Table 7:** ***Summary***

| Hypothesis | Relationships | Beta | SD | T Value | P value | Decision |
|---|---|---|---|---|---|---|
| H1 | HF -> RDS | 0.021 | 0.057 | 0.378 | 0.705 | Not Supported |
| H2 | EF -> RDS | 0.167 | 0.060 | 2.768 | 0.006 | Supported |
| H3 | VF -> RDS | 0.213 | 0.078 | 2.748 | 0.006 | Supported |
| H4 | RI -> RDS | 0.399 | 0.068 | 5.880 | 0.000 | Supported |

### 5.2 Coefficient of Determination ($R^2$)

The coefficient of determination ($R^2$) was examined to assess the explanatory power of the structural model. As shown in Table 8, Road Safety recorded an $R^2$ value of 0.527, with an adjusted $R^2$ of 0.521. This indicates that approximately 52.7% of the variance in road safety is explained by the antecedent constructs, human factor, environmental factor, vehicle factor, and road infrastructure. The close alignment between the unadjusted and adjusted $R^2$ values suggests that the model is parsimonious and free from overfitting concerns. Overall, these results demonstrate that the proposed framework possesses moderate explanatory power, providing meaningful insights into the determinants of road safety. The information is provided in Table 8 below.

**Table 8:** ***R-Square ($R^2$)***

| Construct | R-Square | Adjusted R-Square |
|---|---|---|
| **RDS** | 0.527 | 0.521 |

### 5.3 Effect Size

The $f^2$ effect sizes were examined to evaluate the relative contribution of each predictor to road safety. As shown in Table 9, all predictors demonstrated small to moderate effects. Specifically, environmental factor ($f^2 = 0.023$) and vehicle factor ($f^2 = 0.027$) exhibited small effects, while human factor ($f^2 = 0.001$) showed a negligible contribution. In contrast, road infrastructure factor recorded the highest effect size ($f^2 = 0.119$), which falls within the small to moderate range, indicating its comparatively stronger influence on road safety outcomes. Overall, these results suggest that while each factor contributes to explaining road safety, infrastructure plays a more prominent role relative to environmental, human, and vehicle factors.

**Table 9:** ***Effect Size ($f^2$)***

| Variable | F-Square Value | Effect Size |
|---|---|---|
| EF | 0.023 | Small |
| HF | 0.001 | Small |
| RI | 0.119 | Small to Moderate |
| VF | 0.027 | Small |

### 5.4 Predictive Relevance ($Q^2$)

Predictive relevance was assessed using the $Q^2$ statistic derived from the blindfolding procedure in PLS-SEM. This method evaluates the model's ability to predict omitted data points, with positive $Q^2$ values indicating predictive relevance. Conventionally, values of 0.02, 0.15, and 0.35 are interpreted as small, moderate, and large predictive relevance, respectively (Keskin, 2013; Samartha & Kodikal, 2018). As shown in Table 10, Road Safety recorded a $Q^2$ value of 0.510, which exceeds the threshold of 0.35 and therefore demonstrates strong predictive relevance. This result confirms that the exogenous constructs human factor, environmental factor, vehicle factor, and road infrastructure collectively provide substantial predictive capability for the endogenous construct of road safety. The information is provided in Table 10 below.

**Table 10:** ***Predictive Relevance***

| Variable | $Q^2$ Predict |
|---|---|
| **RDS** | 0.510 |

## 6. Discussion

The empirical results of this study provide valuable insights into the multidimensional determinants of road safety. The explanatory power of the model ($R^2 = 0.527$) demonstrates that more than half of the variance in road safety is accounted for by the antecedent constructs human factor, environmental factor, vehicle factor, and road infrastructure. This confirms that road safety outcomes are not shaped by a single dimension but rather emerge from the interplay of environmental, technological, and infrastructural elements.

The strongest predictor of road safety was road infrastructure ($\beta = 0.399$, $p < 0.001$), affirming the critical role of road design, quality, and maintenance in reducing accident risks. This finding aligns with sustainable safety theory, which emphasizes infrastructure as a cornerstone of accident prevention. It also resonates with prior studies that highlight how well-planned infrastructure reduces exposure to hazards and mitigates the severity of accidents.

Vehicle factor ($\beta = 0.213$, $p = 0.006$) and environmental factor ($\beta = 0.167$, $p = 0.006$) also contributed significantly, underscoring the importance of vehicle safety standards and external conditions such as weather and surroundings. These results suggest that technological improvements in vehicles and proactive environmental management can enhance safety outcomes. In contrast, Human Factor ($\beta = 0.021$, $p = 0.705$) was not significant, indicating that driver behaviour variables in this context may be less influential compared to structural and technological determinants. This finding diverges from traditional behavioural theories of road safety, suggesting that in the Malaysian context, systemic and infrastructural interventions may yield greater impact than individual behavioural changes alone.

The effect size ($f^2$) analysis reinforces these conclusions. While all predictors demonstrated small to moderate contributions, Road Infrastructure recorded the highest effect size ($f^2 = 0.119$), confirming its comparatively stronger influence. Environmental and Vehicle Factors contributed modestly, while Human Factor was negligible. This hierarchy of effects highlights the need for prioritizing infrastructure development and vehicle safety measures in national road safety strategies.

Predictive relevance ($Q^2 = 0.510$) further validates the robustness of the model, confirming that the exogenous constructs possess strong predictive capability for road safety. This demonstrates that the framework is not only explanatory but also predictive, making it a reliable tool for policy formulation and strategic planning.

Taken together, these findings advance the understanding of road safety by demonstrating that infrastructure, vehicle, and environmental factors are the most decisive elements, while human factors play a limited role in this context. The results provide strong empirical support for a systemic approach to road safety, emphasizing that sustainable improvements require integrated strategies that combine infrastructure investment, vehicle safety technologies, and environmental management. The information supporting these conclusions is provided in Tables 7–10 and Figure 2 and 3.

### 6.1 Theoretical Implication

This study contributes to the theoretical advancement of road safety research by empirically validating a multidimensional framework that integrates human, environmental, vehicle, and infrastructure factors. The findings highlight that road safety outcomes are predominantly shaped by systemic and structural determinants, with Road Infrastructure emerging as the strongest predictor. This supports sustainable safety theory, which emphasizes the role of infrastructure in minimizing exposure to risks and mitigating accident severity.

Interestingly, the non-significant effect of human factor challenges traditional behavioural theories that place driver behaviour at the centre of accident causation. Instead, the results suggest that in the Malaysian context, systemic interventions such as infrastructure improvements and vehicle safety standards may be more impactful than individual behavioural changes. This divergence from conventional perspectives enriches the theoretical discourse by positioning road safety as a product of integrated systems rather than isolated human actions.

Moreover, the strong predictive relevance ($Q^2 = 0.510$) confirms that the proposed model is not only explanatory but also predictive, offering a reliable theoretical tool for future research. By demonstrating the relative contributions of each factor, this study advances the literature on road safety by providing empirical evidence that supports a holistic, systems-based approach.

### 6.2 Practical Implication

From a practical standpoint, the results carry significant implications for policymakers, practitioners, and stakeholders in road safety management. The dominant role of Road Infrastructure underscores the need for sustained investment in road design, maintenance, and safety engineering. Enhancing infrastructure quality can directly reduce accident risks and improve overall safety outcomes.

The significant contributions of vehicle and environmental factors highlight the importance of enforcing vehicle safety standards, promoting regular maintenance, and integrating advanced safety technologies. At the same time, environmental management such as weather monitoring systems, hazard warnings, and roadside safety measures can further strengthen safety outcomes.

The negligible effect of Human Factor suggests that interventions focused solely on driver behaviour may have limited impact unless complemented by systemic reforms. This finding calls for a shift in policy emphasis toward structural and technological solutions, while still maintaining educational and enforcement programs as supportive measures.

Overall, the study provides actionable insights for designing integrated road safety strategies. Policymakers should prioritize infrastructure development, strengthen vehicle safety regulations, and incorporate environmental management into national safety plans. By adopting a multidimensional approach, Malaysia can move closer to achieving sustainable road safety outcomes.

## 7. Conclusion

This study examined the multidimensional determinants of road safety by integrating Human, Environmental, Vehicle, and Infrastructure factors within a structural equation modelling framework. The findings demonstrate that the proposed model explains a moderate proportion of variance in road safety ($R^2$ = 0.527), with strong predictive relevance ($Q^2$ = 0.510). Among the predictors, Road Infrastructure emerged as the most influential determinant, followed by Vehicle and Environmental Factors, while Human Factor showed negligible impact.

These results provide empirical support for a systems-based perspective of road safety, emphasizing that structural and technological interventions are more decisive than individual behavioural factors in shaping safety outcomes. The study contributes to theory by reinforcing sustainable safety principles and challenging traditional behaviour-centric approaches. Practically, it highlights the need for integrated strategies that prioritize infrastructure development, vehicle safety standards, and environmental management to achieve sustainable improvements in road safety.

### 7.1 Future Research Recommendation

While the study offers important insights, several avenues for future research remain. First, the insignificant role of Human Factor suggests the need for deeper investigation into behavioural dimensions of road safety, particularly in contexts where enforcement, cultural norms, and driver education may vary. Future studies could incorporate more nuanced measures of human behaviour, such as risk perception, compliance with traffic laws, or psychological factors influencing driving practices. Second, longitudinal research designs would allow for the examination of how improvements in infrastructure and vehicle safety technologies translate into long-term reductions in accidents. This would strengthen causal inferences and provide evidence for sustained policy interventions. Third, comparative studies across different regions or countries could enrich the understanding of contextual differences in road safety determinants. Such cross-national analyses would help identify whether the dominance of infrastructure factors is unique to Malaysia or reflects broader global patterns. Finally, future research could expand the model to include governance and institutional factors, such as policy enforcement, regulatory frameworks, and stakeholder collaboration. Integrating these dimensions would provide a more comprehensive view of systemic influences on road safety and strengthen the applicability of findings for policy formulation.

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