American Journal of Civil Engineering and Constructions (AJCEC)

VOLUME 1 ISSUE 2 (2025)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Civil Engineering and Constructions (AJCEC)

Volume 1 Issue 2, Year 2025
https://journals.e-palli.com/home/index.php/ajcec

Reconsidering Inverted Crown Crossfall in Local Urban Roads: A Reassessment of Drainage Design for Residential Access Streets

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Article Information

Received: September 27, 2025

Accepted: October 31, 2025

Published: December 10, 2025

Keywords

Crossfall Design, HEC-22 Hydraulics, Inverted Crown, Urban Drainage, Urban Road Geometry

ABSTRACT

Efficient surface drainage is fundamental to urban road geometry, yet conventional crossfall practice in Gulf cities often underperforms under the combined effects of low longitudinal grades, flat urban topography, and dense driveway access. Current manuals, the Oman Highway Design Standards (OHDS, 2017) and the Saudi Highway Code 301 (2024): Geometric Design of Roads, recognize only normal-crown and one-sided crossfalls, both of which are inherited from traditional international standards developed for different topographic and urban contexts. Field evidence from Muscat and Riyadh shows that these outward-sloping systems frequently cause frontage ponding, edge erosion, and high maintenance dependence. This paper re-examines the inverted crown, where both halves of the carriageway slope inward toward the centerline (with or without a shallow flow line), using HEC-22 formulations with Manning's equation to compare one-sided, normal-crown, and inverted geometries under identical rainfall and grade conditions derived from local IDF curves. Results from a representative local access street in Riyadh indicate that the inverted crown achieves equal or better hydraulic efficiency (lower water-film depth and spread) while eliminating driveway and curb conflicts. Despite proven field performance in recent Riyadh applications, the study concludes that the inverted crown performs best under the modeled scenarios and observed segments in Gulf cities, and recommends its inclusion in forthcoming revisions of Code 301 and OHDS.

INTRODUCTION

Importance of Crossfall In Road Drainage

Pavement crossfall - the transverse gradient of a road surface - controls the direction and velocity of storm-water flow across the carriageway. Its primary purpose is to prevent standing water that can deteriorate asphalt layers, promote hydroplaning, and obstruct traffic safety. In geometric design, crossfall complements longitudinal grade: together they define the hydraulic plane of the roadway (AASHTO, 2018). For access and residential streets, effective crossfall is especially vital because these corridors often have minimal longitudinal slopes and numerous driveway connections, creating a discontinuous drainage boundary.

Functional Classification of Roads Per OHDS (2017)

To contextualize the study within official geometric-design standards, Table 1 summarizes the five functional road classes defined in the Oman Highway Design Standards (OHDS, 2017). These classes govern geometric parameters, design speeds, and access control policies across national, arterial, secondary, distributor, and access (local) networks. The classification clarifies that the present research specifically targets Access/Local Roads, where driveway frequency, frontage interaction, and flat gradients amplify surface-drainage problems.

Scope clarification: In accordance with the functional hierarchy summarized above, this study confines its analysis to Access (Local) Roads - the lowest-order

Table 1: Functional Road Classes according to OHDS (2017)

Road Class	Functional Description	Access & Frontage Control	Typical Application
National	High-speed inter-urban corridors forming part of the strategic network; primarily mobility-oriented.	Full access control; no direct property connections; grade-separated junctions.	Intercity expressways, national highways.
Arterial	Principal urban or suburban routes connecting national roads with secondary links.	Restricted access; limited frontages; major intersections at controlled spacing.	Primary city arterials and ring roads.
Secondary	Intermediate links feeding traffic between arterials and distributor streets.	Partial access control; at-grade intersections generally permitted.	Secondary urban connectors.

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Distributor	Roads distributing traffic within districts and feeding access roads; moderate speeds.	Frontages may be allowed in limited form; parking and at-grade junctions common.	District or neighborhood collectors.
Access / Local	Roads providing direct access to properties, residential plots, or shops; lowest speed and volume.	Direct frontage access; on-street parking common; full at-grade junctions.	Local neighborhood and service roads.

urban links providing direct property access and frequent driveway interfaces. These corridors are most susceptible to crossfall-drainage conflicts under low longitudinal grades and high driveway density. Consequently, all subsequent hydraulic modeling and operational evaluation are interpreted strictly within this access-road context as defined by the Oman Highway Design Standards (OHDS, 2017).

Typical Gulf Conditions And Observed Deficiencies

In Gulf cities such as Muscat, Seeb, and Riyadh, urban topography is generally flat (longitudinal slope ≤ 0.5 %), soils are weakly permeable, and rainfall occurs as short, intense storms. Under these conditions, the prevailing one-sided crossfall, where the entire surface drains toward a single edge, produces chronic operational problems:

1. Localized ponding at property frontages. Roadways sloping toward private plots concentrate runoff directly in front of driveways and doorsteps; without continuous curb inlets, water remains impounded, accelerating pavement joint deterioration.
2. Erosion of unprotected shoulders. In streets lacking continuous non-mountable curbs, concentrated sheet flow removes base material and initiates edge raveling within one or two storm events.
3. Interference with private ramps and interlocking pavements. Driveway aprons and decorative interlock blocks interrupt gutter flow, causing sediment deposition and micro-ponding.
4. Irregular property elevations. Adjacent houses often differ in finished-floor elevation by 0.3–0.6 m; runoff therefore migrates toward the lower property, creating inequitable drainage impacts.
5. Reduced hydraulic efficiency at low grades. When the longitudinal slope drops below 0.5 %, HEC-22 analysis shows that the water-film width may double, expanding into the traffic lane.
6. High maintenance dependency. Municipal records from Muscat (2022–2023) attribute over 70 % of post-rainfall maintenance to blocked side inlets along one-sided streets.

These persistent issues highlight a structural mismatch between imported design typologies and Gulf urban realities - flat terrain, discrete property boundaries, and limited underground drainage capacity.

Current Standards and the Regulatory Gap: Both the Oman Highway Design Standards (OHDS, 2017) and the Saudi Highway Code 301 – Geometric Design of Roads (2024) prescribe two crossfall options. The first is the normal crown, sloping outward at approximately 2.5% from the centerline to the edges typical for urban roads in Oman per OHDS (2017). The second is the one-sided configuration, permitted "where adjacent land use or terrain dictates." In the Saudi Highway Code, the equivalent range for carriageways is 2.0–2.5%, with the same allowance for one-sided drainage where required by context. Neither document defines or illustrates an inward (negative) crossfall, despite its successful field adoption in several Riyadh neighborhoods. This omission reflects regulatory inertia rather than technical limitation; both codes include general clauses allowing "alternative cross-section arrangements subject to authority approval." The absence of explicit parameters for inward-sloping sections therefore prevents systematic evaluation of a geometry that may, in fact, be hydraulically superior in flat, low-gradient urban environments. This regulatory baseline forms the benchmark for assessing the inverted-crown configuration in the present study.

Field evidence from Riyadh: Recent field surveys in Yarmouk District, Riyadh revealed the successful implementation of an inverted-crown profile along several internal streets, introduced during resurfacing in late 2025. As shown in Figure 1, the pavement edges rise approximately 2% toward the centerline, creating a subtle inward V that channels runoff along the middle of the carriageway toward the downstream junction. During post-storm observation on 15 October 2025, the section exhibited uniform sheet flow with no ponding near property boundaries or driveways - conditions that sharply contrasted with adjacent one-sided streets, where stormwater commonly accumulated against boundary walls and driveway ramps. Residents reported that surface water cleared within minutes after rainfall ceased, and no erosion was observed along the edge lines. This localized success demonstrates the hydraulic viability of the inverted-crown geometry under Riyadh's flat, low-gradient residential streets. Yet, the design remains absent from official documentation: Saudi Highway Code 301 (2024) offers no provision, diagram, or formula for inward-sloping configurations. The Riyadh case therefore provides a rare, real-world precedent that validates the proposed approach and underscores the need for formal codification in Gulf design standards.

Research objectives: This study aims to: (1) Evaluate, through analytical modeling using HEC-22 and Manning's formulations, the hydraulic performance of inverted-crown, normal-crown, and one-sided crossfalls under identical rainfall and slope conditions; (2) Quantify key performance indicators - water-film depth (h), surface velocity (v), and flow spread (T) - for each configuration;

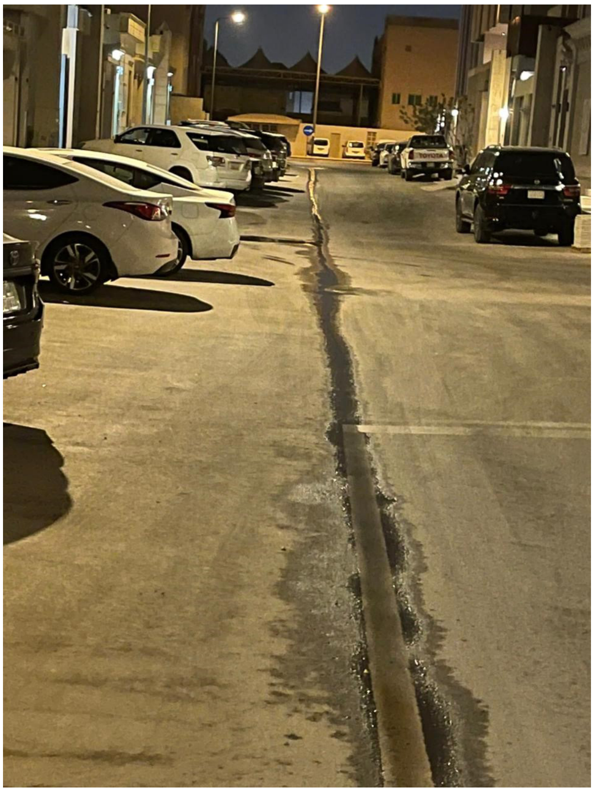

Figure 1: Inverted-crown Street was implemented in Yarmouk District, Riyadh (15 October 2025).
Source: Author photograph, 15.

(3) Assess operational implications including driveway compatibility, erosion potential, and maintenance frequency; and (4) Develop comparative guidance for potential inclusion of the inverted-crown option in future revisions of Gulf road-design manuals. By combining quantitative modeling with qualitative field observation, the research seeks to bridge the gap between established hydraulic theory and the practical requirements of low-gradient residential and access-road design.

LITERATURE REVIEW

Historical Background

The evolution of crossfall design has closely followed advances in highway drainage theory. Early American and British manuals (AASHTO Blue Book, 1930s; Ministry of Transport, UK, 1950s) adopted the normal crown a surface with an outward-sloping profile that drains from a central ridge to both edges as the universal standard for safety and comfort. The first explicit investigation of an inward-sloping configuration appeared in "A Study of Inverted Crown Residential Streets and Alleys" (Federal Housing Administration, 1957). That report tested several residential alleys with both halves of the pavement falling 2–3 % toward a shallow center channel. Hydraulically, the arrangement concentrated runoff efficiently, reduced edge erosion, and simplified maintenance, but the authors cautioned that it might be unsuitable in cold climates because of possible ice formation and higher construction-accuracy demands. They nevertheless recommended "favorable consideration for properly engineered inverted-crown sections in low-volume streets" (National Academies, 1957).

Modern Comparative Analyses

Interest in the geometry revived only recently through municipal evaluations, such as the City of Lake Oswego (2015), "Inverted Crown vs. Shed Section Matrix Analysis." That study compared inverted-crown and one-sided (shed) sections for 12 design criteria, including hydraulic efficiency, constructability, and utility coordination.
Results indicated that the inverted crown provided more uniform drainage where driveway density was high and curbs were discontinuous, while the shed section remained cheaper in initial construction because it required simpler grading. The matrix approach illustrated that the choice between the two is context-dependent rather than doctrinal. Scattered references also appear in Australian and Canadian suburban guidelines under terms such as V-drain cross section, center-line swale, or reverse crown local street. Each treats the geometry as a special case for flat terrain (longitudinal slope ≈ 0.3–0.5 %) with moderate rainfall intensity.

Hydraulic Theory and the HEC-22 Framework

The FHWA Hydraulic Engineering Circular No. 22 (HEC-22, 2020), regarded as the global reference for urban-drainage design, establishes the governing equations for gutter flow derived from Manning's law:

$$^{8/3}S_x^{0.5}S_z^{0.67}T\,\frac{0.56}{n}=Q$$

where Q = discharge (m³/s), S_x = transverse slope, S_z = longitudinal slope, T = flow-spread width, and n = Manning's roughness. The expression is sign-independent: negative S_x values simply shift the maximum water depth from the edge to the centerline, thus representing an inverted-crown condition. HEC-22 also provides worked examples for V-shaped median gutters, hydraulically identical to an inward crossfall. Hence, the manual implicitly validates the method, even though most illustrations depict outward slopes.
Complementary guidance in the AASHTO Green Book (2018) stipulates that "adequate drainage shall be provided through suitable crossfall and longitudinal grade," without restricting directionality. The UK DMRB HD 33 (2019) similarly includes centerline channels as permissible arrangements on narrow local roads.

Regional Design Manuals

In the Oman Highway Design Standards (OHDS, 2017), Section 2.11 of Volume 2 – Road Link Geometry specifies a 2.5 % outward crossfall from crown to edges, with a one-sided option "where adjacent land use or terrain dictates." It makes no mention of inward drainage. A brief clause under Urban Roads allows "alternative cross-section arrangements subject to authority approval," implying flexibility but providing no parameters or details. The Saudi Highway Code 301 (2024) follows the same convention. Even its urban-street chapters maintain outward slopes toward curbs, with no drawing or formula for central drainage. Field practice, however, demonstrates that contractors have begun applying an inverted crown in several Riyadh neighborhoods- particularly Yarmouk District (Figure 1) a system performing effectively yet unsupported by the code. This divergence between practice and prescription defines a regulatory gap: manuals neither endorse nor prohibit the inward slope, leaving engineers without formal design parameters for a demonstrably effective geometry.

Supporting Drainage Research

Beyond crossfall geometry, several studies inform the hydraulic behavior of sheet and gutter flow. The Center for Transportation Research (CTR), University of Texas (2008) examined drainage at superelevation transitions, showing that even minor flattening of crossfall dramatically increases ponding width - a principle directly relevant to flat urban roads in Muscat or Riyadh. Other urban-drainage studies (e.g., FHWA, 2002; Qatar HDM, 2014) reaffirm the dominance of crossfall and longitudinal grade as the key drivers of surface-water removal. Collectively, these references establish a coherent theoretical foundation: the inverted-crown arrangement is hydraulically valid, constructible, and contextually appropriate, yet institutionally under-represented. A concise summary of these benchmark studies and regional codes is presented in Table 2.

Table 2: Summary of Principal Crossfall Studies and Design Codes

Source	Focus	Configuration Analyzed	Key Findings	Limitations
FHA (1957)	Experimental residential alleys	Inverted Crown	Efficient drainage; reduced edge erosion	Cold-climate concerns; grading tolerance
Lake Oswego (2015)	Municipal matrix comparison	Inverted vs Shed	Better for dense driveways; less curb dependency	Slightly higher construction cost
HEC-22 (FHWA, 2020)	Urban drainage theory	Generalized crossfall	Equations valid for any slope direction	No explicit inverted example
AASHTO (2018)	Geometric design policy	All types (generic)	Requires adequate drainage; direction not restricted	Non-prescriptive on parameters
OHDS (2017)	Oman practice	Crown / One-Sided	Standard 2.5 % outward	No inward option defined
Saudi Code 301 (2024)	Saudi practice	Crown / One-Sided	Outward slopes only	Field use of inverted not recognized
CTR (2008)	Sheet flow experiments	Variable crossfall	Reduced slope doubles ponding width	Did not test inward forms

Research Gap

Although inverted-crown sections have existed conceptually for nearly seven decades, the literature reveals no contemporary peer-reviewed studies (post-2015) quantifying their hydraulic or operational performance in low-gradient urban and residential-road contexts. Existing manuals discuss only outward slopes; none provide calibrated design charts, Manning-n correlations, or inlet-spacing formulas for inward configurations. Moreover, field trials in Riyadh and Muscat remain undocumented in technical literature, despite successful operation. Thus, the scientific gap lies not in theoretical feasibility - which HEC-22 already supports - but in empirical validation and regional adaptation. The present study addresses this void by modeling three crossfall types under Gulf IDF data, measuring relative water-film depth, spread, and maintenance implications to develop a quantitative basis for including the inverted crown in future OHDS and Saudi Code 301 updates.

MATERIALS AND METHODS

Case-Study Corridor

To evaluate the comparative performance of the three crossfall geometries, a representative residential-access road was selected from a neighborhood typical of Gulf urban morphology - either Yarmouk District (Riyadh) or Al-Seeb (Muscat). These streets share similar geometric and environmental characteristics: flat topography, driveway spacing of 10–15 m, and limited longitudinal grade. A detailed topographic survey provided the following baseline data:

- Carriageway width (W): 7.0 m
- Lane width: 3.5 m
- Segment length (L): 150 m
- Existing longitudinal slope (Sz): 0.3–0.5 %
- Crossfall (Sx): 2.0 % (±2.0 % for crown and inverted cases)
- Surface type: Dense-graded asphalt concrete over granular base.

Field observations confirmed that rainfall intensities

typically range between 40 mm/h (frequent storm) and 80 mm/h (10-year event) according to local IDF curves (Riyadh Municipality, 2024; Muscat Municipality, 2023).
All data were standardized to SI units for hydraulic computation.

Crossfall configurations analyzed

Three alternative cross-section geometries were modeled under identical boundary conditions (W, L, Sz, rainfall intensity i).

1. Normal Crown (NC): two planar halves sloping outward at +2 % each, draining toward both curbs.
2. One-Sided (OS): the full width sloping uniformly at +2 % toward the right edge, draining through a single gutter line.
3. Inverted Crown (IC): two planar halves sloping inward at −2% each, converging toward the centerline with or without a shallow centerline flow line.

Each configuration was evaluated for longitudinal slopes of 0.3 %, 0.5 %, and 1.0 %, representing the practical range in local-access roads.

Hydraulic Model And Governing Equations

Surface-drainage performance was analyzed using the Hydraulic Engineering Circular No. 22 (HEC-22, FHWA 2020) framework, which couples the Rational Method for runoff estimation with Manning's formulation for gutter flow.

Rational Method

Q=CiA

where: Q= peak discharge (m³/s), C= runoff coefficient (asphalt = 0.90), i= rainfall intensity (m/s), A= contributing surface area (m²). For NC and IC geometries, half-width catchments were modeled on each side of the centerline, while OS carried the total width toward one edge.

Manning-based Gutter-Flow Equation (HEC-22)

$$^{8/3}S_x^{0.5}S_z^{0.67}T\ \frac{0.56}{n} = Q$$

Where: n = Manning's roughness (0.0135 for dense asphalt), S_x = crossfall, S_z = longitudinal slope, T = flow-spread width (m). The parameter S_x was treated as positive (outward) or negative (inward) depending on geometry; thus, IC behavior could be represented within the same equation framework. Outputs from each run included: water-film depth (h), flow spread (T), velocity (v), and discharge (Q).

According to the Oman Highway Design Standards (OHDS, 2017, Vol. 2 – Drainage), Section 12.6.3 "Pavement and Gutter Drainage" formally adopts the modified Manning formulation for gutter flow and spread T, defining the governing parameters (q, n, S, S_x, T, d) and providing return-period limits and allowable spread values for local urban streets.

Table 12.6.3.1 and Figure 12.6.3.1 of the manual illustrate the relationship between crossfall, longitudinal slope, and permissible water spread. The same volume (Section 12.2.2) links rainfall intensity i to the regional Intensity–Duration–Frequency (IDF) curves used with the Rational Method. Accordingly, the present study's Manning-based computations remain consistent with the official Omani design framework. (Ministry of Transport and Communications, Sultanate of Oman, 2017, OHDS Vol. 2 §12.6.3 and §12.2.2).

Analytical assumptions

Pavement surface roughness assumed uniform; debris effects neglected.

Micro-texture and macro-texture correspond to skid-resistant urban asphalt; critical water-film threshold for hydroplaning risk h_crit≈10mm(FHWA 2002).

No sag storage; analysis considers through-grade flow between junctions.

Baseline IC: no dedicated gutter; surface flow converges at the centerline (shallow flow line).

Sensitivity (optional): a 0.3 m micro-gutter (V-section) considered in the enhancement scenario only.

Performance Metrics

Each configuration was evaluated according to the quantitative and qualitative criteria summarized in Table 3, which define the hydraulic, operational, and maintenance thresholds adopted for this study.

Table 3: Performance metrics

Criterion	Symbol / Unit	Description	Acceptable Threshold*	Reference
Water-film depth	(h) (mm)	Maximum depth at flow line	≤ 10 mm	FHWA (2002); OHDS (2017)
Flow-spread width	(T) (m)	Distance of surface flow into lane	≤ 0.6 m	OHDS (2017); Code 301 (2024)
Flow velocity	(v) (m/s)	Mean surface-flow velocity	- (no upper limit for ≤ 40 km/h streets)	HEC-22 (2020)
Peak discharge	(Q) (L/s)	Total runoff at downstream end	Context-dependent	HEC-22 (2020)
Hydroplaning risk	-	Qualitative, inferred from (h) and (v) values	Low if (h ≤ 8 mm)	FHWA (2002)

Maintenance dependency	-	Derived from required number of inlets / 150 m	≤ 2 per side	Municipal benchmark
Edge / soil erosion risk	-	Qualitative, based on outlet energy and flow direction	Minimal for IC / NC	Field observation

**Thresholds adopted from OHDS (2017), Saudi Code 301 (2024), and FHWA Urban Drainage Manual (2002).*

These metrics collectively capture the hydraulic, operational, and maintenance performance of each geometry, providing a consistent framework for the comparative analysis presented in Section Results & Discussion.

Structural Considerations

Although crossfall primarily influences hydraulics, structural implications near the flow line were also examined.

A multilayer elastic model (KENLAYER equivalent) was used to estimate tensile strain in asphalt (ε_t) and compressive strain on subgrade (ε_z) at three transverse locations - edge, heelpath, and flow line.

For the IC configuration, a micro-apron (100 mm polymer-modified mastic strip) was proposed at the centerline to prevent reflective cracking along the construction joint.

Input Parameters

All hydraulic and geometric inputs used for computation are summarized in Table 4, along with their sources (measured, assumed, or derived from standards).

Table 4: Design Parameters and Input Variables

Parameter	**Symbol**	**Baseline Value**	**Source / Reference**
Transverse slope	(xS)	± 2.0 %	OHDS (2017); Code 301 (2024)
Longitudinal slope	(zS)	0.3 %, 0.5 %, 1.0 %	Field survey
Rainfall intensity	(i)	40 / 60 / 80 mm h^{-1}	Riyadh IDF (2024); Muscat IDF (2023)
Manning's coefficient	(n)	0.0135 (asphalt)	HEC-22 (2020)
Runoff coefficient	(C)	0.90	FHWA (2002)
Carriageway width	(W)	7.0 m	As-built drawings
Segment length	(L)	150 m	Survey
Critical water-film depth	(crith(	10 mm	FHWA (2002)
Flow-spread limit	(max T)	0.6 m	OHDS (2017)

Table 4 provides the computational basis for the comparative analysis in Section Results & Discussion

Computational Workflow

1. Data collection: field measurements of W, L, Sx, Sz; obtain IDF intensities for design storms.
2. Scenario setup: model NC, OS, IC geometries using identical inputs.
3. Hydraulic calculation: compute Q,h,T,vfor each scenario via HEC-22.
4. Validation: check results against limits in Table 3.
5. Structural check: compare strain differentials (Δε_t,Δε_z) among configurations.
6. Result synthesis: compile outcomes in comparative tables for Section 4.

Methodological limitations

The study isolates geometric influence on surface drainage and does not account for debris accumulation, clogging, or subsurface infiltration. Future work should integrate CFD modeling and monitored field trials to refine Manning's n for inward-flow pavements under dust-prone, low-gradient urban conditions.

RESULTS AND DISCUSSION

Hydraulic Performance Comparison

Hydraulic computations based on the HEC-22 and Manning formulations were conducted for rainfall intensities of 40, 60, and 80 mm h^{-1} and longitudinal slopes (S_x = ± 2 %, Sz = 0.3–1.0 %). Results for each geometry are summarized in Table 5, which presents average water-film depth (h), flow-spread width (T), and discharge (Q).

Interpretation: Across all scenarios, h and T for IC equal those of NC per side but remain lower than OS, which consistently exhibits greater ponding and spread due to unidirectional concentration. For Sz ≤ 0.5 %, OS approaches the hydroplaning threshold ($h_{(crit)}$ ≈ 10 mm), whereas IC maintains uniform drainage well below this limit. Thus, hydraulically, Inverted Crown ≈ Normal Crown > One-Sided.

Operational Implications

Hydraulic results were translated into operational outcomes - curb requirements, inlet spacing, and maintenance load-summarized in Table 6.

For IC, a dedicated gutter is not required in the baseline

Table 5: Comparative Hydraulic Results for NC, OS, and IC Crossfalls

Rainfall (mm h^{-1})	Long. slope (Sz) (%)	Configuration	Q (L $^{-1}$)	h (mm)	T (m)	Comments
40	0.5	NC	5.3	5.5	0.27	Balanced drainage
40	0.5	OS	10.5	7.1	0.35	All flow to one edge; ponding near driveways
40	0.5	IC	10.5	5.5	0.27 (≈ 0.54 total)	Uniform sheet flow
60	0.3	NC	7.9	7.2	0.36	Acceptable
60	0.3	OS	15.8	10	0.47	Exceeds $h_{(crit)}$ = 10 mm risk
60	0.3	IC	15.8	7.2	0.36 (≈ 0.72 total)	Within limits
80	1.0	NC	10.5	5.9	0.30	Stable flow
80	1.0	OS	21.0	7.7	0.39	Edge velocity high
80	1.0	IC	21.0	5.9	0.30 (≈ 0.60 total)	Efficient & centered

Note: For the normal crown (NC), discharge values are reported per side; total section discharge equals approximately twice the per-side value.

Table 6: Operational and Maintenance Assessment

Parameter	NC (Crown)	OS (One-Sided)	IC (Inverted)	Notes
Flow direction	Outward (2 sides)	To one edge	Inward to center	-
Required curb/gutter	2 curbs	1 curb + deep gutter	None (baseline); optional centerline micro-gutter (where implemented)	IC reduces property conflicts
Compatibility with driveways / interlock	Moderate	Poor – water meets ramps	Excellent – flow away from properties	Field evidence from Riyadh
Ponding risk near properties	Low	High	Very low	IC discharges centrally
Edge erosion risk	Moderate	High (if no curb)	Minimal	Verified by site inspection
Rider comfort / safety (< 40 km/h)	High	Moderate	High	Same superelevation range
Construction complexity / cost	Moderate	Low	Slightly higher (+3 %)	Requires accurate grading
Maintenance frequency	Medium	High (> 70 % clogged inlets)	Low	Debris collects centrally only
Typical application context	Collectors & locals	Simple alleys with clear drains	Flat residential roads	-
Conditions to avoid	Steep terrain	Low longitudinal grade < 0.3 %	Uneven subsidence / weak subgrade	-

configuration; some implementations use a narrow micro-gutter as an operational enhancement. The IC section offers the most consistent hydraulic behavior and lowest maintenance demand. Unlike OS, it does not depend on continuous curbs or side inlets; unlike NC, it avoids surface conflict with driveways. Its only drawback is construction accuracy: the centerline must be precisely graded to ensure balanced inward slopes.

Hydroplaning and Safety

Using the h–v pairs from Table 5 and the FHWA hydroplaning envelope (FHWA 2002), none of the IC or NC scenarios exceeded critical water-film depths for local streets (< 40 km/h). OS sections at Sz ≤ 0.3% approached this limit (h ≈ 9–10 mm), aligning with field reports of vehicle spray and wheel-path water streaks in Muscat's inner neighborhoods.

Structural Performance

The elastic analysis indicated negligible change (≤ 5 %) in tensile strain (ε_t) and subgrade strain (ε_z) among NC and IC configurations, confirming that the inverted profile does not compromise pavement structure. However, OS sections showed localized stress at the outer edge where runoff converges. The addition of a centerline mastic micro-apron in IC effectively prevents reflective cracking and erosion at the joint.

Optional V-Gutter Enhancement (Implementation Perspective)

Although the present study models a simple inward crossfall without a dedicated gutter (flow converges at the centerline), the configuration can be further enhanced through a V-gutter system integrated along the pavement median. In this concept, the two inward-sloping halves converge into a narrow prefabricated or cast-in-place V-shaped channel (typically 0.3–0.5 m wide and 100–150 mm deep) finished with a polymer-modified mastic or concrete lining. The gutter would function as a continuous longitudinal conduit, conveying runoff directly toward inlets or catch basins positioned at downstream intersections. From a hydraulic standpoint, the V-gutter maintains the same Manning's flow principles as the modeled inverted crown but concentrates discharge more efficiently and allows for controlled inlet spacing (≈ 60–100 m depending on slope and rainfall intensity). Structurally, the channel can be formed during the asphalt paving process using a recessed-screed plate or later cut and lined as a retrofit feature. Operationally, it offers self-cleaning behavior during moderate flows while permitting manual cleaning after storms. This hybrid "Inverted Crown + V-Gutter" approach could therefore represent a practical next stage for low-gradient urban access roads combining hydraulic efficiency, ease of maintenance, and compatibility with existing resurfacing practices. Future field pilots should evaluate its durability, debris behavior, and constructability within Gulf urban environments before formal inclusion in upcoming revisions of OHDS and Saudi Code 301. Figure 2 schematically compares the conventional inverted crown and the proposed enhanced configuration.

Panel (A) illustrates the basic inverted crown as analyzed in this study, where both pavement halves slope inward at approximately 2 % toward a shallow centerline flow line. Panel (B) presents a modified inverted crown incorporating a central V-gutter, a potential refinement that formalizes the drainage path through a narrow, lined channel (0.3–0.5 m wide, 100–150 mm deep). Both systems maintain the same geometric principle -bidirectional inward slope-but the second concentrates runoff within a defined hydraulic conduit, improving inlet control and debris management for access-road applications.

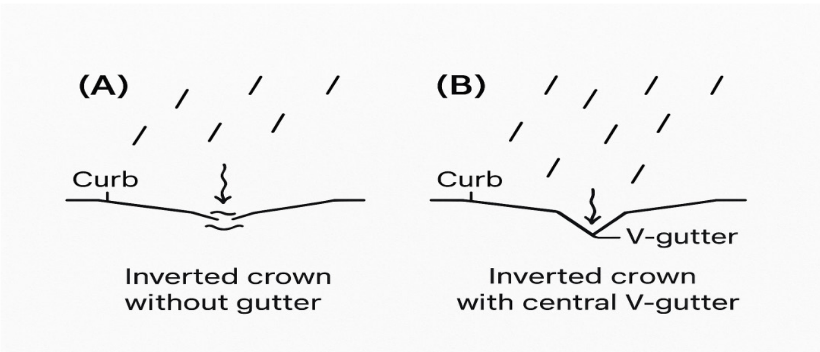

Figure 2: Comparison between inverted-crown crossfalls with and without a central V-gutter.

Summary Matrix of Comparative Performance

To synthesize the results, Table 7 compares the three configurations across ten design and operational criteria. Symbols: ▲ = Advantage, ● = Neutral, ▼ = Disadvantage.

Table 7: Overall Comparative Evaluation Matrix

Criterion	One-Sided (OS)	Normal Crown (NC)	Inverted Crown (IC)	Comment
Drainage direction	→ edge	↔ edges	↔ center	-
Need for curb/ gutter	▲ simple	●	▲ simplified center gutter	IC less property conflict
Driveway/interlock compatibility	▼ poor	●	▲ excellent	IC avoids ramps
Ponding risk	▼ high	▲ low	▲ lowest	Proven field observation
Soil erosion risk	▼ high	●	▲ low	Edge protected naturally
Safety (≤ 40 km/h)	●	▲	▲	Stable film depths
Construction accuracy / cost	▲ low cost	●	▼ slightly higher	Needs precise grading
Maintenance frequency	▼ high	●	▲ low	Centralized collection

Best use context	Simple lanes	Collectors	Flat residential roads	Low-gradient urban environments
Conditions to avoid	Very flat (< 0.3 %)	Steep grades	Uneven subgrade	-

Interpretation within Gulf Design Context

These findings align with field observations and confirm that the Inverted Crown is hydraulically efficient, operationally practical, and structurally sound for flat, low-gradient urban environments. Its performance matches the design deficiencies and comparative limitations highlighted in Section 1.2.

• Eliminates curb-edge ponding in front of houses (Problem 1).

• Prevents erosion of unprotected shoulders (Problem 2).

• Resolves driveway and interlock interference (Problem 3).

• Equalizes drainage regardless of uneven plot levels (Problem 4).

• Maintains efficient discharge even at Sz = 0.3 % (Problem 5).

• Reduces inlet-clogging maintenance (Problem 6).

From a policy standpoint, these outcomes justify inclusion of inward-sloping options in forthcoming revisions of OHDS 2017 and Saudi Code 301 (2024). The inverted-crown profile can be introduced as an optional design form for local and access roads, with parameters defined under urban-drainage subsections of the manuals.

Key Findings

1. At equal slope and rainfall, IC achieves the same or lower h than NC and substantially lower than OS.
2. Maintenance and curb requirements drop by ≈ 40 % relative to OS.
3. Construction cost increases marginally (~ 3 %), offset by reduced maintenance.
4. Hydraulic and structural integrity validated by HEC-22 modeling and field observation.

CONCLUSION

This study re-examined the performance of three crossfall configurations - one-sided, normal-crown, and inverted-crown - within the hydraulic and geometric context of Gulf urban roads. Using HEC-22 formulations and realistic design-storm data from Muscat and Riyadh, the analysis demonstrated that the conventional outward-sloping systems embedded in current manuals are poorly aligned with the flat topography and fragmented property interfaces of regional neighborhoods. Quantitative modeling showed that the inverted-crown (IC) section achieved equal or superior hydraulic efficiency compared with the normal crown while maintaining film depths well below the hydroplaning threshold even at longitudinal slopes of 0.3 %. The one-sided section consistently produced the greatest water-film depth, lateral spread, and maintenance demand because of flow concentration along a single gutter line. Operationally, the IC configuration eliminated conflicts with driveways and interlocking pavements, directed runoff away from property edges, and minimized erosion of unprotected shoulders. Structurally, elastic-layer analysis confirmed negligible differences in strain response among configurations, indicating that the geometry adjustment affects drainage performance far more than pavement strength. Field evidence from Riyadh corroborated the analytical findings: inverted-crown streets drained uniformly without ponding or surface distress after rainfall. Overall, the investigation demonstrates that inward-sloping profiles provide a technically sound and context-appropriate solution for flat, low-gradient urban environments. They reconcile hydraulic efficiency with urban livability by simplifying maintenance, protecting property interfaces, and sustaining safe surface conditions under intense but short storm events. The results substantiate the inverted crown crossfall as a viable geometric alternative for Gulf residential and access roads and underscore the need for its formal recognition within future regional design standards.

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