



EXIT RAMP DESIGN AT DUAL-CARRIAGEWAY INTERCHANGES: POTENTIAL IMPLICATIONS FOR OPERATING SPEEDS

Marko Šoštarić, Marijan Jakovljević, Juraj Leonard Vertlberg, Marko Švajda, David Gruhonjić
University of Zagreb, Faculty of Transport and Traffic Sciences, Croatia

Abstract

Designing exit ramps at road interchanges requires careful integration of geometric standards, traffic flow characteristics, and safety considerations. A recurring challenge is the substantial difference between operating speeds on the main road and on ramps, which can create critical conflict points and elevate crash risk. This paper examines current design practices for ramps in interchange areas, focusing on how geometric parameters and interchange configurations influence driver behavior and speed adaptation. Through a comparative analysis of ramp design standards and measured radii across selected countries, the study examines how horizontal curvature is defined and implemented in practice. Particular attention is given to the consistency of curve radii associated with identical posted speed limits and the implications of geometric variability for driver expectancy and speed adaptation. The analysis identifies substantial dispersion of radii within the same speed categories in several countries, indicating that reliance on minimum-radius criteria alone does not ensure uniform geometric environments. By reviewing international design guidelines and comparing them with real-world ramp geometry, the paper highlights inconsistencies between formal minimum-radius definitions and their practical application. The findings suggest that ramps designed strictly according to minimum design-speed principles may result in noticeably different curvature for the same nominal speed, potentially reducing predictability in transition zones. Based on the comparative evaluation, the study proposes that ramp design practice could be improved by replacing minimum-radius requirements with recommended radius ranges for specific speed categories. Such an approach would support greater geometric consistency, reinforce self-explaining infrastructure, and promote more stable speed transitions between mainline and ramp traffic. The results support the need for updated design methodologies that better reflect actual operating speeds and promote safer transitions between mainline and ramp traffic.

Keywords: interchange ramps, operating speed, speed transitions, geometric design, road safety

1 Introduction

Grade-separated interchanges are critical elements of motorway and dual-carriageway networks, providing controlled connections between traffic streams operating at different speeds. Within these systems, ramps function as transitional links where vehicles decelerate, accelerate, merge, or diverge. Because ramps represent zones of rapid speed adjustment and increased driver workload, their geometric design plays a decisive role in both operational performance and safety. A fundamental challenge in ramp design arises from the contrast between relatively high and uniform speeds on the mainline and substantially lower speeds required on ramps.

Drivers leaving a motorway must quickly adapt to reduced speeds dictated by curvature, alignment, visibility, and downstream conditions. Empirical evidence from large-scale naturalistic driving studies demonstrates that operating speeds on freeway ramps are strongly influenced by horizontal curvature, as well as by upstream traffic speed and terminal control conditions [1]. Observed speed profiles show considerable variation along ramp alignments, with drivers progressively decelerating on exit ramps and accelerating on entrance ramps. These findings suggest that traditional design-speed-based approaches may not always align with actual speed selection behavior.

Speed differentials and speed variability in interchange areas are closely linked to safety performance. Statistical analyses of crash data indicate that accident occurrence varies across ramp segments and speed-change lanes, with typical crash types including single-vehicle run-off-road events and multi-vehicle rear-end or sideswipe collisions associated with merging and lane-changing maneuvers [2]. Factors such as ramp configuration, traffic volume, ramp length, and the length of acceleration and deceleration lanes significantly influence crash frequency, with longer speed-change lanes generally contributing to lower accident rates. National statistics from Croatia further confirm that interchange areas account for a disproportionately high share of motorway crashes, underscoring the importance of ramp geometry and speed adaptation in overall network safety [3]. A United States study showed that about half of all ramp crashes occurred when drivers were exiting the motorway section, where speed was a key contributor to these crashes. The most common crash type was run-off-road [4]. Despite comprehensive geometric design standards, discrepancies persist between prescribed design assumptions and real-world driver behavior. Most existing guidelines rely primarily on design speed as the governing parameter for horizontal alignment, whereas actual operating speeds depend on a broader combination of geometric, perceptual, and contextual influences. Consequently, ramps designed strictly according to minimum geometric criteria may not always produce consistent speed environments or clearly self-explaining alignments.

This paper therefore investigates interchange ramp design with emphasis on the relationship between horizontal geometry, operating speed transitions, and safety outcomes. By combining international design guidance with empirical findings on driver behavior and crash characteristics, the study evaluates how effectively current standards support consistent speed adaptation. Through comparative analysis of national practices, the paper identifies key limitations and outlines potential directions for improving ramp design to achieve safer and more predictable speed transitions.

2 Analysis of existing ramp design standards

In all analyzed countries, interchange ramps are defined as connecting roadways that enable vehicles to enter or exit a grade-separated facility while operating at lower speeds than the mainline carriageway. Although terminology and classification differ slightly, ramps are generally categorized according to their geometric configuration (direct, semidirect, loop/indirect) and functional role (entry or exit). In the United States, ramp design is governed primarily by the AASHTO Policy on Geometric Design of Highways and Streets, which defines ramps as auxiliary roadways designed for reduced operating speeds and specifies geometric elements based on a selected design speed. Minimum horizontal curve radii are determined as a function of design speed, superelevation, and allowable side friction, with tabulated minimum values provided for each design speed [5-7].

German motorway design guidelines (RAA) define ramps as integral components of interchange layouts with standardized geometric configurations. Minimum curve radii are prescribed for selected design speeds, ensuring geometric consistency and speed adaptation.

While advisory speeds may be posted in practice, geometric design is based on minimum radius requirements derived from dynamic and safety criteria [8]. Slovenian regulations define ramps within the broader framework of road alignment design. Horizontal alignment consists of straight sections, circular curves, and transition curves, with minimum radii specified according to project speed and crossfall. Tabulated minimum radii are provided for each design speed, representing limiting geometric values [9]. Serbian design guidelines similarly classify ramps by type and function and prescribe minimum geometric parameters based on design speed. Minimum horizontal curve radii are defined in tabular form for each speed category and serve as the governing parameter for alignment design [10]. Croatian regulations establish minimum curve radii for roads outside settlements based on project speed, superelevation, and allowable side friction. Although the regulation does not provide ramp-specific radius tables, interchange ramps are designed using the same minimum-radius principles applied to general road alignment [11]. Across all analyzed countries, the definition of horizontal curvature is therefore based on the concept of minimum radius (R_{min}) associated with a selected design speed. These minimum values represent limiting conditions, while actual implemented radii may exceed R_{min} depending on spatial constraints, interchange configuration, and design practice. The presented results represent a meta-analysis of more than 40 interchange ramp locations across five countries: Croatia, Slovenia, Serbia, Germany, and the United States. For each location, the posted speed limit (where available) and the corresponding measured horizontal curve radius were recorded based on satellite-based geometric reconstruction. The objective was to evaluate the degree of consistency between posted speeds and actual implemented radii, as well as to compare national design practices in real-world application. Table 1 shows the results of the meta-analysis.

Table 1 Relative variation of ramp curve radii for comparable speed limits across analyzed countries

Country	Method of defining ramp curve radius	Observed variation in ramp radii for the same speed limit
Croatia	Minimum radius (R_{min})	56%
Slovenia	Minimum radius (R_{min})	24%
Serbia	Minimum radius (R_{min})	3%
Germany	Minimum radius (R_{min})	6%
United States	Minimum radius (R_{min})	30%

In Croatia, the majority of analyzed ramps were posted at 40 km/h, with measured radii ranging from approximately 45 m to 80 m. Most values fall between approximately 59 m and 73 m, indicating moderate clustering around a central range, but with noticeable variability. Lower radii (45-50 m) were observed at certain locations, while the largest value (80 m) represents a significantly flatter geometry for the same nominal speed. For 50 km/h ramps, measured radii of 70-73 m were recorded, and the single 60 km/h ramp exhibited a substantially larger radius of 129 m. Overall, Croatian practice shows compliance with minimum-radius principles but allows considerable flexibility in actual geometric realization. Figure 1 shows differences in ramp geometry in Croatia. Both satellite images were captured at approximately the same scale and illustrate two interchange ramps with the same speed limit and with horizontal curve radii of 45 m and 70 m, respectively. The difference in geometric layout is clearly visible.



Figure 1 Example of geometric variability in ramp radii with identical speed limits

Slovenian ramps posted at 40 km/h exhibit notably tighter clustering. Measured radii range between 44 m and 56 m, with most values concentrated within a narrow interval around 48-55 m. This indicates relatively uniform geometric application for equivalent speed limits. The limited dispersion suggests a stronger adherence to standardized geometric solutions or more consistent application of minimum-radius criteria in practice.

In Serbia, the analyzed sample reveals even greater uniformity for 50 km/h ramps, where several separate locations all exhibit identical measured radii of 98 m. For 40 km/h ramps, values of 63-65 m were observed, again demonstrating limited variation. This consistency indicates a highly standardized approach to ramp design, likely reflecting direct implementation of tabulated minimum or near-minimum radii without substantial geometric deviation. German examples present a different pattern. Posted speed limits are not consistently displayed on ramps, and in some cases no explicit limit is provided. Measured radii, usually ranging between approximately 60 m and 73 m, were recorded across the analyzed sites, including ramps associated with advisory speeds or inferred operating speeds. The absence of consistent posted limits suggests that German practice relies more strongly on geometric self-explanation rather than regulatory speed control. At the same time, measured radii show moderate variation, indicating that while minimum-radius principles exist in national guidelines, practical implementation is influenced by interchange configuration and operational context rather than rigid standardization. In the United States, ramps posted at 20-25 mph (approximately 32-40 km/h) exhibit substantial variation in measured radii, ranging from 41 m to 79 m. While several ramps cluster around 44-55 m, one location displays a significantly larger radius (79 m) for the same posted speed. This variability reflects the design flexibility permitted under AASHTO guidelines, where minimum radii are defined but designers frequently exceed minimum values depending on spatial constraints and interchange layout.

Overall, the comparative analysis demonstrates that all analyzed countries apply minimum-radius-based design principles; however, real-world implementation varies significantly. For ramps with comparable speed limits of approximately 40 km/h, the observed variation in curve radii differs substantially between countries. Croatia shows the largest dispersion, with radii varying by approximately 56%, while the United States exhibits a variation of about 30%. Slovenia demonstrates moderate variability of approximately 24%, whereas Germany (6%) and Serbia (3%) show considerably higher geometric consistency. These findings confirm that although design standards are structurally similar across countries, the practical application of minimum-radius criteria varies in terms of consistency and flexibility.

3 Discussion

The results indicate that, although all analyzed countries formally base ramp geometry on the concept of minimum radius (R_{\min}) associated with a selected design speed, the actual radii implemented in practice are far from uniform. For equivalent posted speeds, substantial variation in measured radii was observed, particularly in Croatia and the United States, and to a moderate extent in Germany. Only Slovenia and Serbia demonstrated relatively consistent geometric realization for identical speed categories. This finding highlights a fundamental issue in current ramp design practice: the reliance on minimum-radius criteria alone does not ensure geometric consistency or predictable speed environments. From a driver's perspective, interchange ramps represent critical transition zones where rapid speed adaptation is required. If ramps signed with the same speed limit exhibit significantly different curvature, the roadway ceases to be fully self-explaining. A 40 km/h ramp with a radius of 45 m produces a markedly different driving experience from a 40 km/h ramp with a radius of 80 m. Such discrepancies may lead to inconsistent speed behavior, misjudgment of curvature severity, and increased variability in deceleration patterns. In environments where drivers rely on visual cues and prior experience, large geometric dispersion within the same nominal speed category can reduce expectancy and compromise operational stability. The observed variation also suggests that compliance with minimum-radius requirements alone does not provide sufficient control over the resulting driving environment. Because R_{\min} represents a limiting condition rather than a target value, designers frequently select radii significantly above the minimum depending on spatial constraints, terrain, or interchange configuration. While this flexibility allows context-sensitive solutions, it may also produce unintended inconsistency across the network.

A potential improvement to current design methodology would be the introduction of recommended radius ranges for specific ramp speed categories, rather than relying exclusively on minimum values. Defining both lower and upper recommended bounds could help standardize geometric expectations while still permitting necessary flexibility. Such an approach would support greater uniformity in curvature for equivalent speed limits, thereby reinforcing driver expectancy and promoting more homogeneous operating speeds. Establishing radius ranges could also facilitate clearer differentiation between speed categories and strengthen the self-explaining character of interchange design. By aligning geometric form more closely with perceived speed environment, the risk of overestimation or underestimation of appropriate speed may be reduced. Ultimately, enhancing geometric consistency across similar ramp types could contribute to improved safety performance by stabilizing speed transitions and reducing variability in driver response. The findings therefore suggest that future ramp design practice should move beyond minimum-radius compliance toward a more consistency-oriented framework that explicitly addresses geometric uniformity and driver perception. Further research should focus on investigating the causal relationship between geometric variability in ramp curvature, operating-speed behaviour, and accident occurrence in interchange areas in order to better quantify the safety implications of inconsistent ramp design.

4 Conclusion

This study examined interchange ramp design practices in selected countries with particular emphasis on the relationship between posted speed limits and implemented horizontal curve radii. Although all analyzed national standards define minimum radii (R_{\min}) based on design speed, the comparative meta-analysis of more than 40 ramp locations revealed that real-world geometric implementation varies considerably. While Slovenia and Serbia demonstrated relatively consistent radii for equivalent speed categories, Croatia and the United States showed substantial dispersion.

Germany presented a distinct case, where speed limits are not always explicitly posted on ramps and geometric form appears to serve as the primary speed-regulating mechanism. The findings highlight a key limitation of current design approaches: the use of minimum-radius criteria alone does not ensure geometric uniformity or predictable speed environments. R_{\min} values represent limiting technical thresholds rather than target design parameters, allowing significant flexibility in practical application. As a result, ramps signed with identical speed limits may differ substantially in curvature, potentially affecting driver expectancy and speed adaptation. In transition zones such as interchange ramps, where rapid deceleration or acceleration is required, such inconsistency may contribute to increased speed variability and operational instability. The results suggest that improving ramp design consistency may require a shift from purely minimum-based geometric control toward a framework that also considers recommended radius ranges for specific speed categories. Introducing both lower and upper reference bounds could help reduce excessive geometric dispersion while maintaining necessary design flexibility. A more consistency-oriented approach would support self-explaining infrastructure, enhance predictability for drivers, and contribute to safer and more stable speed transitions between mainline and ramp traffic. Ultimately, achieving safer interchange environments requires not only compliance with minimum geometric criteria but also systematic attention to geometric coherence, driver perception, and operating speed behavior across the network.

References

- [1] Brewer, M.A., Stibbe, J.: Investigation of Design Speed Characteristics on Freeway Ramps using SHRP2 Naturalistic Driving Data, Transportation Research Record: Journal of the Transportation Research Board, 2673 (2019) 3, DOI: 10.1177/0361198118823515
- [2] Bauer, K.M., Harwood, D.W.: Statistical Models of Accidents on Interchange Ramps and Speed-Change Lanes, Report No. FHWA-RD-97-106, Federal Highway Administration (FHWA), U.S. Department of Transportation, Washington, D.C., June 1998.
- [3] Ministry of the Interior of the Republic of Croatia (MUP): Traffic Accident Database of the Republic of Croatia, Zagreb, Croatia
- [4] McCartt, A.T., Northrup, V.S., Retting, R.A.: Types and Characteristics of Ramp-Related Motor Vehicle Crashes on Urban Interstate Roadways in Northern Virginia, Journal of Safety Research, 35 (2004) 1, pp. 107–114, DOI: 10.1016/j.jsr.2003.09.019
- [5] American Association of State Highway and Transportation Officials (AASHTO): A Policy on Geometric Design of Highways and Streets, 4th edition, Washington, D.C., 2001.
- [6] Texas Department of Transportation (TxDOT): Traffic and Safety Analysis Procedures Manual, Chapter 9 – Segment Analysis, TxDOT, Austin, TX, USA
- [7] Transportation Research Board: Highway Capacity Manual, 7th edition, National Academies Press, Washington, D.C., 2022.
- [8] Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV): Guidelines for the Design of Motorways (RAA – Richtlinien für die Anlage von Autobahnen), Cologne, Germany, 2008. (English translation 2011)
- [9] Republic of Slovenia, Ministry of Transport: Regulation on Road Design (Pravilnik o projektiranju cest), Official Gazette of the Republic of Slovenia, Nos. 91/05, 26/06, 109/10 – ZCes-1, 36/18, 132/22 – ZCes-2, Ljubljana, 2005.
- [10] Public Enterprise “Roads of Serbia” (Putevi Srbije): Priručnik za projektovanje puteva u Republici Srbiji – Funkcionalni elementi i površine puteva, Denivelisane raskrsnice i priključci, Beograd, Srbija, 2012.
- [11] Republic of Croatia, Ministry of Maritime Affairs, Transport and Communications: Regulation on Basic Conditions that Public Roads Outside Settlements and Their Elements Must Meet from the Traffic Safety Perspective, Official Gazette of the Republic of Croatia (Narodne novine), No. 110/2001, Zagreb, 2001.