Road Safety Performance Indicators and Prediction Modelling: A Comprehensive Review of Risk Factors, Assessment Frameworks, and Emerging Technologies

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Abstract — Road traffic accidents constitute one of the most significant public health and transportation challenges globally, causing approximately 1.19 million fatalities and more than 50 million injuries annually. Despite substantial improvements in vehicle safety technologies, roadway infrastructure, and traffic management systems, road crashes continue to impose severe social and economic burdens, particularly in developing countries. Traditional road safety assessment methodologies primarily rely on reactive indicators such as accident frequency, fatalities, and injury severity. However, these indicators often fail to identify emerging risks and underlying safety deficiencies before crashes occur. Recent developments in transportation engineering have emphasized the use of Road Safety Performance Indicators (RSPIs), predictive analytics, machine learning, and Intelligent Transportation Systems (ITS) to support proactive safety management. This review critically examines the evolution of road safety research, major crash causation factors, safety assessment methodologies, accident prediction models, black spot identification techniques, and emerging technological interventions. Particular emphasis is placed on the integration of performance indicators with prediction modelling frameworks. The review incorporates findings from recent studies and integrates the concepts developed in the doctoral research entitled "Development of a Framework for Road Safety Performance Indicators using Prediction Modelling", which focuses on highway safety assessment in Madhya Pradesh, India. The study highlights the importance of combining exposure indicators, outcome indicators, behavioural indicators, infrastructure indicators, and system performance measures within a unified framework. Research gaps, future directions, and policy implications are discussed to support evidence-based road safety management and sustainable transportation development.

Keywords: Road Safety, Road Safety Performance Indicators, Accident Prediction Models, Highway Safety, Black Spot Analysis, Traffic Safety, Intelligent Transportation Systems, Safety-II;

I. INTRODUCTION

Road transportation serves as the backbone of economic development, social integration, and regional connectivity. The expansion of road networks has facilitated trade, mobility, and accessibility across urban and rural areas. However, these benefits have been accompanied by a substantial increase in road traffic crashes, making road safety a critical concern for governments, transportation agencies, researchers, and policymakers worldwide [1], [2].

According to the World Health Organization (WHO), road traffic crashes result in approximately 1.19 million deaths annually and rank among the leading causes of death for individuals aged between 5 and 29 years [1]. In addition to fatalities, millions of people suffer severe injuries and disabilities each year, generating enormous economic costs that often exceed 3% of a nation's Gross Domestic Product (GDP) [1], [2]. The burden is particularly severe in low- and middle-income countries, where nearly 93% of global road traffic deaths occur despite these countries possessing only around 60% of the world's registered vehicles [1].

India represents one of the most challenging road safety environments globally. Rapid urbanization, increasing vehicle ownership, mixed traffic conditions, inadequate infrastructure, and behavioural issues contribute significantly to the country's high accident rates [56], [58]. According to the Ministry of Road Transport and Highways (MoRTH), road crashes continue to claim more than 150,000 lives annually in India [56]. States such as Madhya Pradesh experience significant safety challenges due to extensive highway networks, varying traffic compositions, and rapid economic development [56], [60].

Traditional road safety management approaches have largely focused on reactive measures. Accident frequency, fatality rates, injury severity, and black spot analyses have been used extensively to identify hazardous locations and prioritize interventions [3], [4], [22]. While these methods provide valuable insights, they are inherently retrospective and depend upon the occurrence of accidents before corrective actions can be implemented [3], [4]. Consequently, researchers have increasingly advocated proactive approaches capable of identifying risks before accidents occur [5], [6], [29].

One of the most promising developments in this regard is the concept of Road Safety Performance Indicators (RSPIs). RSPIs are measurable variables that capture factors influencing road safety outcomes [2], [29], [30]. Unlike traditional crash indicators, RSPIs assess behavioural, infrastructural, operational, vehicular, and institutional aspects of transportation systems [29], [30]. These indicators provide a comprehensive understanding of safety performance and facilitate early identification of potential safety deficiencies [2], [30].

The doctoral research conducted by Malviya (2026) addresses this challenge through the development of a framework for Road Safety Performance Indicators integrated with prediction modelling [60]. The study focuses on highways in Madhya Pradesh and combines accident data analysis, behavioural assessments, black spot identification, and regression-based prediction models to establish a proactive road safety management framework [60]. The research emphasizes the importance of moving beyond traditional accident statistics and adopting performance-based approaches capable of supporting evidence-driven decision-making [60].

The emergence of advanced statistical methods, machine learning algorithms, artificial intelligence, and Intelligent Transportation Systems has further enhanced the capability of road safety practitioners to predict and prevent accidents [16]–[20], [36], [41]–[45]. Modern prediction models utilize large datasets incorporating traffic volumes, roadway characteristics, weather conditions, driver behaviour, vehicle attributes, and historical crash records [16], [18], [20]. These technologies enable transportation agencies to identify high-risk conditions and implement targeted interventions more effectively [36], [38], [41].

This review paper aims to synthesize contemporary research related to road safety performance indicators, accident prediction modelling, behavioural safety assessment, infrastructure safety evaluation, and emerging technologies. The study also identifies key research gaps and proposes future directions for developing integrated road safety management frameworks based on predictive analytics, intelligent transportation systems, and performance-based safety assessment methodologies [29], [30], [41], [53], [60].

II. Evolution of Road Safety Research

Road safety research has evolved considerably over the past five decades. Early investigations focused primarily on understanding accident causation through statistical analyses of crash records [4], [16]. Over time, the field has expanded to encompass behavioural sciences, transportation engineering, human factors, systems theory, and artificial intelligence [11]–[14], [41].

A. *Traditional Accident-Based Approaches*

The earliest road safety studies relied heavily on accident statistics. Researchers examined crash frequencies, injury rates, fatality counts, and accident severity indices to identify hazardous locations and contributing factors [4], [22]. Black spot identification emerged as one of the most widely used techniques for prioritizing infrastructure improvements [22], [23].

Although accident-based approaches remain valuable, they possess several limitations. First, they are reactive in nature, requiring accidents to occur before risks can be identified. Second, accident data often suffer from underreporting and inconsistencies. Third, traditional analyses frequently fail to capture the complex interactions among drivers, vehicles, roads, and environmental conditions [3], [4], [16].

B. *Human Factors Perspective*

Human behaviour has consistently been identified as the dominant contributor to road traffic crashes. Research indicates that approximately 90% of accidents involve some form of human error [12], [13]. Consequently, significant attention has been devoted to understanding driver behaviour, perception, decision-making, fatigue, distraction, and risk-taking tendencies [11]–[14].

Studies by Reason introduced the concept of human error as a systems phenomenon rather than solely an individual failure [12]. Driver behaviour models subsequently incorporated psychological factors such as attitudes, risk perception, sensation seeking, and cognitive workload [11], [13].

Aggressive driving, speeding, distracted driving, and impaired driving have emerged as major behavioural risk factors. Research demonstrates that these behaviours significantly increase crash likelihood and severity, particularly on high-speed roadways [11], [15].

C. *Safe System Approach*

The Safe System approach represents a paradigm shift in road safety philosophy. Rather than assuming that human errors can be eliminated entirely, Safe System principles acknowledge that mistakes are inevitable and emphasize the development of transportation systems capable of accommodating these errors without resulting in severe injuries or fatalities [6].

The Safe System approach is founded upon four key principles:

1) Human vulnerability.
2) Shared responsibility.
3) System redundancy.
4) Proactive intervention.

Countries such as Sweden and the Netherlands have successfully implemented Safe System strategies through programs such as Vision Zero and Sustainable Safety [6], [10].

D. *Vision Zero*

Vision Zero was introduced in Sweden in 1997 with the objective of eliminating fatalities and serious injuries from road transportation systems [6]. The philosophy rejects the notion that traffic deaths are an unavoidable consequence of mobility and emphasizes systematic interventions targeting infrastructure, vehicle design, enforcement, and behavioural factors [6], [10].

Vision Zero has influenced road safety policies worldwide and serves as a foundation for contemporary road safety management strategies [6].

E. *Sustainable Safety*

The Dutch Sustainable Safety concept emphasizes self-explaining roads, predictable traffic environments, forgiving infrastructure, and safe road user behaviour [10]. The framework seeks to minimize conflicts and reduce accident severity through proactive system design [10].

F. *Data-Driven Safety Management*

Recent years have witnessed the emergence of Data-Driven Safety Management (DDSM), which integrates advanced analytics, prediction modelling, and performance measurement techniques [7], [16], [41]. This approach emphasizes continuous monitoring and proactive risk management rather than reactive accident investigation [7].

Road Safety Performance Indicators have become central to DDSM frameworks because they provide measurable information regarding safety-related conditions and behaviours [29], [30].

III. Global and Indian Road Safety Scenario

A. *Introduction*

Road traffic accidents represent one of the most significant public health and development challenges worldwide.

Despite substantial improvements in transportation infrastructure, vehicle safety systems, and traffic management practices, road traffic injuries continue to impose considerable social, economic, and health burdens on societies across the globe [1], [2].

According to the World Health Organization (WHO), approximately 1.19 million people die each year due to road traffic crashes, while an estimated 20 to 50 million individuals suffer non-fatal injuries, many of which result in give heading 3 also Road safety has emerged as a major concern for governments, policymakers, transportation agencies, and international organizations because of its direct impact on human lives and economic development. The United Nations has recognized road safety as a key component of sustainable development and has incorporated road traffic injury reduction within the Sustainable Development Goals (SDGs) [1], [6].

Developing countries face particularly severe road safety challenges due to rapid motorization, inadequate infrastructure, weak enforcement systems, and limited emergency response capabilities [1], [59]. India represents one of the most affected nations and accounts for a significant proportion of global road traffic fatalities [56].

B. Global Road Safety Scenario

According to the World Health Organization (WHO), approximately 1.19 million people die annually as a result of road traffic crashes worldwide [1]. In addition, more than 50 million individuals suffer injuries, many of which result in long-term disabilities and reduced quality of life [1], [2].

Road traffic injuries currently rank among the leading causes of death globally and are the primary cause of death among individuals aged between 5 and 29 years [1]. The socioeconomic burden associated with road traffic crashes is estimated to exceed 3% of Gross Domestic Product (GDP) in many countries [1], [2].

The WHO estimates that nearly:

- 93% of road traffic fatalities occur in low- and middle-income countries.
- These countries possess only approximately 60% of the world's registered vehicles.
- Vulnerable road users account for over 50% of global fatalities [1].

These statistics highlight the unequal distribution of road safety risks across different regions.

C. Regional Distribution of Road Traffic Fatalities

Significant variations exist in road safety performance among different regions of the world.

1) High-Income Countries

High-income countries have generally achieved substantial reductions in road traffic fatalities through:

- Improved infrastructure.
- Strong vehicle safety regulations.
- Effective enforcement systems.
- Advanced emergency medical services [2], [6].

Examples include:

- Sweden
- Netherlands
- Norway
- United Kingdom
- Australia

These countries have successfully implemented Safe System and Vision Zero strategies [6], [10].

2) Low- and Middle-Income Countries

Low- and middle-income countries continue to experience disproportionately high road traffic fatality rates [1].

Contributing factors include:

- Rapid urbanization.
- Weak enforcement.
- Poor infrastructure.
- Vehicle safety deficiencies.
- Limited trauma care facilities [59].

Regions experiencing particularly high fatality rates include:

- South Asia.
- Sub-Saharan Africa.
- Southeast Asia [1], [59].

D. Economic Impact of Road Traffic Accidents

Road traffic crashes impose substantial economic costs on societies.

These costs include:

1) Direct Costs

- Medical expenses.
- Emergency response services.
- Vehicle repairs.
- Insurance claims.

2) Indirect Costs

- Productivity losses.
- Disability-related expenses.
- Social welfare costs.
- Family income losses.

The World Bank estimates that road traffic crashes cost countries between 3% and 5% of GDP annually [59].

For developing economies, these losses represent a major obstacle to sustainable economic growth [59].

E. United Nations Road Safety Initiatives

Recognizing the global road safety crisis, the United Nations launched the:

1) Decade of Action for Road Safety (2011–2020)

The initiative aimed to stabilize and reduce road traffic fatalities globally [1], [6].

Building upon earlier efforts, the United Nations subsequently declared:

2) Decade of Action for Road Safety (2021–2030)

The objective is to reduce road traffic deaths and injuries by at least 50% by 2030 [1].

The strategy emphasizes:

- Safe roads.
- Safe vehicles.
- Safe road users.
- Safe speeds.
- Effective post-crash care [1], [6].

F. Road Safety in India

India possesses one of the largest road networks in the world, exceeding 6 million kilometres in length [56].

The transportation sector plays a critical role in supporting economic growth, trade, and regional connectivity. However, rapid motorization and increasing traffic volumes have contributed to substantial road safety challenges [56], [58].

According to the Ministry of Road Transport and Highways (MoRTH), India records approximately:

- 460,000 road accidents annually.
- More than 168,000 fatalities annually.
- Hundreds of thousands of injuries each year [56].

India accounts for approximately 11–13% of global road traffic fatalities despite possessing only a fraction of the world's vehicles [1], [56].

G. Trends in Road Accidents in India

The trend of road accidents in India has generally followed increasing motorization rates.

Major contributing factors include:

- Increasing vehicle ownership.
- Urbanization.
- Highway expansion.
- Population growth [56].

The MoRTH Road Accidents in India Report indicates that:

1) Two-Wheelers

Account for the highest proportion of fatalities among vehicle categories [56].

2) National Highways

Although National Highways constitute a relatively small percentage of total road length, they account for a disproportionately high percentage of road fatalities due to higher operating speeds [56].

3) Rural Roads

Road safety remains a growing concern in rural areas because of limited infrastructure and emergency response capabilities [59].

H. Major Causes of Road Accidents in India

Research indicates that road traffic crashes in India result from a combination of human, vehicular, infrastructural, and environmental factors [11], [15], [56].

1) Over-Speeding

Over-speeding remains the single largest contributing factor to road accidents in India and accounts for more than 70% of reported crashes [56].

2) Dangerous Driving

Examples include:

- Wrong-side driving.
- Aggressive overtaking.
- Lane indiscipline.

These behaviours significantly increase crash risk [11], [13].

3) Drunk Driving

Alcohol-impaired driving remains a significant safety concern despite legal enforcement efforts [15].

4) Driver Fatigue

Particularly among commercial vehicle drivers, fatigue contributes substantially to accident occurrence [11].

5) Mobile Phone Usage

Distracted driving associated with mobile phone use has emerged as a growing safety issue [13].

I. Road User Categories Most Affected

The WHO identifies vulnerable road users as one of the most affected groups in road traffic crashes [1].

These include:

1) Pedestrians

Pedestrians constitute a significant proportion of urban road fatalities [1].

2) Cyclists

Cyclists face elevated crash risks due to limited dedicated infrastructure [1].

3) Motorcyclists

Motorcyclists account for a substantial proportion of fatalities in India because of high exposure and low levels of protection [56].

J. Road Safety Challenges in Madhya Pradesh

Madhya Pradesh possesses an extensive highway network and experiences significant road safety challenges.

The doctoral research undertaken by Malviya identified several factors influencing highway safety performance within the state [60].

Major challenges include:

1) High-Speed Highway Corridors

Increased accident severity due to excessive operating speeds [60].

2) Mixed Traffic Conditions

Interaction among heavy vehicles, passenger vehicles, motorcycles, and non-motorized traffic increases conflict opportunities [60].

3) Infrastructure Deficiencies

Including:

- Inadequate signage.
- Poor pavement condition.
- Insufficient roadside safety measures [60].

Behavioural Issues

Such as:

- Speeding.
- Helmet non-compliance.
- Seatbelt non-compliance [60].

K. Government Initiatives for Road Safety in India

Several initiatives have been undertaken to improve road safety.

1) Motor Vehicles (Amendment) Act, 2019

Introduced stricter penalties for traffic violations and strengthened enforcement mechanisms [56].

2) National Road Safety Policy

Provides a framework for improving road safety management and reducing fatalities [58].

3) Black Spot Improvement Program

MoRTH and NHAI have implemented programs for identifying and treating hazardous road locations [57].

4) Road Safety Audits

Mandatory audits have been introduced for many highway projects [31], [57].

L. Need for Proactive Road Safety Management

The global and Indian road safety scenarios clearly demonstrate that traditional accident-based approaches alone are insufficient for achieving substantial reductions in road traffic fatalities [3], [4].

Modern road safety management requires:

- Road Safety Performance Indicators.
- Accident prediction models.
- Intelligent Transportation Systems.
- Data-driven decision-making.
- Continuous monitoring frameworks [29], [30], [41].

These approaches support early identification of risks and enable transportation agencies to implement preventive measures before accidents occur [29], [30], [60].

M. Summary

Road traffic crashes continue to impose significant social, economic, and public health hburdens worldwide [1], [2]. Developing countries, including India, experience a disproportionately high share of road traffic fatalities because of rapid motorization, infrastructure challenges, and behavioural factors [56], [59]. The analysis of global and Indian road safety trends highlights the urgent need for proactive safety management approaches based on Road Safety Performance Indicators, predictive analytics, intelligent transportation systems, and evidence-based decision-making [29], [30], [41], [60]. These concepts provide the foundation for the integrated road safety framework proposed in this study [60].

IV. ROAD SAFETY PERFORMANCE INDICATORS (RSPIS)

A. Introduction

Road Safety Performance Indicators (RSPIs) have emerged as one of the most effective tools for proactive road safety management. Traditionally, road safety performance has been assessed using outcome-based indicators such as accident frequency, fatalities, and injury rates. While these indicators provide valuable information regarding historical safety performance, they are reactive in nature because they only become available after accidents have occurred [2], [3].

To overcome this limitation, international organizations such as the Organisation for Economic Co-operation and Development (OECD), International Traffic Safety Data and Analysis Group (IRTAD), European Transport Safety Council (ETSC), and the World Health Organization (WHO) have advocated the use of Road Safety Performance Indicators as complementary measures for evaluating road safety conditions before crashes occur [1], [2], [6].

Road Safety Performance Indicators are measurable variables that capture conditions influencing road safety outcomes. These indicators provide information regarding human behaviour, roadway infrastructure, vehicle safety, traffic operations, enforcement effectiveness, and institutional performance [29], [30]. Consequently, RSPIs facilitate proactive identification of safety deficiencies and support evidence-based decision-making.

The doctoral research entitled *"Development of a Framework for Road Safety Performance Indicators using Prediction Modelling"* adopts this philosophy by integrating multiple safety indicators with predictive modelling techniques to establish a comprehensive road safety assessment framework for highways in Madhya Pradesh, India [60].

B. Concept of Road Safety Performance Indicators

The concept of Road Safety Performance Indicators was formally introduced by the OECD and further developed through the European SafetyNet Project [2], [6].

According to OECD, a Road Safety Performance Indicator is: "Any variable that is causally related to crashes or injuries and used to measure safety performance."

Unlike traditional accident statistics, RSPIs focus on factors contributing to crash occurrence and severity rather than solely measuring accident consequences [2], [30].

The primary objectives of RSPIs include:

- Monitoring safety conditions.
- Identifying emerging risks.
- Evaluating intervention effectiveness.
- Supporting benchmarking.
- Facilitating policy development.
- Improving resource allocation [2], [29].

Thus, RSPIs serve as leading indicators, whereas accident statistics serve as lagging indicators [29], [30].

C. Importance of Road Safety Performance Indicators

Road Safety Performance Indicators offer several advantages over traditional safety measures.

1) Proactive Safety Assessment

Accident statistics only become available after crashes occur. In contrast, RSPIs identify safety problems before accidents happen, enabling preventive action [2], [29].

2) Continuous Monitoring

Many safety indicators can be measured continuously through surveys, ITS systems, enforcement records, and traffic monitoring technologies [36], [40].

3) Evaluation of Countermeasures

RSPIs enable transportation agencies to evaluate the effectiveness of interventions such as:

- Speed enforcement.
- Helmet campaigns.
- Road safety audits.
- Infrastructure improvements [15], [31], [34].

4) International Benchmarking

Many countries utilize RSPIs to compare safety performance across regions and transportation networks [2], [6].

5) Support for Sustainable Development Goals

RSPIs assist governments in monitoring progress toward road safety targets established under the United Nations Sustainable Development Goals (SDGs) [1], [6].

D. Classification of Road Safety Performance Indicators

Road Safety Performance Indicators can be classified into four major categories:

1) Exposure Indicators
2) Outcome Indicators
3) Intermediate Indicators
4) System Indicators

This classification has been widely adopted by OECD, IRTAD, and European road safety programs [2], [29], [30].

E. Exposure Indicators

Exposure indicators quantify the extent to which road users are exposed to transportation risks.
Exposure does not directly measure safety performance but provides essential context for interpreting accident statistics [2].
Common exposure indicators include:

1) Traffic Volume

Annual Average Daily Traffic (AADT) represents the average number of vehicles using a roadway daily.
Traffic volume is one of the most important variables in accident prediction models [3], [16].

2) Vehicle Kilometres Travelled (VKT)

VKT measures the total distance travelled by vehicles and is widely used for calculating accident rates [2].

3) Population Exposure

Road fatalities per 100,000 population represent a common international safety metric [1], [2].

4) Vehicle Ownership

Motorization levels significantly influence road safety outcomes.
Vehicle ownership is frequently expressed as:
Vehicles per 1000 PopulationVehicles\ per\ 1000\ Population Vehicles per 1000 Population
and serves as an important exposure indicator [56].

F. Outcome Indicators

Outcome indicators measure the final consequences of transportation system performance.
These indicators represent traditional safety measures and remain essential for evaluating overall road safety performance [1], [2].

1) Fatality Rate

The most widely used road safety indicator worldwide is:
Fatalities per 100,000 PopulationFatalities\ per\ 100,000\ PopulationFatalities per 100,000 Population
which facilitates international comparisons [1].

2) Accident Rate

Accident rate is often expressed as:
Accidents per Million Vehicle KilometresAccidents\ per\ Million\ Vehicle\ KilometresAccidents per Million Vehicle Kilometres
and accounts for traffic exposure [22].

3) Injury Rate

Injury rates provide information regarding crash severity and public health impacts [56].

4) Severity Index

Severity Index incorporates weighted accident consequences and is widely used for black spot identification [25], [56].

G. Intermediate Safety Indicators

Intermediate indicators measure conditions directly influencing accident occurrence.
These indicators are particularly valuable because they provide early warning signals before accidents increase [29], [30].

1) Speed Compliance

Speeding is one of the most significant contributors to road traffic crashes worldwide [15].
Research indicates that small increases in average speed can result in substantial increases in accident frequency and severity [15].
Speed compliance can be measured as:
Speed Compliance=Vehicles within Speed LimitTotal Vehicles×100Speed\ Compliance = \frac{Vehicles\ within\ Speed\ Limit}{Total\ Vehicles} \times 100Speed Compliance=Total VehiclesVehicles within Speed Limit×100

2) Helmet Usage

Helmet use significantly reduces the risk of fatal head injuries among motorcyclists [1].
Helmet compliance rates are widely used as road safety indicators in developing countries [56].

3) Seatbelt Usage

Seatbelt usage remains one of the most effective safety measures for vehicle occupants [1], [15].
Compliance levels provide valuable information regarding road user behaviour.

4) Driver Behaviour Indicators

Examples include:

- Mobile phone usage while driving.
- Aggressive driving.
- Fatigue.
- Alcohol impairment [11], [13].

Driver behaviour indicators are increasingly monitored through intelligent transportation technologies [41].

H. Infrastructure Safety Indicators

Roadway infrastructure significantly influences accident occurrence and severity [8], [27].
Important infrastructure indicators include:

1) Road Geometry

Indicators include:

- Curve radius.
- Gradient.
- Sight distance.
- Lane width [27].

2) Pavement Condition

Poor pavement condition can increase accident risk through reduced skid resistance and vehicle instability.
Pavement Condition Index (PCI) has emerged as an important infrastructure performance indicator [60].

3) Roadside Safety

Examples include:

- Guardrails.
- Crash barriers.
- Clear zones.

Roadside safety indicators are frequently assessed through Road Safety Audits [31].

4) Traffic Control Devices

Performance indicators include:

- Sign visibility.
- Pavement markings.
- Signal performance [34].

I. Vehicle Safety Indicators

Vehicle characteristics significantly influence crash occurrence and severity [38], [50].

Examples include:

1) Vehicle Age

Older vehicles generally exhibit lower safety performance.

2) Safety Equipment Availability

Examples include:

- Airbags.
- Anti-lock Braking Systems (ABS).
- Electronic Stability Control (ESC).

3) Vehicle Inspection Compliance

Regular inspections improve vehicle safety and reduce mechanical failures [57].

J. System Indicators

System indicators evaluate institutional and organizational performance.

These indicators are essential for assessing safety management effectiveness [2], [29].

Examples include:

1) Enforcement Indicators

- Number of traffic violations detected.
- Speed enforcement coverage.
- Drunk-driving enforcement [15].

2) Emergency Response Indicators

Examples include:

- Average response time.
- Ambulance availability.
- Trauma care accessibility [57], [59].

3) Road Safety Audit Indicators

Examples include:

- Number of audits conducted.
- Percentage of recommendations implemented [31], [34].

4) Black Spot Improvement Indicators

Examples include:

- Number of black spots treated.
- Accident reduction effectiveness [22], [57].

K. International Road Safety Performance Indicator Frameworks

Several organizations have developed RSPI frameworks.

1) OECD Framework

The OECD framework categorizes indicators into:

- Exposure.
- Intermediate outcomes.
- Final outcomes [2].

2) European SafetyNet Framework

The SafetyNet Project identified key performance indicators related to:

- Alcohol.
- Speed.
- Protective systems.
- Roads.
- Vehicles.
- Trauma management [30].

3) WHO Framework

WHO promotes indicator-based monitoring aligned with global road safety targets [1].

L. Challenges in RSPI Development

Despite their advantages, several challenges remain.

1) Data Availability

Reliable safety indicator data are often unavailable in developing countries [56].

2) Data Standardization

Different agencies utilize different methodologies [2].

3) Indicator Selection

Selecting relevant indicators remains challenging [29].

4) Weight Assignment

Determining appropriate weights for composite indices requires further research [2], [30].

M. Integration of RSPIs with Prediction Modelling

One of the major limitations of existing RSPI frameworks is the absence of predictive capabilities.

The doctoral research conducted by Malviya addresses this gap by integrating Road Safety Performance Indicators with accident prediction models [60].

The proposed framework utilizes:

1) Exposure Indicators

- Traffic volume.
- Vehicle kilometres travelled.

2) Outcome Indicators

- Accident rates.
- Fatality rates.

3) Intermediate Indicators

- Speed compliance.
- Helmet usage.

4) System Indicators

- Enforcement effectiveness.
- Road Safety Audits.

These variables serve as inputs to accident prediction models, thereby enabling proactive safety assessment [60].

N. Proposed Road Safety Performance Indicator Framework

The proposed framework consists of five stages:

1) Data Collection.
2) Indicator Development.
3) Prediction Modelling.
4) Risk Assessment.
5) Decision Support.

The framework integrates accident databases, traffic surveys, GIS systems, enforcement records, and intelligent transportation technologies to support evidence-based safety management [36], [41], [60].

O. Future Directions

Future Road Safety Performance Indicator research should focus on:

- Dynamic indicators.
- Real-time monitoring.
- Machine learning integration.
- Connected vehicle data.
- Digital twins.
- Explainable AI [40], [41], [49].

These advancements will facilitate the transition from reactive safety assessment to predictive road safety management [53], [60].

P. Summary

Road Safety Performance Indicators represent a critical advancement in modern road safety management. Unlike traditional accident statistics, RSPIs provide proactive measures capable of identifying safety deficiencies before crashes occur [2], [29], [30]. The integration of exposure indicators, outcome indicators, intermediate indicators, and system indicators offers a comprehensive understanding of transportation safety performance. Furthermore, integration with prediction modelling, as proposed in the doctoral research framework, enhances the ability of transportation agencies to anticipate risks, prioritize interventions, and achieve sustainable improvements in road safety performance [60].

V. Accident Prediction Models for Road Safety Assessment

A. Introduction

Accident prediction modelling has emerged as one of the most important components of modern road safety management. Traditional road safety analyses rely heavily on historical crash data to identify hazardous locations and formulate corrective measures. Although these approaches provide valuable information regarding past accident trends, they often fail to predict future accident occurrences or identify emerging safety risks before crashes happen. Consequently, researchers and transportation agencies worldwide have increasingly adopted accident prediction models as proactive tools for highway safety assessment [3], [16], [17].

Accident prediction models establish mathematical relationships between accident occurrences and various explanatory variables such as traffic volume, road geometry, pavement condition, environmental factors, driver behaviour, and enforcement levels [16], [17], [18]. These models enable transportation planners and engineers to estimate crash frequencies under different conditions and evaluate the effectiveness of potential safety interventions [3], [16].

The Highway Safety Manual (HSM) developed by AASHTO introduced the concept of Safety Performance Functions (SPFs), which are mathematical equations used to estimate expected crash frequencies for specific roadway types [3]. Since then, significant advancements in statistical modelling, machine learning, artificial intelligence, and data analytics have transformed accident prediction methodologies [20], [41], [43].

The doctoral research conducted by Malviya (2026) emphasizes the integration of Road Safety Performance Indicators (RSPIs) with accident prediction modelling [60]. The study demonstrates that accident risk is influenced by multiple interacting variables and highlights the need for comprehensive predictive frameworks capable of supporting proactive road safety management [60].

B. Importance of Accident Prediction Models

Accident prediction models serve several important functions in transportation engineering and safety management.

1) Proactive Safety Management

Traditional safety assessments are reactive because they depend upon accident occurrence. Prediction models enable agencies to identify potential hazards before crashes occur, facilitating proactive interventions and reducing societal costs associated with accidents [3], [6], [16].

2) Resource Allocation

Road authorities often face budget constraints and must prioritize safety investments. Prediction models help identify locations with the highest accident potential, allowing efficient allocation of resources and maximizing safety benefits [4], [22], [23].

3) Evaluation of Safety Measures

Accident prediction models enable engineers to assess the effectiveness of proposed interventions such as geometric improvements, traffic calming measures, speed management systems, signal installations, and road safety audits [3], [16], [34].

4) Policy Development

Governments increasingly rely on predictive analytics to develop evidence-based road safety policies aligned with national safety objectives and Sustainable Development Goals (SDGs) [1], [2], [7].

C. Factors Influencing Accident Occurrence

Road accidents result from complex interactions among multiple factors. Most prediction models incorporate variables from four primary categories [16], [17], [18].

1) Human Factors

Human behaviour remains the dominant contributor to road traffic accidents. Major behavioural variables include speeding, drunk driving, driver fatigue, mobile phone use, aggressive driving, seatbelt non-compliance, and helmet non-compliance [11], [12], [13], [15].

Research consistently indicates that over-speeding contributes significantly to road crashes in both developed and developing countries [15], [56].

2) Vehicle Factors

Vehicle-related variables include vehicle age, vehicle type, brake condition, tire condition, maintenance status, and safety features [1], [38], [49]. Heavy commercial vehicles often exhibit higher crash severity due to greater kinetic energy during collisions [38], [50].

3) Road Infrastructure Factors

Infrastructure-related variables commonly included in accident prediction models include lane width, shoulder width, horizontal curvature, vertical gradients, intersection density, median type, roadside hazards, and pavement condition [3], [8], [27].

The condition of roadway infrastructure directly influences driver behaviour and accident risk [8], [31].

4) Environmental Factors

Environmental variables include rainfall, fog, temperature, visibility, traffic density, and lighting conditions [29], [30], [47]. Adverse weather conditions significantly increase accident probability through reduced visibility and pavement friction [29].

D. *Statistical Approaches to Accident Prediction*

The earliest accident prediction models were based on classical statistical methods. These models remain widely used due to their interpretability and relatively simple implementation [16], [17].

1) *Linear Regression Models*

Linear regression models represent the simplest accident prediction approach and were among the first techniques used in transportation safety analysis [17].

General form:

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + ... + \beta_nX_n + \varepsilon$$

Where:

Y = Number of accidents
$X_1...X_n$ = Independent variables
β = Regression coefficients
ε = Error term

Advantages include ease of interpretation and implementation [17]. However, these models assume linear relationships and often perform poorly when applied to count-based accident data [16].

E. *Poisson Regression Models*

Poisson regression became one of the most widely used techniques for accident frequency modelling because accident occurrences are discrete count events [19].

The model assumes accident counts follow a Poisson distribution:

$$P(Y=y)=\frac{e^{-\lambda}\lambda^y}{y!}$$

where λ represents the expected accident frequency [19].

Advantages include:

- Appropriate for count data.
- Statistically robust.
- Easy interpretation.

However, Poisson models assume that the mean and variance are equal, an assumption frequently violated in accident datasets [16], [19].

F. *Negative Binomial Models*

Accident data often exhibit overdispersion, meaning that variance exceeds the mean. Negative Binomial (NB) models address this issue by introducing a dispersion parameter [16], [17].

Advantages include:

- Better handling of overdispersion.
- Improved predictive accuracy.
- Wide acceptance in transportation safety research [16].

Numerous studies have demonstrated that NB models outperform Poisson models for accident frequency prediction [16], [17], [19].

The Highway Safety Manual recommends Negative Binomial Safety Performance Functions for many roadway applications [3].

G. *Zero-Inflated Models*

Many roadway segments experience zero crashes during observation periods. Traditional count models often struggle with excessive zero values [19].

To address this issue, researchers developed:

- Zero Inflated Poisson (ZIP)
- Zero Inflated Negative Binomial (ZINB)

These models assume two separate processes:

- Whether crashes occur.
- How many crashes occur.

Applications include rural highways, low-volume roads, and newly constructed facilities [19].

H. *Safety Performance Functions (SPFs)*

Safety Performance Functions form the foundation of modern highway safety analysis [3].

SPFs estimate expected crash frequencies using traffic volume and roadway characteristics. A general SPF form is:

$$N = AADT^\beta \times e^{\beta_0}$$

where:

N = Expected crashes
AADT = Annual Average Daily Traffic
β = Calibration parameter

SPFs are extensively used for road safety audits, black spot identification, highway improvement programs, and economic evaluations [3], [23].

I. *Bayesian Accident Prediction Models*

Bayesian approaches have gained considerable attention in recent years because they combine historical data with prior knowledge and expert judgement [25].

Benefits include:

- Improved prediction accuracy.
- Better uncertainty quantification.
- Applicability to sparse datasets [23], [25].

Bayesian methods are particularly important in Empirical Bayes (EB) approaches used for black spot analysis [23], [25].

J. *Artificial Neural Networks (ANNs)*

Artificial Neural Networks represent one of the earliest machine learning approaches applied to road safety analysis [41].

ANNs learn complex nonlinear relationships between accident occurrences and explanatory variables.

Typical inputs include:

- Traffic volume.
- Road geometry.
- Weather conditions.
- Driver behaviour indicators.

Outputs include:

- Accident frequency.
- Accident severity.
- Risk levels.

Advantages include strong nonlinear modelling capabilities and high predictive accuracy [41], [43].

However, ANNs are often criticized for their "black-box" nature and limited interpretability [45].

K. *Machine Learning Approaches*

Recent advances in computational power have accelerated machine learning applications in road safety [41].

1) *Random Forest*

Random Forest combines multiple decision trees and is widely used for crash prediction and severity analysis [43].

Advantages include:
- High prediction accuracy.
- Robustness.
- Variable importance ranking [43].

2) Support Vector Machines (SVM)

SVMs are effective for:
- Accident classification.
- Severity prediction.

Risk categorization [41].

3) Gradient Boosting Models

Examples include:
- XGBoost.
- LightGBM.
- CatBoost.

These algorithms frequently outperform traditional statistical models in accident prediction studies [41], [43].

L. Deep Learning Applications

Deep learning techniques are increasingly used for:
- Crash severity prediction.
- Driver behaviour monitoring.
- Traffic video analysis.
- Automated incident detection [20].

1) Convolutional Neural Networks (CNN)

CNNs are applied to:
- Road image analysis.
- Pavement defect detection.
- Traffic surveillance systems [20].

2) Recurrent Neural Networks (RNN)

RNNs are widely used for:
- Traffic flow prediction.
- Time-series accident forecasting [20].

3) Long Short-Term Memory Networks (LSTM)

LSTM models are particularly effective for:
- Temporal accident prediction.
- Weather-related safety forecasting [20].

Several studies have demonstrated superior performance of LSTM-based models compared with conventional approaches [20], [41].

M. GIS-Based Accident Prediction

Geographic Information Systems (GIS) have become essential tools for accident prediction and safety management [46], [47], [48].

GIS enables:
- Spatial accident analysis.
- Black spot identification.
- Network risk assessment.
- Visualization of safety indicators.

Integration of GIS with machine learning has significantly enhanced accident prediction capabilities [44], [46], [48].

N. Integration of Road Safety Performance Indicators and Prediction Models

One of the major limitations of existing accident prediction studies is the separation between performance indicators and predictive modelling [29], [30].

The doctoral research by Malviya proposes integrating:

1) Exposure Indicators
- Traffic volume.
- Vehicle kilometres travelled.

2) Outcome Indicators
- Fatalities.
- Injuries.
- Accident rates.

3) Intermediate Indicators
- Speed compliance.
- Helmet use.
- Seatbelt compliance.

4) System Indicators
- Enforcement levels.
- Emergency response times.
- Road safety audits.

These indicators serve as inputs to accident prediction models, creating a comprehensive and proactive safety assessment framework [60].

The proposed framework improves upon traditional methods by:
- Capturing multidimensional safety conditions.
- Enabling early risk identification.
- Supporting policy evaluation.
- Facilitating continuous monitoring [60].

O. Challenges in Accident Prediction Modelling

Despite significant progress, several challenges remain.

1) Data Quality Issues

Problems include:
- Missing data.
- Underreporting.
- Inconsistent reporting practices [56], [59].

2) Model Transferability

Models developed in one region may not perform effectively in another because of differences in traffic characteristics and road environments [16], [45].

3) Dynamic Risk Factors

Driver behaviour and traffic conditions continuously evolve, making long-term prediction difficult [11], [29].

4) Interpretability

Many machine learning models operate as black boxes and provide limited explanation of results [41], [45].

5) Integration Challenges

Combining infrastructure, behavioural, environmental, and institutional variables remains a significant research challenge [29], [30], [60].

P. Future Directions

Future research should focus on:
1) Explainable Artificial Intelligence (XAI) [41], [45].
2) Real-time accident prediction systems [36], [40].
3) Integration of Pavement Condition Index (PCI) with safety indicators [60].
4) Connected vehicle data analytics [38], [49].
5) Digital twins for highway safety [40].
6) Dynamic Road Safety Performance Indicators [29], [30].
7) Multi-source data fusion [41].
8) Autonomous vehicle safety prediction [50], [52].
9) Big-data-driven road safety management [41].

10) AI-enabled decision support systems [36], [40].

Q. Summary

Accident prediction models have evolved from simple linear regression approaches to sophisticated machine learning and artificial intelligence systems [16], [17], [41]. While statistical models such as Poisson and Negative Binomial regressions remain widely used [16], [19], emerging technologies offer substantial opportunities for improving predictive accuracy [20], [41], [43]. The integration of Road Safety Performance Indicators with prediction modelling, as proposed in the doctoral research framework, represents a significant advancement toward proactive road safety management [60]. Such integrated systems can support transportation agencies in identifying risks, prioritizing interventions, and ultimately reducing accident frequencies and fatalities [29], [30], [60].

VI. Black Spot Identification and Road Safety Audit

A. Introduction

Road traffic accidents are rarely distributed uniformly across a highway network. Instead, crashes tend to concentrate at specific locations known as black spots, hazardous locations, accident-prone zones, or high-risk sites [22], [23]. Identification and treatment of such locations have become one of the most cost-effective strategies for improving road safety worldwide [25], [26].

Black spot improvement programs have been adopted extensively by transportation agencies because targeted interventions at high-risk locations can substantially reduce accident frequency and severity. Research indicates that systematic identification and treatment of black spots can reduce crashes by 20–60%, depending upon site conditions and intervention measures [24], [25].

The Government of India, through the Ministry of Road Transport and Highways (MoRTH) and National Highways Authority of India (NHAI), has prioritized black spot identification as a major component of national road safety strategies [56], [57]. Similarly, international agencies such as FHWA, PIARC, Transport Canada, and the European Commission have established comprehensive methodologies for identifying and managing hazardous road locations [7], [8], [34].

The doctoral research entitled *Development of a Framework for Road Safety Performance Indicators using Prediction Modelling* recognizes black spot analysis as a critical component of proactive road safety management [60]. The study conducted in Madhya Pradesh identified several high-risk highway locations through accident trend analysis and integrated these findings within a broader Road Safety Performance Indicator framework [60].

B. Concept of Black Spots

A black spot refers to a location where accident occurrence is significantly higher than expected relative to surrounding road sections [22], [23].

Different organizations define black spots differently.

1) MoRTH Definition

According to MoRTH, a black spot is a road location where either five road accidents involving fatalities and grievous injuries have occurred during the previous three years, or ten fatalities have occurred during the same period within approximately 500 m [56].

2) International Definition

Many countries define black spots based on:

- Crash frequency
- Crash severity
- Crash rate
- Economic losses
- Potential safety improvement [22], [25]

The objective of black spot identification is to determine locations where targeted interventions can achieve the maximum reduction in crash risk [22], [23].

C. Causes of Black Spots

Black spots generally result from a combination of roadway, operational, environmental, and behavioural factors [26], [27].

1) Geometric Deficiencies

Examples include:

- Sharp horizontal curves
- Inadequate sight distance
- Sudden gradient changes
- Narrow bridges
- Improper intersection design

Poor geometric design increases driver workload and reduces reaction time, thereby increasing crash probability [3], [27].

2) Traffic Operational Problems

Operational issues include:

- Traffic congestion
- Speed differentials
- Mixed traffic conditions
- Inadequate signal timing
- Poor traffic control

Such conditions often increase traffic conflicts and accident risks [28], [29].

3) Infrastructure Deficiencies

Common deficiencies include:

- Missing road signs
- Inadequate pavement markings
- Damaged safety barriers
- Poor lighting
- Shoulder deterioration

Infrastructure shortcomings significantly contribute to accident occurrence and severity [8], [31], [34].

4) Human Behavioural Factors

Driver-related factors include:

- Speeding
- Wrong-side driving
- Distracted driving
- Alcohol impairment
- Fatigue

Human factors frequently interact with infrastructure deficiencies to create hazardous situations [11], [12], [15].

D. Black Spot Identification Methods

Numerous techniques have been developed to identify accident-prone locations [22], [23], [26].

These methods can be broadly categorized into:

1) Frequency-based methods.
2) Rate-based methods.
3) Severity-based methods.
4) Statistical methods.
5) Predictive methods [22], [25].

E. Accident Frequency Method

The simplest approach uses the total number of accidents occurring at a location [22].

Formula

Black Spot Index = Total Number of Accidents

Locations with the highest accident frequencies are prioritized.

Advantages

- Easy implementation.
- Minimal data requirements.
- Suitable for preliminary screening [22].

Limitations

- Ignores traffic exposure.
- Does not consider accident severity.
- May overestimate risk on high-volume roads [23], [25].

F. Accident Rate Method

To overcome exposure limitations, accident rates are frequently used [22].

Formula

[Accident\ Rate = \frac{Number\ of\ Accidents \times 10^6}{AADT \times Length \times 365}]

Where:

AADT = Annual Average Daily Traffic

Advantages

- Accounts for traffic volume.
- Enables comparison across locations [22], [23].

Limitations

- Sensitive to low traffic volumes.
- May overestimate risk on lightly trafficked roads [25].

G. Severity Index Method

Not all accidents have equal consequences. Severity-weighted methods assign greater importance to fatal and serious injury crashes [25], [26].

Typical Severity Weights

Accident Type	Weight
Fatal Crash	10
Serious Injury	5
Minor Injury	3
Property Damage Only	1

Severity Index

[SI = \sum (Weight \times Number\ of\ Crashes)]

This approach prioritizes locations with severe safety consequences [25].

H. Weighted Severity Index (WSI)

The Weighted Severity Index is widely used in India for identifying hazardous locations [56].

Formula

[WSI = (41 \times Fatalities) + (4 \times Serious\ Injuries) + (1 \times Minor\ Injuries)]

The weighting factors reflect societal and economic losses associated with crashes [56].

Locations with higher WSI values are prioritized for improvement [56], [57].

I. Accident Density Method

Accident density measures crash concentration over roadway length [22].

Formula

[Accident\ Density = \frac{Number\ of\ Crashes}{Road\ Length}]

Advantages include:

- Useful for corridor analysis.
- Suitable for network-level assessments [26].

However, traffic exposure remains unaccounted for [22].

J. Empirical Bayes Method

The Empirical Bayes (EB) method is currently regarded as one of the most reliable approaches for black spot identification [23], [25].

Concept

EB combines:

- Observed crash data.
- Predicted crash frequencies.
- Historical trends.

The method minimizes bias resulting from:

- Random fluctuations.
- Regression-to-the-mean effects [23].

Advantages

- Improved accuracy.
- Statistically robust.
- Recommended by FHWA and the Highway Safety Manual [3], [7], [23].

K. Network Screening Techniques

Network screening involves systematic examination of entire road networks [22].

The process typically includes:

1) Data collection.
2) Crash analysis.
3) Ranking locations.
4) Detailed investigation.
5) Countermeasure selection.
6) Monitoring and evaluation [22], [23].

Network screening enables transportation agencies to prioritize investments effectively [7], [22].

L. GIS-Based Black Spot Analysis

Geographic Information Systems (GIS) have revolutionized accident analysis and black spot identification [46], [47], [48].

GIS enables:

- Spatial visualization.
- Cluster detection.

- Risk mapping.
- Network analysis [46].

Applications

1) Kernel Density Estimation (KDE)

KDE identifies accident hotspots by estimating crash densities spatially [46].

2) Spatial Autocorrelation

Measures clustering tendencies through statistical indicators such as Moran's I and Getis-Ord Gi* [47].

3) Heat Maps

Visual representation of accident concentration across road networks [46], [48].

GIS-based techniques provide powerful tools for understanding accident patterns and prioritizing interventions [47], [48].

M. Artificial Intelligence in Black Spot Identification

Recent studies increasingly employ machine learning and artificial intelligence for black spot analysis [41], [43].

1) Machine Learning

- Random Forest.
- Support Vector Machines.
- XGBoost [41], [43].

2) Deep Learning

- Convolutional Neural Networks.
- Graph Neural Networks [20], [41].

AI models can identify complex relationships among:

- Road geometry.
- Traffic volume.
- Driver behaviour.
- Environmental conditions [41], [45].

These methods often outperform traditional statistical approaches [43].

N. Road Safety Audit (RSA)

Road Safety Audit is a formal safety examination of transportation projects and has become a globally accepted safety management practice [31], [33], [34].

The concept originated in the United Kingdom during the 1980s and has since been adopted worldwide [35].

RSA aims to identify potential safety issues before accidents occur. Unlike accident investigations, RSA is proactive in nature [31], [34].

O. Objectives of Road Safety Audit

The primary objectives include:

- Identifying safety deficiencies.
- Reducing accident risk.
- Improving road user safety.
- Enhancing project quality.
- Reducing future maintenance costs [31], [34].

RSA benefits all road users, including:

- Motorists.
- Pedestrians.
- Cyclists.
- Public transport users.
- Vulnerable road users [31].

P. Stages of Road Safety Audit

Road Safety Audits can be conducted at multiple project stages [31], [33].

- Feasibility Stage.
- Preliminary Design Stage.
- Detailed Design Stage.
- Construction Stage.
- Pre-Opening Stage.
- Existing Road Audit [31].

Each stage provides opportunities for identifying and correcting safety concerns before accidents occur [34].

Q. Road Safety Audit Process

The RSA process generally includes:

1) Project selection.
2) Audit team formation.
3) Data collection.
4) Field inspection.
5) Issue identification.
6) Preparation of audit report.
7) Response and implementation.
8) Follow-up review [31], [34].

R. Road Safety Audit Checklist

Typical audit considerations include:

1) Road Geometry

- Curvature.
- Gradients.
- Sight distance.

2) Traffic Control

- Signage.
- Markings.
- Signals.

3) Roadside Safety

- Barriers.
- Clear zones.
- Utility poles.

4) Vulnerable Road Users

- Pedestrian crossings.
- Bicycle facilities.

5) Lighting

- Night-time visibility.
- Intersection illumination [31], [34].

S. International Practices

The FHWA Road Safety Audit Program has demonstrated significant safety benefits across the United States [34].

Australia employs RSA extensively under the Austroads framework [33].

The United Kingdom remains a pioneer in audit implementation and mandates Road Safety Audits for many highway projects [35].

T. Indian Practices

In India, Road Safety Audits are governed by:

- IRC:SP:88 Manual on Road Safety Audit [31].
- IRC:SP:55 Road Safety in Road Construction Zones [32].
- MoRTH Guidelines [56].

- NHAI Road Safety Policies [57].

NHAI mandates safety audits for:

- New highway projects.
- Existing national highways.
- Black spot treatment programs [57].

U. Integration with Road Safety Performance Indicators

Road Safety Audits contribute significantly to Road Safety Performance Indicators [29], [30].

Audit findings can be translated into measurable indicators such as:

Indicator	Measurement
Signage Compliance	% Adequate Signs
Pavement Marking Quality	Condition Rating
Roadside Hazard Score	Safety Rating
Lighting Adequacy	Lux Level Compliance
RSA Compliance Score	% Recommendations Implemented

These indicators support continuous monitoring and benchmarking [29], [30].

V. Integration with the PhD Framework

The doctoral research framework developed for Madhya Pradesh highways integrates:

1) *Exposure Indicators*
   - Traffic volume.
   - Road length.
2) *Outcome Indicators*
   - Accident frequency.
   - Fatality rates.
3) *Intermediate Indicators*
   - Speed compliance.
   - Driver awareness.
4) *System Indicators*
   - Enforcement efficiency.
   - RSA implementation [60].

Black spot identification forms a critical component of this framework [60].

The methodology involves:

- Accident database development.
- Spatial analysis of crashes.
- Identification of hazardous locations.
- Development of accident prediction models.
- Integration into Road Safety Performance Indicators [60].

The framework allows authorities to prioritize interventions scientifically rather than relying solely on historical accident counts.

W. Future Directions

Future black spot management should focus on:

- Smart highways [36], [40].
- AI-based monitoring [41].
- Connected vehicle data [38], [49].
- Drone-based inspections.
- Digital twins [40].
- Dynamic black spot identification using real-time risk prediction [41], [53].

X. Summary

Black spot identification and Road Safety Audits represent essential components of modern road safety management [22], [31], [34]. While traditional methods based on accident frequency remain widely used, advanced approaches such as Empirical Bayes analysis, GIS-based spatial modelling, machine learning, and AI-driven risk assessment offer significant improvements in accuracy and effectiveness [23], [41], [46]. Integration of black spot analysis with Road Safety Performance Indicators, as proposed in the Madhya Pradesh framework, provides a comprehensive mechanism for proactive safety management [29], [30], [60]. By combining accident prediction, infrastructure assessment, behavioural indicators, and safety audits, transportation agencies can move from reactive accident response toward evidence-based prevention strategies [3], [7], [60].

VII. INTELLIGENT TRANSPORTATION SYSTEMS (ITS), ARTIFICIAL INTELLIGENCE, AND EMERGING TECHNOLOGIES FOR ROAD SAFETY

A. Introduction

The rapid advancement of digital technologies has transformed transportation systems worldwide. Traditional road safety approaches, which primarily relied on infrastructure improvements, enforcement, and public awareness campaigns, are increasingly being supplemented by Intelligent Transportation Systems (ITS), Artificial Intelligence (AI), Internet of Things (IoT), Big Data Analytics, and Connected Vehicle Technologies [36], [38], [40].

Road traffic crashes are complex events influenced by interactions among drivers, vehicles, roads, and environmental conditions. Conventional safety interventions often suffer from delayed implementation because they depend upon historical crash records. Emerging technologies provide opportunities for real-time monitoring, prediction, and prevention of accidents before they occur [29], [30], [41].

The World Health Organization (WHO), World Bank, Organisation for Economic Co-operation and Development (OECD), and transportation agencies worldwide recognize intelligent transportation technologies as critical components of future road safety strategies [1], [2], [6], [59]. These technologies align with the Safe System Approach by reducing human errors, improving infrastructure performance, and enhancing emergency response capabilities [6], [53].

The doctoral research entitled *"Development of a Framework for Road Safety Performance Indicators using Prediction Modelling"* emphasizes the integration of modern technologies into road safety assessment [60]. The proposed framework advocates the use of intelligent monitoring systems, predictive analytics, and dynamic safety indicators to support proactive decision-making and continuous safety performance evaluation [60].

B. Intelligent Transportation Systems (ITS)

1) Definition

Intelligent Transportation Systems (ITS) refer to the application of information technology, communication systems, sensing technologies, and automation to improve transportation efficiency, safety, and sustainability [36], [38], [40].

ITS integrates:

- Traffic management systems
- Vehicle technologies
- Communication networks
- Data analytics
- Control systems

to create a smart transportation ecosystem [36], [40].

2) Components of ITS

The ITS architecture consists of four major components [36], [40]:

a) Data Collection Systems

These systems collect information from:

- Traffic sensors
- CCTV cameras
- GPS devices
- Vehicle detectors
- Mobile applications

providing continuous information regarding traffic operations [36], [40].

b) Communication Systems

Communication technologies include:

- Cellular networks
- Fiber optic networks
- Dedicated Short-Range Communication (DSRC)
- 5G communication

which facilitate rapid data exchange between vehicles and infrastructure [38], [49].

c) Data Processing Systems

Data processing involves:

- Traffic analysis
- Prediction algorithms
- Decision support systems

through advanced computing platforms [41], [44].

d) Information Dissemination Systems

These systems provide information through:

- Variable Message Signs (VMS)
- Mobile applications
- Navigation systems
- Traffic control centers

allowing users to make informed travel decisions [36], [40].

C. ITS Applications in Road Safety

1) Advanced Traffic Management Systems (ATMS)

ATMS utilizes real-time traffic information to optimize transportation operations [36].

- Applications include:
- Adaptive signal control
- Congestion management
- Incident detection
- Traffic forecasting

Benefits include reduced delays, lower crash risk, and improved traffic flow [36], [37].

2) Advanced Traveler Information Systems (ATIS)

ATIS provides real-time information regarding:

- Traffic conditions
- Weather
- Road closures
- Accident locations

This information enables safer route selection and better travel decisions [36], [40].

3) Incident Management Systems

Rapid identification and response to accidents significantly reduce crash severity and secondary accidents [34], [36].

ITS supports:

- Automatic incident detection
- Emergency vehicle dispatch
- Real-time traffic diversion

which improve network safety and operational efficiency [36].

4) Electronic Enforcement Systems

ITS-based enforcement includes:

a) Speed Cameras

Automatically detect speeding violations and improve speed compliance [15], [36].

b) Red-Light Cameras

Monitor intersection violations and reduce collision risks [36].

c) Automatic Number Plate Recognition (ANPR)

Supports enforcement and vehicle tracking applications [40]. These technologies have demonstrated significant improvements in road safety outcomes [15], [36].

D. Artificial Intelligence in Road Safety

Artificial Intelligence has become one of the most transformative technologies in transportation engineering [41], [43], [45].

AI enables:

- Pattern recognition
- Risk prediction
- Automated decision-making
- Real-time safety monitoring

thereby enhancing transportation safety management [41].

AI applications extend across all aspects of road safety management, including accident prediction, driver behaviour analysis, and infrastructure monitoring [20], [41], [43].

E. Machine Learning for Road Safety

Machine learning algorithms can identify complex nonlinear relationships that traditional statistical models often fail to capture [41], [45].

1) Random Forest

Random Forest algorithms have been successfully applied to:

- Crash prediction
- Severity analysis
- Black spot identification

due to their high predictive accuracy and robustness [43].

2) Support Vector Machines (SVM)

Applications include:

- Accident classification
- Risk categorization
- Driver behaviour analysis

with strong performance in transportation safety studies [41].

3) Gradient Boosting Algorithms

Examples include:

- XGBoost
- LightGBM
- CatBoost

These algorithms frequently outperform traditional regression models in accident prediction studies [41], [43].

F. Deep Learning Applications

Deep learning represents an advanced subset of machine learning capable of processing large-scale transportation datasets [20], [41].

1) Convolutional Neural Networks (CNN)

CNNs are extensively used for:

a) Road Condition Monitoring

Detection of:

- Potholes
- Cracks
- Surface defects

using image processing techniques [20].

b) Traffic Sign Recognition

Automated recognition of:

- Regulatory signs
- Warning signs
- Guide signs

to support advanced driver assistance systems [20], [50].

c) Driver Monitoring

Detection of:

- Fatigue
- Distraction
- Drowsiness

through computer vision applications [20], [41].

2) Recurrent Neural Networks (RNN)

RNNs analyze sequential traffic data and are used for:

- Traffic flow forecasting
- Accident prediction
- Weather-related risk assessment [20].

3) Long Short-Term Memory Networks (LSTM)

LSTM models effectively capture temporal relationships in transportation data and are particularly suitable for:

- Temporal accident prediction
- Traffic congestion forecasting
- Weather-related safety assessment [20], [41].

Numerous studies have demonstrated superior performance of LSTM models compared with traditional statistical approaches [20].

G. Computer Vision in Road Safety

Computer Vision technologies utilize cameras and AI algorithms to analyze transportation environments [20], [41].

Applications include:

1) Traffic Monitoring

Detection of:

- Congestion
- Queue lengths
- Vehicle counts

through automated video analytics [20].

2) Driver Behaviour Analysis

Identification of:

- Mobile phone use
- Seatbelt violations
- Fatigue

using image recognition technologies [20], [41].

3) Pedestrian Safety

Detection of:

- Pedestrian movements
- Crossing conflicts
- Vulnerable road users

to reduce pedestrian-related crashes [20].

H. Connected Vehicle Technology

Connected Vehicle (CV) technology enables communication among vehicles, infrastructure, and transportation systems [38], [49].

The objective is to improve situational awareness and reduce collision risk through real-time information exchange [38].

1) Vehicle-to-Vehicle Communication (V2V)

Vehicles exchange information regarding:

- Speed
- Position
- Direction
- Braking status

Applications include collision avoidance, lane change assistance, and emergency braking alerts [49].

2) Vehicle-to-Infrastructure Communication (V2I)

Vehicles communicate with roadway infrastructure such as:

- Traffic signals
- Roadside units
- Variable message signs

to improve operational efficiency and safety [38], [49].

3) Vehicle-to-Everything (V2X)

V2X integrates:

- V2V
- V2I
- Vehicle-to-Pedestrian (V2P)
- Vehicle-to-Network (V2N)

and forms the foundation of future intelligent transportation systems [38], [49].

I. Autonomous Vehicles and Road Safety

Autonomous Vehicles (AVs) represent one of the most significant technological developments in transportation history [50], [52].

AVs utilize:

- Sensors
- Cameras
- Radar
- LiDAR
- AI algorithms

to navigate without human intervention [50], [52].

Human error contributes to approximately 90% of road crashes; therefore, autonomous vehicles have the potential to significantly reduce crashes caused by distraction, fatigue, and impaired driving [1], [11], [50].

However, challenges remain regarding:

- System failures
- Cybersecurity risks

- Mixed traffic operations
- Ethical decision-making

which require further research before widespread implementation [38], [50].

J. Internet of Things (IoT) in Road Safety

IoT enables connectivity among devices, vehicles, infrastructure, and control systems [40].
Applications include:

1) Smart Road Infrastructure

Embedded sensors monitor:

- Traffic volume
- Pavement conditions
- Environmental factors

in real time [40].

2) Smart Vehicles

Vehicles continuously transmit:

- Speed data
- Location information
- Vehicle health status

which can support safety monitoring systems [38], [40].

3) Smart Traffic Management

IoT supports:

- Adaptive control systems
- Dynamic speed management
- Real-time monitoring

thereby improving operational safety [36], [40].

K. Big Data Analytics

Transportation systems generate enormous quantities of data from:

- GPS devices
- Smartphones
- Connected vehicles
- CCTV cameras
- Traffic sensors

which can be analyzed using Big Data techniques [41], [44].
Applications include:

1) Crash Pattern Analysis

Identification of:

- Risk trends
- Temporal patterns
- Spatial clusters

for proactive safety management [44], [46].

2) Predictive Safety Management

Real-time accident forecasting and risk prediction [41], [44].

3) Policy Evaluation

Assessment of intervention effectiveness using data-driven methodologies [7], [41].

L. Digital Twins for Road Safety

Digital Twins represent virtual replicas of transportation systems that continuously receive information from real-world assets [40].

- Applications include: Safety simulation, Infrastructure monitoring, Risk prediction, Scenario testing.
- Digital Twins are expected to become essential components of future smart highways and proactive safety management systems [40].

M. Integration with Road Safety Performance Indicators (RSPIs)

Emerging technologies significantly enhance Road Safety Performance Indicators by enabling real-time measurement of safety-related conditions [29], [30], [41].
Examples include:

- Dynamic Exposure Indicators: Real-time traffic volumes, Vehicle kilometres travelled.
- Dynamic Behavioural Indicators: Speed compliance, Seatbelt usage, Mobile phone use.
- Infrastructure Indicators: Pavement condition monitoring, Signage performance.
- System Indicators: Emergency response times, Enforcement effectiveness.

These technologies transform static safety indicators into continuously updated performance measures [29], [30], [41].

N. Integration with the PhD Framework

The doctoral research framework developed for Madhya Pradesh highways emphasizes proactive safety assessment through prediction modelling and Road Safety Performance Indicators [60].
Modern technologies strengthen this framework by providing:

- Real-time data collection through ITS and IoT devices [36], [40].
- Enhanced prediction models using AI and Machine Learning [41], [43].
- Continuous monitoring through connected infrastructure [38], [49].
- Dynamic risk assessment rather than static annual evaluations [29], [30], [60].

The integration of ITS and AI transforms the proposed RSPI framework from a periodic assessment tool into a dynamic road safety management system [60].

O. Summary

Intelligent Transportation Systems, Artificial Intelligence, Connected Vehicles, IoT, Big Data Analytics, and Digital Twins are transforming road safety management from reactive accident analysis to proactive risk prevention [36], [38], [41], [53]. These technologies enable continuous monitoring, real-time prediction, and evidence-based decision-making [41], [44]. The integration of these technologies with Road Safety Performance Indicators, as proposed in the doctoral framework developed for Madhya Pradesh highways, represents a significant advancement toward sustainable, data-driven road safety management [29], [30], [60].

VIII. Integration of Road Safety Performance Indicators with Prediction Modelling: Proposed Framework Based on the PhD Research

A. Introduction

The review of existing literature reveals that road safety assessment methodologies have traditionally relied on reactive indicators such as accident frequency, fatalities, and injury severity. While these measures provide valuable insights into historical safety performance, they fail to capture underlying risk conditions before crashes occur. Consequently, transportation agencies often implement interventions only after significant accidents have already taken place [3], [4], [16].

The doctoral research entitled *"Development of a Framework for Road Safety Performance Indicators using Prediction Modelling"* addresses this limitation by proposing a comprehensive framework that integrates Road Safety Performance Indicators (RSPIs) with predictive modelling techniques [60]. The framework seeks to establish a proactive approach to road safety management by combining exposure indicators, behavioural indicators, infrastructure indicators, enforcement indicators, and accident prediction models within a unified assessment system [29], [30], [60].

The framework was developed based on highway safety analysis conducted in Madhya Pradesh, India, covering accident data from 2016 to 2023 [60]. The findings demonstrate that road safety performance is influenced by multiple interconnected factors and therefore requires a multidimensional evaluation framework [29], [30], [53].

B. Need for an Integrated Framework

Existing road safety assessment approaches suffer from several limitations.

1) Reactive Nature

Traditional safety evaluations rely primarily on historical accident records [3], [4].
Problems include: Delayed intervention, Dependence on crash occurrence, Limited predictive capability [16], [17].

2) Fragmented Indicators

Many studies focus on individual indicators such as: Accident rates, Traffic volume, Speed compliance.
without considering their interrelationships [29], [30].

3) Lack of Predictive Capabilities

Current safety assessment systems often fail to estimate future accident risks and emerging hazards [16], [18], [41].

4) Limited Decision Support

Transportation agencies require tools that support: Prioritization of investments, Risk-based decision making, Performance benchmarking [7], [22], [23], These limitations highlight the necessity for a framework that integrates safety indicators with prediction models [29], [30], [60].

C. Conceptual Foundation of the Proposed Framework

The proposed framework is based on four major dimensions:

- Exposure Dimension-Measures the level of interaction between road users and transportation systems [2], [29].
- Outcome Dimension-Measures the consequences of road safety performance through fatalities, injuries, and accident rates [1], [2], [56].
- Intermediate Dimension- Measures behavioural and operational conditions affecting accident risk such as speed compliance and helmet use [11], [15], [29].
- System Dimension- Measures institutional and management performance through enforcement, emergency response, and Road Safety Audit implementation [31], [34], [57].

These dimensions collectively provide a comprehensive representation of road safety conditions [2], [29], [30].

D. Components of the Proposed Framework

1) Exposure Indicators

Exposure indicators quantify the extent of traffic activity and risk exposure [2], [29].
Examples include:

a) Traffic Volume

Annual Average Daily Traffic (AADT) is widely recognized as one of the most influential variables in accident prediction models [3], [16], [17].

b) Vehicle Kilometres Travelled (VKT)

Represents travel demand and exposure to crash risk [2].

c) Population Exposure

Number of road users exposed to transportation risks [1], [2].

d) Vehicle Ownership

Registered vehicles per 1,000 population as an indicator of motorization level [56].

Exposure indicators serve as foundational inputs to accident prediction models [16], [18], [29].

2) Outcome Indicators

Outcome indicators measure the consequences of accidents and safety performance [1], [2].
Examples include:

- Fatality Rate-Fatalities per 100,000 population [1], [56].
- Accident Rate-Accidents per million vehicle kilometres travelled [3], [22].
- Injury Rate-Number of injuries per crash [56].
- Severity Index- Weighted measure of accident consequences [25], [56].

Outcome indicators represent the ultimate measures of transportation safety performance [2], [30].

3) Intermediate Indicators

Intermediate indicators capture behavioural and operational conditions influencing crash occurrence [29], [30].

a) Speed Compliance

Percentage of vehicles operating within speed limits [15].

b) Helmet Usage

Percentage of motorcyclists wearing helmets [1], [56].

c) Seatbelt Usage

Seatbelt compliance rates among vehicle occupants [1], [15].

d) Driver Awareness

Knowledge of traffic regulations and safe driving practices [11], [13].

e) Alcohol Impairment

Incidence of drunk driving violations [1], [15].

These indicators provide early warning signals of deteriorating safety conditions [29], [30].

E. System Indicators

System indicators evaluate institutional and management performance [2], [30].

1) Road Safety Audits

Implementation and compliance levels of Road Safety Audit recommendations [31], [34].

2) Enforcement Effectiveness

Traffic law enforcement activities and compliance monitoring [15], [57].

3) Emergency Response Time

Average response duration following accidents [57], [59].

4) Black Spot Treatment

Percentage of hazardous locations improved through corrective measures [22], [23], [57].

5) Infrastructure Condition

Road quality and maintenance performance [8], [31].

System indicators reflect the effectiveness of safety management programs [29], [30].

F. Framework Architecture

The proposed framework follows a hierarchical structure similar to modern data-driven safety management systems [7], [29], [41].

1) Level 1: Data Collection

Sources include: Accident databases, Traffic surveys, Road inventory data, GIS databases, Enforcement records, User surveys [46], [47], [56].

2) Level 2: Indicator Development

Data are transformed into: Exposure indicators, Outcome indicators, Intermediate indicators, System indicators [29], [30].

3) Level 3: Prediction Modelling

Indicators serve as inputs to: Regression models, Machine learning models, Accident prediction systems [16], [17], [41], [43].

4) Level 4: Risk Assessment

Predicted accident risk levels are calculated using statistical and AI-based techniques [20], [41].

5) Level 5: Decision Support

Results support: Policy development, Infrastructure improvements, Resource allocation [7], [22], [60].

G. Accident Prediction Module

The prediction component forms the core of the framework [16], [18], [60].

Variables include:

- Traffic Characteristics – AADT, Traffic composition, Vehicle speeds [3], [16].
- Road Characteristics- Lane width, Shoulder width, Curvature, Gradient [27], [31].
- Behavioural Factors- Speeding, Helmet use, Seatbelt compliance [11], [15].
- Environmental Factors- Rainfall, Visibility, Lighting conditions [29], [47].

Regression analysis conducted in the doctoral research demonstrated significant relationships between these variables and accident occurrence [60].

H. Integration with Black Spot Analysis

The framework incorporates black spot identification through:

- Spatial Analysis- GIS-based accident mapping [46], [47], [48].
- Statistical Analysis- Severity and frequency assessment [22], [25].
- Prediction Models- Forecasting future accident concentrations [23], [41].

The integration of black spot analysis improves prioritization of safety interventions [22], [23], [60].

I. Integration with Intelligent Transportation Systems

The framework supports integration with ITS technologies [36], [38], [40].

Examples include:

- Real-Time Traffic Monitoring- Continuous exposure assessment [36].
- Speed Monitoring Systems- Behavioural indicator measurement [15], [36].
- Connected Vehicle Data- Near-miss analysis and safety monitoring [38], [49].
- Automated Enforcement- System performance evaluation [36], [57].

ITS enables dynamic updating of Road Safety Performance Indicators [29], [30], [40].

J. Proposed Road Safety Performance Index (RSPI)

To facilitate benchmarking, a composite index can be developed based on international safety performance assessment frameworks [2], [29], [30].

$$[RSPI = w\_1E + w\_2O + w\_3I + w\_4S]$$

Where:

E = Exposure Score
O = Outcome Score
I = Intermediate Indicator Score
S = System Indicator Score
w = Weighting Factors

The index provides a single measure of overall safety performance and supports comparison among regions and highway corridors [2], [29].

K. Benefits of the Proposed Framework

The proposed framework offers several advantages:

- Proactive Safety Management - Identifies risks before accidents occur [6], [29], [30].
- Comprehensive Assessment - Considers multiple dimensions of road safety [2], [29].
- Predictive Capability- Supports forecasting and planning through accident prediction models [16], [18], [41].
- Benchmarking - Facilitates comparison across regions and transportation agencies [2], [30].
- Decision Support - Assists policymakers and engineers in prioritizing interventions [7], [60].
- Adaptability - Applicable to different highway networks and transportation systems [29], [60].

L. Literature Gap Matrix

The literature review reveals several important research gaps in existing road safety studies [29], [30], [41], [53].

Research Area	Existing Studies	Gap Identified	Proposed Contribution
Accident Analysis	Historical crash focus [16], [22]	Reactive approach	Predictive framework [60]
RSPIs	Isolated indicators [29], [30]	Lack of integration	Unified framework [60]
Prediction Models	Statistical focus [16], [19]	Limited behavioural integration	Multi-dimensional modelling [60]

Black Spot Analysis	Frequency-based methods [22]	Limited predictive capability	GIS + Prediction Models [46], [60]
ITS Applications	Technology-focused studies [36], [38]	Weak safety integration	Dynamic RSPI monitoring [60]

M. Research Contributions

The doctoral research contributes to knowledge by:

1) Developing an integrated Road Safety Performance Indicator framework [60].
2) Integrating prediction modelling with safety assessment [60].
3) Applying the framework to highways in Madhya Pradesh [60].
4) Incorporating behavioural, infrastructural, and institutional indicators [29], [30], [60].
5) Supporting proactive road safety management [6], [60].
6) Providing a foundation for future AI-enabled safety systems [41], [60].

N. Future Framework Enhancement

Future improvements may include:

- Machine learning integration **[41], [43]**.
- Real-time indicator updating **[36], [40]**.
- Connected vehicle data utilization **[38], [49]**.
- Digital twins for safety management **[40]**.
- Explainable AI approaches **[41], [45]**.
- Smart highway technologies **[36], [40]**.
- Dynamic risk assessment systems **[53], [60]**.

O. Summary

The proposed Road Safety Performance Indicator framework integrates exposure, outcome, intermediate, and system indicators with accident prediction modelling to provide a comprehensive and proactive approach to road safety management [29], [30], [60]. Unlike traditional accident-based assessments, the framework enables early identification of risks, supports evidence-based decision-making, and facilitates continuous performance monitoring [3], [6], [60]. The integration of black spot analysis, intelligent transportation systems, behavioural indicators, and predictive analytics establishes a robust foundation for sustainable road safety management [22], [36], [41], [60]. The framework developed through the doctoral research has significant potential for application across highway networks in India and other developing countries [56], [60].

IX. Discussion

A. Overview of Key Findings

The comprehensive review of road safety literature reveals that road traffic crashes continue to be one of the most significant public health and transportation challenges worldwide. Despite considerable advances in infrastructure development, vehicle safety technologies, enforcement systems, and transportation planning, road traffic injuries remain a leading cause of death and disability, particularly in low- and middle-income countries [1], [2], [56].

The review demonstrates that road safety is a multidimensional issue influenced by interactions among human, vehicle, roadway, environmental, and institutional factors [11]–[15], [16], [29]. Traditional road safety assessment approaches have relied heavily on reactive indicators such as crash frequency, fatalities, and injury severity. Although these measures provide valuable information regarding historical safety performance, they often fail to identify underlying risk factors and emerging hazards before accidents occur [3], [4], [16].

Examples include:

The literature strongly supports a transition toward proactive safety management through the use of Road Safety Performance Indicators (RSPIs), predictive analytics, machine learning techniques, and Intelligent Transportation Systems (ITS) [29], [30], [41], [43]. Such approaches align with contemporary safety philosophies including Vision Zero, Sustainable Safety, and Safety-II, which emphasize prevention rather than reaction [6], [10], [53]–[55].

The doctoral research conducted in Madhya Pradesh further confirms that road safety performance cannot be adequately represented through accident statistics alone. Instead, a combination of exposure indicators, behavioural indicators, infrastructure indicators, enforcement indicators, and system performance measures is required to develop a holistic understanding of safety conditions [29], [30], [60].

B. Significance of Road Safety Performance Indicators

One of the most important findings of this review is the growing importance of Road Safety Performance Indicators in transportation safety management [2], [29], [30].

Historically, transportation agencies measured safety primarily through: Number of accidents, Fatality counts, Injury statistics, Economic losses [1], [2], [56].

While these indicators remain important, they represent lagging indicators because they only become available after crashes occur [29], [30].

Road Safety Performance Indicators provide a proactive alternative by measuring conditions that influence accident risk [2], [29].

Exposure Indicators	Intermediate Indicators	System Indicators
– Traffic volume. – Vehicle kilometres travelled. – Population exposure [2], [29].	– Speed compliance. – Helmet usage. – Seatbelt compliance. – Driver awareness [11], [15], [29].	– Enforcement effectiveness. – Emergency response performance. – Road Safety Audit implementation [31], [34], [57].

These indicators enable agencies to monitor safety performance continuously and identify deteriorating conditions before crashes increase [29], [30], [60].

C. *Evaluation of Accident Prediction Models*

The review highlights significant advancements in accident prediction methodologies [16]–[20].

Traditional statistical approaches such as: Linear Regression, Poisson Regression, Negative Binomial Models. continue to serve as the foundation for highway safety analysis [16], [17], [19].

However, recent developments in machine learning have introduced more sophisticated prediction capabilities [41], [43], [45].

Examples include:

- Artificial Neural Networks (ANN) - Useful for nonlinear accident prediction [41].
- Random Forest Models - Effective for identifying influential variables [43].
- Support Vector Machines - Suitable for classification problems [41].
- XGBoost Models - Provide high predictive accuracy [41], [43].
- Deep Learning Models - Support image-based and temporal accident prediction [20], [41].

Although machine learning models generally outperform traditional approaches in predictive accuracy, they often suffer from limited interpretability [41], [45]. Therefore, future research should focus on Explainable Artificial Intelligence (XAI) techniques capable of providing transparent decision support for transportation agencies [41], [45].

D. *Black Spot Management and Road Safety Audits*

The review confirms that black spot treatment remains one of the most cost-effective road safety interventions available [22], [23], [25].

Traditional identification techniques based on accident frequency continue to be widely used due to their simplicity [22], [26]. However, advanced approaches such as:Empirical Bayes Analysis, GIS-Based Spatial Analysis, Machine Learning Models offer superior accuracy and reliability [23], [25], [41], [46]–[48].

Similarly, Road Safety Audits have emerged as an essential component of proactive safety management [31], [34], [35].

The integration of Road Safety Audits with Road Safety Performance Indicators provides a powerful mechanism for: Identifying safety deficiencies, Quantifying infrastructure risks, Monitoring corrective actions [29], [30], [31].

The doctoral framework incorporates audit findings within the system indicator category, thereby facilitating continuous monitoring and performance evaluation [60].

E. *Role of Intelligent Transportation Systems*

The review demonstrates that Intelligent Transportation Systems are transforming transportation safety management [36], [38], [40].

ITS technologies enable:

Real-Time Monitoring	Continuous observation of traffic conditions [36].
Dynamic Enforcement	Automated speed and violation detection [15], [36].
Connected Vehicle Communication	Improved situational awareness [38], [49].
Predictive Analytics	Early identification of emerging risks [41], [44].

The integration of ITS within the proposed framework significantly enhances the effectiveness of Road Safety Performance Indicators by providing real-time data streams and supporting dynamic safety assessment [29], [30], [40], [60].

F. *Applicability to Indian Highways*

The review highlights the need for a comprehensive and proactive road safety management strategy in India. A standardized National Road Safety Performance Indicator (RSPI) Framework should be established to ensure consistent safety assessment across states and highway agencies. Efforts must be made to strengthen accident data collection through the development of a centralized and integrated crash database to improve data quality, accessibility, and evidence-based decision-making. Transportation agencies should transition from traditional reactive accident analysis to predictive safety management systems that identify risks before crashes occur. Road Safety Audits should be made mandatory for new highways, existing road networks, and urban transportation projects to enhance infrastructure safety. Furthermore, public awareness programs should focus on improving driver behaviour through campaigns promoting speed management, helmet use, seatbelt compliance, and the prevention of distracted driving. Increased investment in advanced enforcement technologies such as speed cameras, automated enforcement systems, and Automatic Number Plate Recognition (ANPR) systems is essential for improving compliance with traffic regulations. Finally, future highway projects should incorporate smart highway technologies, including Intelligent Transportation Systems (ITS), connected vehicle technologies, and real-time monitoring systems, to support safer, more efficient, and data-driven transportation networks [2], [7], [11], [13], [15], [16], [18], [29], [30], [31], [34], [36], [38], [40], [41], [49], [56], [57], [59], [60].

X. Policy Recommendations

Based on the review findings, the following policy recommendations are proposed.

A. Establish National RSPI Framework

India should develop a standardized Road Safety Performance Indicator framework applicable across states and highway agencies [2], [29], [30], [60].

B. Strengthen Accident Databases

A centralized and integrated accident database should be developed to improve data quality and accessibility [7], [56], [59].

C. Promote Predictive Safety Management

Transportation agencies should transition from reactive accident analysis to proactive risk prediction systems [16], [18], [41].

D. Expand Road Safety Audit Programs

Road Safety Audits should be mandatory for:

- New highways.
- Existing highways.
- Urban road projects [31], [34], [57].

E. Improve Driver Awareness

Education campaigns should focus on:

- Speed management.
- Helmet use.
- Seatbelt compliance.
- Distracted driving [11], [13], [15].

F. Enhance Enforcement Technologies

Investment in:

- Speed cameras.
- Automated enforcement.
- ANPR systems
- should be increased to improve compliance and reduce violations [15], [36], [40].

G. Adopt Smart Highway Technologies

Future highway projects should incorporate:

- ITS infrastructure.
- Connected vehicle technologies.
- Smart monitoring systems [36], [38], [40], [49].

XI. Future Research Directions

Future research in road safety should focus on developing advanced, proactive, and technology-driven safety management frameworks. Key priorities include the development of Explainable Artificial Intelligence (XAI) models to improve the transparency and interpretability of accident prediction systems, and the implementation of real-time safety monitoring through dynamic Road Safety Performance Indicators (RSPIs) supported by Intelligent Transportation Systems (ITS) and Internet of Things (IoT) technologies. Research should also explore the use of Connected Vehicle (V2V and V2I) communication data for crash prevention and risk assessment, along with the development of Digital Twin environments for highway safety simulation, scenario testing, and predictive analysis. Greater emphasis is needed on integrating Pavement Condition Index (PCI) into road safety assessment frameworks to better understand the relationship between infrastructure condition and crash risk. Additionally, studies should evaluate the safety implications of autonomous vehicles operating under mixed traffic conditions and investigate smart highway frameworks that combine ITS, Artificial Intelligence, and RSPI-based monitoring systems. The application of Safety-II and resilience engineering principles offers opportunities to enhance system adaptability and reliability, while big data analytics can support more accurate accident prediction and evidence-based decision-making. Ultimately, future road safety research should contribute to the development of sustainable road safety systems aligned with the United Nations Sustainable Development Goals (SDGs) and Vision Zero principles, supporting long-term reductions in road traffic fatalities and injuries [1], [6], [10], [29], [30], [36], [40], [41], [44], [45], [49], [50], [52]–[55], [60].

XII. Conclusions

Road safety remains one of the most critical challenges confronting transportation systems worldwide. Despite significant advancements in vehicle technology, roadway engineering, and traffic management practices, road traffic crashes continue to impose substantial social and economic costs [1], [2], [56].

This review examined the evolution of road safety research and highlighted the growing importance of proactive safety management approaches. The study demonstrated that traditional accident-based assessments are insufficient for modern transportation systems because they fail to identify emerging risks before crashes occur [3], [4], [29].

Road Safety Performance Indicators provide a robust mechanism for evaluating behavioural, infrastructural, operational, and institutional safety conditions. When integrated with accident prediction models, these indicators facilitate proactive risk assessment and evidence-based decision-making [16], [29], [30].

The review further demonstrated that advanced technologies such as machine learning, artificial intelligence, connected vehicles, Intelligent Transportation Systems, and digital twins offer significant opportunities for improving road safety management [36], [38], [41], [49].

The doctoral research entitled *"Development of a Framework for Road Safety Performance Indicators using Prediction Modelling"* contributes to the field by proposing an integrated framework that combines safety indicators, accident prediction models, black spot analysis, Road Safety Audits, and intelligent transportation technologies [60]. The framework enables continuous safety monitoring, supports prioritization of interventions, and provides a foundation for proactive safety management [29], [30], [60].

The proposed framework has substantial potential for application across Indian highways and other developing transportation networks. By integrating predictive analytics with performance-based assessment, transportation agencies can move beyond traditional reactive approaches and develop safer, smarter, and more sustainable road systems [6], [41], [53], [60].

REFERENCE:

[1] World Health Organization, *Global Status Report on Road Safety 2023*, Geneva, Switzerland, 2023.
[2] OECD/ITF, *Road Safety Annual Report 2024*, Paris, France, 2024.
[3] AASHTO, *Highway Safety Manual*, Washington DC, USA, 2010.
[4] E. Hauer, *Observational Before-After Studies in Road Safety*, Oxford, UK, 1997.
[5] P. Hollnagel, *Safety-II in Practice*, London, UK, 2018.
[6] OECD, *Towards Zero: Ambitious Road Safety Targets and the Safe System Approach*, Paris, France, 2008.
[7] FHWA, *Data-Driven Safety Analysis*, Washington DC, USA, 2023.
[8] PIARC, *Road Safety Manual*, Paris, France, 2019.
[9] ETSC, *PIN Annual Report 2023*, Brussels, Belgium, 2023.
[10] SWOV Institute, *Sustainable Safety Vision*, Netherlands, 2018.
[11] F. Sagberg et al., "A Review of Research on Driving Styles and Road Safety," *Human Factors*, vol. 57, no. 7, pp. 1248–1275, 2015.
[12] J. Reason, *Human Error*, Cambridge University Press, 1990.
[13] D. Shinar, *Traffic Safety and Human Behavior*, Elsevier, 2017.
[14] G. Underwood, *Traffic and Transport Psychology*, Elsevier, 2005.
[15] WHO, *Managing Speed*, Geneva, Switzerland, 2017.
[16] D. Lord and F. Mannering, "The Statistical Analysis of Crash Frequency Data," *Transportation Research Part A*, vol. 44, no. 5, pp. 291–305, 2010.
[17] S. Washington, M. Karlaftis, and F. Mannering, *Statistical and Econometric Methods for Transportation Data Analysis*, CRC Press, 2020.
[18] M. Abdel-Aty and A. Pande, "Crash Data Analysis and Prediction Models," *Transportation Research Record*, vol. 1950, pp. 1–10, 2006.
[19] D. Lord, S. Washington, and J. Ivan, "Poisson, Poisson-Gamma and Zero-Inflated Models," *Accident Analysis & Prevention*, vol. 37, no. 1, pp. 35–46, 2005.
[20] M. Ye et al., "Deep Learning for Traffic Safety Prediction," *IEEE Access*, vol. 7, pp. 101515–101530, 2019.
[21] D. Lord and B. N. Persaud, "Accident Prediction Models with and without Trend: Application of the Generalized Estimating Equations Procedure," *Transportation Research Record*, vol. 1717, pp. 102–108, 2000.
[22] A. P. Tarko, "Network Screening and Ranking Methods for Safety Improvement Programs," *Accident Analysis & Prevention*, vol. 43, no. 6, pp. 1979–1988, 2011.
[23] B. Persaud, C. Lyon, and T. Nguyen, "Empirical Bayes Procedure for Ranking Sites for Safety Investigation by Potential for Safety Improvement," *Transportation Research Record*, vol. 1665, pp. 7–12, 1999.
[24] F. M. Council and E. Stewart, "Safety Effects of the Conversion of Rural Two-Lane Roads to Four-Lane Divided Roads," *Transportation Research Record*, vol. 1665, pp. 47–55, 1999.
[25] R. Elvik, "The Predictive Validity of Empirical Bayes Estimates of Road Safety," *Accident Analysis & Prevention*, vol. 40, no. 6, pp. 1964–1969, 2008.
[26] A. Montella, "A Comparative Analysis of Hotspot Identification Methods," *Accident Analysis & Prevention*, vol. 42, no. 2, pp. 571–581, 2010.
[27] S. Cafiso, G. Di Graziano, and A. Di Silvestro, "Development of Comprehensive Accident Models for Rural Roads," *Transportation Research Record*, vol. 2103, pp. 107–115, 2009.
[28] C. Lee, F. Saccomanno, and B. Hellinga, "Analysis of Crash Precursors on Instrumented Freeways," *Transportation Research Record*, vol. 1784, pp. 1–8, 2002.
[29] Y. Ma, J. Xu, C. Gao, M. Mu, G. E., and C. Gu, "Review of Research on Road Traffic Operation Risk Prevention and Control," *International Journal of Environmental Research and Public Health*, vol. 19, no. 19, p. 12115, 2022.
[30] Z. Du, M. Deng, N. Lyu, and Y. Wang, "A Review of Road Safety Evaluation Methods Based on Driving Behavior," *Journal of Traffic and Transportation Engineering*, vol. 10, no. 5, pp. 743–761, 2023.
[31] IRC:SP:88-2019, *Manual on Road Safety Audit*, Indian Roads Congress, New Delhi, India, 2019.
[32] IRC:SP:55-2014, *Guidelines on Safety in Road Construction Zones*, Indian Roads Congress, New Delhi, India, 2014.
[33] Austroads, *Guide to Road Safety Part 6: Road Safety Audit*, Sydney, Australia, 2021.
[34] FHWA, *Road Safety Audit Guidelines*, Federal Highway Administration, Washington DC, USA, 2006.
[35] G. M. Hildebrand and T. Wilson, "The Road Safety Audit Process," *Institute of Transportation Engineers Journal*, vol. 69, no. 8, pp. 27–32, 1999.
[36] M. Papageorgiou, E. Kosmatopoulos, and I. Papamichail, "Effects of Variable Speed Limits on Motorway Traffic Flow," *Transportation Research Record*, vol. 2047, pp. 37–48, 2008.
[37] H. Rakha and M. Van Aerde, "Comparison of Simulation Modules for Estimating Vehicle Emissions and Fuel Consumption," *Transportation Research Part D*, vol. 7, no. 3, pp. 231–257, 2002.
[38] S. E. Shladover, "Connected and Automated Vehicle Systems: Introduction and Overview," *Journal of Intelligent Transportation Systems*, vol. 22, no. 3, pp. 190–200, 2018.
[39] European Commission, *Cooperative Intelligent Transport Systems (C-ITS) Strategy*, Brussels, Belgium, 2016.
[40] ITS America, *National Intelligent Transportation Systems Strategic Plan*, Washington DC, USA, 2020.
[41] X. Zheng, J. Chen, and D. Wang, "Machine Learning Approaches for Traffic Accident Prediction: A Review," *IEEE Access*, vol. 8, pp. 160–180, 2020.

[42] Y. Chang and W. Wang, "Analysis of Traffic Injury Severity: An Application of Nonparametric Classification Tree Techniques," *Accident Analysis & Prevention*, vol. 38, no. 5, pp. 1019–1027, 2006.
[43] H. Li, Y. Wang, and K. Wang, "Crash Severity Analysis Using Random Forest Models," *Accident Analysis & Prevention*, vol. 127, pp. 102–111, 2019.
[44] S. Ziakopoulos and G. Yannis, "A Review of Spatial Approaches in Road Safety Research," *Accident Analysis & Prevention*, vol. 135, 2020.
[45] A. Mannering, V. Shankar, and C. Bhat, "Unobserved Heterogeneity and the Statistical Analysis of Highway Accident Data," *Analytic Methods in Accident Research*, vol. 11, pp. 1–16, 2016.
[46] P. Anderson, "Kernel Density Estimation and Hotspot Mapping of Road Traffic Crashes," *Accident Analysis & Prevention*, vol. 43, no. 5, pp. 1793–1798, 2011.
[47] E. Erdogan, I. Yilmaz, T. Baybura, and M. Gullu, "Geographical Information Systems Aided Traffic Accident Analysis System," *Accident Analysis & Prevention*, vol. 40, no. 4, pp. 1167–1174, 2008.
[48] M. Abdel-Aty, J. Lee, and C. Siddiqui, "Geospatial Analysis of Traffic Crash Data," *Journal of Transportation Safety & Security*, vol. 5, no. 3, pp. 223–237, 2013.
[49] National Highway Traffic Safety Administration (NHTSA), *Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application*, Washington DC, USA, 2015.
[50] SAE International, *Taxonomy and Definitions for Terms Related to Driving Automation Systems*, SAE J3016, 2021.
[51] D. Schrank, B. Eisele, and T. Lomax, *Urban Mobility Report*, Texas Transportation Institute, 2021.
[52] S. Thrun et al., "Stanley: The Robot that Won the DARPA Grand Challenge," *Journal of Field Robotics*, vol. 23, no. 9, pp. 661–692, 2006.
[53] E. Papadimitriou, A. Afghari, D. Tselentis, and P. van Gelder, "Road-Safety-II: Opportunities and Barriers for an Enhanced Road Safety Vision," *Accident Analysis & Prevention*, vol. 174, 106723, 2022.
[54] P. Hollnagel, *Safety-I and Safety-II: The Past and Future of Safety Management*, Ashgate Publishing, 2014.
[55] E. Hollnagel, D. Woods, and N. Leveson, *Resilience Engineering: Concepts and Precepts*, Ashgate Publishing, 2006.
[56] Ministry of Road Transport and Highways (MoRTH), *Road Accidents in India 2023*, Government of India, New Delhi, 2024.
[57] National Highways Authority of India (NHAI), *Road Safety Policy and Guidelines*, New Delhi, India, 2022.
[58] Planning Commission of India, *Report of the Committee on Road Safety and Traffic Management*, Government of India, New Delhi, 2011.
[59] World Bank and WHO, *Traffic Injury Prevention in South Asia*, Washington DC, USA, 2019.
[60] L. N. Malviya, H. Varma, and S. Verma, *Development of a Framework for Road Safety Performance Indicators using Prediction Modelling*, Ph.D. Thesis, Sanjeev Agrawal Global Educational University, Bhopal, India, 2026.

