

Geometric Design of Highways: Special Reference to Cambers

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Abstract:

Highway geometric design plays a vital role in ensuring safe, efficient, and sustainable transportation systems. Among the essential geometric components, camber or cross slope significantly contributes to pavement drainage, vehicle stability, and overall roadway performance. Proper camber design enables the rapid removal of surface water, thereby reducing the risks of hydroplaning, pavement deterioration, and traffic accidents. Conversely, inadequate camber may lead to water stagnation, structural pavement damage, and reduced driving safety. This paper explores the significance of camber in highway engineering by examining its objectives, classifications, design standards, and functional applications. The study also reviews the recommendations provided by the Indian Roads Congress (IRC) and compares them with international practices such as the AASHTO guidelines. Furthermore, selected case studies related to drainage deficiencies and pavement failures are discussed to highlight the practical importance of scientifically designed cambers. The findings indicate that appropriate camber design improves pavement longevity, enhances road safety, and supports sustainable highway infrastructure development.

Keywords — Highway geometric design, camber, cross slope, pavement drainage, IRC guidelines, hydroplaning, roadway safety.

INTRODUCTION

Transportation infrastructure plays a vital role in economic development and regional connectivity. Highways are designed to facilitate the safe, efficient, and economical movement of traffic while ensuring user comfort and operational reliability. The geometric design of highways comprises several important elements, including horizontal alignment, vertical alignment, gradients, sight distance, super elevation, and cross-sectional features. Among these components, camber is considered one of the most essential elements because of its direct influence on pavement drainage and structural performance.

Camber, commonly referred to as cross slope, is the transverse inclination provided on the road surface to enable the rapid removal of rainwater from the pavement. Effective drainage is necessary to prevent water accumulation, which can weaken pavement layers, reduce subgrade strength, and accelerate pavement deterioration. The Indian Roads Congress (IRC, 1980) recommends suitable camber values to ensure both pavement preservation and traffic safety under varying climatic and traffic conditions. Several studies have highlighted the relationship between inadequate drainage and highway safety issues. Poor drainage conditions can increase the likelihood of hydroplaning, skidding, and roadway accidents, especially during heavy rainfall.

Highway cross slopes significantly affect the lateral movement of surface water and are therefore critical to maintaining safe roadway operations. Consequently, proper camber design has

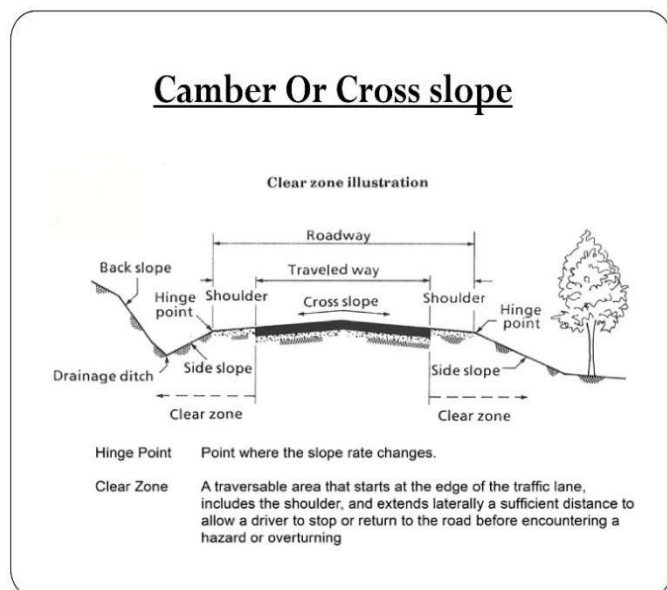
become an important aspect of sustainable highway engineering, contributing to improved pavement durability, reduced maintenance costs, and enhanced road safety.

2. Objectives of the Study

The present study aims to examine the role and significance of camber in highway geometric design and its impact on pavement performance and road safety. The specific objectives of the research are as follows:

1. To investigate the importance of camber as a fundamental element in highway geometric design.
2. To study and compare the various types of cambers commonly adopted in highway engineering practices.
3. To analyse the standards and recommendations related to camber design as prescribed by the Indian Roads Congress (IRC) and international agencies.
4. To assess the relationship between camber, surface drainage efficiency, pavement durability, and traffic safety.
5. To examine relevant case studies highlighting the effects of inadequate drainage and improper camber on pavement failures and roadway performance.

3. Concept of Camber in Highway Engineering



Camber, commonly known as cross slope, refers to the transverse inclination provided on the surface of a roadway to ensure the effective drainage of rainwater. In most highway pavements, the central portion of the road is kept slightly elevated relative to the edges so that surface water can flow quickly toward the pavement edges. This arrangement helps prevent water accumulation on the roadway surface and protects the pavement structure from moisture-related damage. The provision of camber in highway design serves several important purposes, including:

- Efficient removal of rainwater from the pavement surface
- Prevention of water infiltration into the underlying subgrade layers
- Protection of pavement materials from moisture damage
- Reduction in the risk of skidding and hydroplaning
- Enhancement of pavement strength and service life

Proper camber design is therefore essential for maintaining both pavement performance and traffic safety. Inadequate drainage caused by insufficient cross slope can lead to pavement distress, structural deterioration, and increased accident risks. Mahdy and Kamal (2012) reported that improper drainage conditions significantly contribute to pavement failures and adversely affect roadway safety and maintenance efficiency.

4. Importance of Camber in Highway Design

4.1 Drainage Efficiency

Efficient drainage is one of the primary functions of camber in highway design. Surface water accumulation on pavements is a major factor contributing to pavement deterioration and structural damage. When rainwater remains stagnant on the

road surface, it gradually penetrates the pavement layers and weakens the subgrade, thereby reducing the overall strength and stability of the pavement structure.

Properly designed camber facilitates the rapid removal of surface runoff, minimising water stagnation and protecting the pavement from moisture-related distress. This emphasised that adequate cross slope is essential for effective drainage and plays a significant role in reducing hydroplaning risks and ensuring safe highway operations.

4.2 Road Safety

Camber also contributes significantly to roadway safety, particularly during adverse weather conditions. Inadequate drainage decreases the friction between vehicle tyres and the pavement surface, increasing the likelihood of skidding and traffic accidents. During heavy rainfall, a thin layer of water may develop between the tyre and pavement surface, resulting in hydroplaning and loss of vehicle control.

Recent studies on highway safety have demonstrated that pavement surface conditions and drainage efficiency strongly influence accident frequency and severity. Therefore, the provision of appropriate camber is essential for maintaining adequate tire-pavement interaction and improving driving safety under wet conditions.

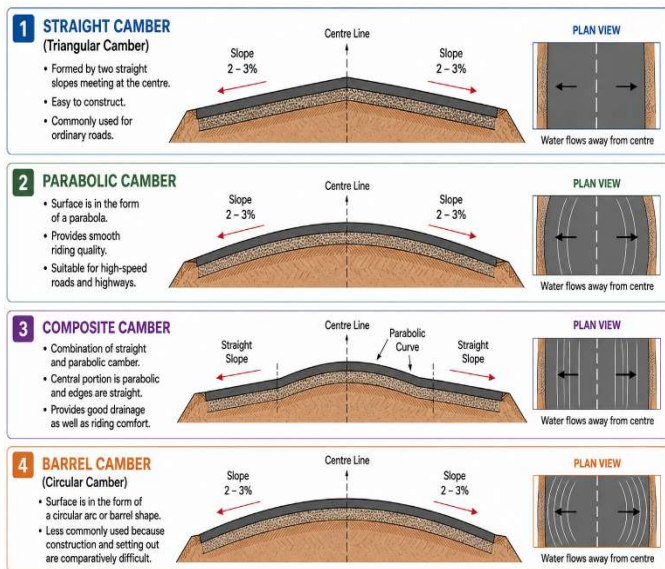
4.3 Pavement Durability

The durability and service life of highway pavements are directly influenced by drainage performance. Water infiltration into pavement layers can lead to several forms of pavement distress, including rutting, cracking, stripping, and pothole formation. Excess moisture weakens the pavement foundation and accelerates structural deterioration in both flexible and rigid pavements.

Proper camber design helps prevent excessive moisture penetration by enabling quick surface drainage, thereby preserving pavement integrity and extending pavement life. Research related to pavement distress has indicated that inadequate drainage systems significantly contribute to premature pavement failures and increased maintenance requirements.

5. Types of Cambers

Different types of cambers are adopted in highway engineering depending on factors such as traffic volume, pavement type, climatic conditions, and construction requirements. The commonly used forms of camber are discussed below.



5.1 Straight Camber

Straight camber consists of two straight slopes extending from the centre line toward the edges of the pavement. The two inclined surfaces meet at the crown of the road, forming a simple triangular cross-section.

Advantages

- Simple and easy to construct
- Economical in terms of maintenance and execution

5.2 Parabolic Camber

In parabolic camber, the road surface is shaped in the form of a parabolic curve rather than straight slopes. This type of camber offers a gradual change in slope from the centre toward the edges.

Advantages

- Ensures smoother riding quality and greater driving comfort
- More suitable for high-speed highways and modern pavements.

5.3 Composite Camber

Composite camber is formed by combining straight and parabolic profiles. Generally, the central portion The pavement is parabolic, while the outer portions are straight.

Advantages

- Provides improved surface drainage
- Offers a balance between riding comfort, economy, and construction efficiency.

5.4 Barrel Camber

Barrel camber consists of a continuously curved pavement surface resembling the shape of a barrel. The centre portion is rounded smoothly toward the edges.

Advantages

- Facilitates efficient drainage of surface water

6. IRC Recommendations for Camber

The Indian Roads Congress (IRC) has prescribed standard camber values for different types of pavement surfaces to ensure effective drainage, pavement protection, and safe vehicular movement under varying climatic conditions. The recommended camber depends primarily on the permeability and surface characteristics of the pavement material.

The IRC recommended values are presented below:

Pavement Surface	Recommended Camber
Cement Concrete Roads	1.7% – 2%
Bituminous Roads	2% – 3%
Gravel Roads	3% – 4%
Earthen Roads	4% – 5%

Rigid pavements such as cement concrete roads require relatively lower camber because of their impervious surface characteristics, whereas gravel and earthen roads require steeper cambers to facilitate rapid drainage due to their comparatively permeable surfaces.



These recommendations are intended to provide efficient surface water drainage while maintaining vehicle stability, riding comfort, and pavement durability. According to IRC:73-1980, the proper selection of camber is essential for minimising water stagnation and preventing premature pavement deterioration.

7. Factors Affecting Camber Design

The design and selection of camber in highways depend on several engineering and environmental factors. Proper consideration of these factors is essential to ensure efficient drainage, pavement durability, and safe traffic movement. The major factors influencing camber design are discussed below.

7.1 Rainfall Intensity

Rainfall intensity is one of the most important considerations in



camber design. Regions experiencing heavy rainfall require steeper cambers to facilitate the rapid removal of surface water and prevent water stagnation on the pavement surface. Inadequate slopes in such areas may result in poor drainage and increased pavement deterioration.

7.2 Type of Pavement

The permeability and surface texture of pavement materials significantly affect camber requirements.

Impervious surfaces such as cement, concrete and dense bituminous pavements require comparatively smaller cambers because they allow minimal water infiltration. In contrast, gravel and earthen roads require steeper cambers to ensure effective drainage.

7.3 Traffic Speed

Traffic speed also influences the selection of camber. High-speed highways generally require smoother cross slopes and gradual transitions to provide better riding comfort and vehicle stability. Excessive camber on high-speed roads may adversely affect driving comfort and vehicle control.

7.4 Climatic Conditions

Climatic and environmental conditions play a major role in determining suitable camber values. Flood-prone and waterlogged regions require enhanced drainage arrangements and carefully designed cambers to minimise water accumulation and pavement damage during heavy storms and monsoon conditions.

7.5 Pavement Material

Different pavement materials respond differently to moisture exposure. Flexible pavements are generally more vulnerable to moisture-related damage such as rutting, stripping, and cracking, whereas rigid pavements are comparatively less affected. Therefore, flexible pavements often require more effective drainage provisions through appropriate camber design.

8. Case Studies Related to Camber and Drainage

Several studies and practical highway investigations have highlighted the importance of proper camber and drainage systems in maintaining pavement performance and roadway safety. Inadequate drainage and improper cross slopes have frequently been associated with pavement failures, hydroplaning incidents, and increased maintenance costs. The following case studies demonstrate the practical significance of scientifically designed camber in highway engineering.

Live Case Studies: Geometric Design of Highways – Special Reference to Cambers		
CASE STUDY 1: Yamuna Expressway, India		
<p>GOOD DESIGN – Adequate Camber</p> <p>Well-designed camber ensures effective drainage and safe driving even during heavy rainfall.</p>	<p>POOR DESIGN – Inadequate Camber</p> <p>Inadequate camber cause water stagnation leading to hydroplaning and safety hazards.</p>	<p>Observations</p> <ul style="list-style-type: none"> Proper cross slope (camber) provided in Yamuna Expressway ranges from 2% to 2.5%. Effective drainage prevents water logging and enhances pavement life. Inadequate camber sections lead to ponding, hydroplaning risk and increased maintenance.
CASE STUDY 2: Mumbai-Pune Expressway, India		
<p>GOOD DESIGN – Adequate Camber</p> <p>Proper camber with side drains ensures quick runoff of water.</p>	<p>POOR DESIGN – Inadequate Camber</p> <p>Low camber results in water accumulation on pavement edges.</p>	<p>Observations</p> <ul style="list-style-type: none"> Recommended camber: 2% on bituminous pavement. Well-designed sections show no water logging even in heavy rainfall. Poorly designed sections show shoulder ponding and edge breakage.
CASE STUDY 3: State Highway (Rural Stretch), Karnataka, India		
<p>GOOD DESIGN – Adequate Camber</p> <p>Adequate camber on rural highway facilitates proper drainage.</p>	<p>POOR DESIGN – Inadequate Camber</p> <p>Inadequate camber and lack of side drains cause water stagnation.</p>	<p>Observations</p> <ul style="list-style-type: none"> Recommended camber on rural roads: 3%–4% (IRC73-1980). Proper camber increases pavement life and reduces distress. Water stagnation on low camber roads leads to potholes and deformation.
<p>CONCLUSION: Proper Camber (Cross Slope) is critical for effective drainage, pavement durability, and road safety.</p>		

Case Study 1: Highway Cross Slope and Hydroplaning Risk in the United States

That conducted a detailed study was conducted on highway cross slopes using airborne and mobile LiDAR technologies to assess pavement drainage characteristics and hydroplaning risks. The research focused on evaluating the effectiveness of highway cross slopes in facilitating surface water drainage during rainfall conditions. The findings revealed that inadequate cross slopes significantly increase the possibility of hydroplaning, thereby compromising roadway safety and

vehicle stability. The study also demonstrated the effectiveness of advanced digital

technologies in monitoring pavement slopes and supporting highway maintenance planning.

Key Findings

- Inadequate cross slopes reduce the efficiency of surface drainage.
- Hydroplaning risks increase considerably during intense rainfall conditions.
- LiDAR-based technologies provide accurate assessment and monitoring of highway drainage performance.

Case Study 2: Drainage Problems on SC135 Highway, Brazil

A drainage assessment carried out on Highway SC135 in Brazil identified several pavement failures associated with poor drainage conditions. The investigation reported problems such as water stagnation, pavement deformation, and increased accident potential due to ineffective surface runoff management. The study highlighted the importance of proper drainage systems and adequate camber design in preserving pavement integrity and ensuring roadway safety.

Key Findings

- Deficient drainage systems accelerated pavement deterioration.
- Surface runoff management was found to be inadequate.
- Poor maintenance practices increased roadway safety hazards and structural damage.

Case Study 3: Premature Pavement Distress in Virginia, USA

Elfino and Hossain (2007) examined premature pavement failures in Virginia and investigated the influence of drainage systems on pavement performance. The study concluded that

Ineffective drainage arrangements and moisture intrusion were major causes of structural pavement distress. Water

Penetration into pavement layers weakened the structural foundation and considerably reduced pavement service life.

Key Findings

- Drainage systems have a direct impact on pavement durability and service life.
- Water accumulation accelerates structural deterioration in pavement layers.

- Properly designed cross slopes are essential for sustainable pavement performance and long-term roadway stability.

9. Modern Trends in Highway Geometric Design

Modern highway engineering has increasingly shifted toward the development of sustainable, resilient, and technology-driven transportation infrastructure systems. Contemporary geometric highway design not only focuses on traffic efficiency and safety but also emphasises environmental sustainability, intelligent monitoring, and long-term pavement performance. Recent advancements in highway engineering include the adoption of:

- LiDAR-based pavement slope and surface assessment technologies
- Climate-resilient highway drainage and stormwater management systems
- Smart pavement monitoring and data-driven maintenance practices
- Reliability-based and performance-oriented geometric design approaches
- Sustainable runoff control and water conservation techniques.

The integration of advanced technologies has significantly improved the evaluation and maintenance of highway geometric features, particularly pavement cross slopes and drainage systems. Modern tools such as LiDAR, remote sensing, and intelligent monitoring systems enable

continuous assessment of pavement conditions, helping engineers identify drainage deficiencies and structural issues at an early stage. These developments contribute to enhanced roadway safety, improved maintenance efficiency, reduced operational costs, and increased pavement service life.

Furthermore, climate change and extreme weather conditions have increased the importance of resilient drainage design in highway engineering. As a result, modern geometric design practices increasingly incorporate sustainable stormwater

management strategies to minimise flooding risks and ensure long-term infrastructure sustainability.

Conclusion

Camber is a fundamental element of highway geometric design that plays a crucial role in ensuring effective pavement drainage, roadway safety, and structural durability. A properly designed camber facilitates the rapid removal of surface water, thereby reducing water stagnation, preventing pavement deterioration, and minimising the risk of hydroplaning and traffic accidents. Appropriate cross slopes also contribute significantly to

improved riding comfort, reduced maintenance requirements, and extended pavement service life.

The standards prescribed by organisations such as the Indian Roads Congress (IRC) and AASHTO provide scientifically developed guidelines for selecting suitable camber values based on pavement

type, traffic conditions, and environmental factors. These standards help engineers achieve a balance between drainage efficiency, vehicle stability, and pavement performance.

The case studies reviewed in this research clearly indicate that inadequate drainage systems and improper camber design are major causes of pavement distress, structural failures, and roadway safety hazards. Water accumulation and moisture intrusion can significantly weaken pavement layers and accelerate deterioration, leading to increased maintenance costs and reduced roadway reliability.

Therefore, highway engineers and planners must emphasise the adoption of scientifically designed

Cambers, along with sustainable drainage solutions in modern highway projects. Future research in highway geometric design should focus on the development of intelligent drainage monitoring systems, climate-resilient roadway infrastructure, and advanced pavement assessment technologies to enhance long-term highway sustainability and safety.

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