Driving Radius Impact on Interchange Ramps

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ABSTRACT

The geometric elements of interchange ramps are selected to provide a comfortable and safe passage. In previous studies, field measurements on interchange ramps revealed that the lateral acceleration experienced by drivers was lower than the design value derived from the global equation of motion for a known radius, superelevation, and speed. This study aims to explain the deviations using the geometric criteria, noting that the discrepancy between the recorded lateral acceleration and the design value is due to the driving (vehicle path) radius and the critical geometric elements of the horizontal curve (radius, superelevation, deflection angle, curvature change rate, width, number of traffic lanes and directions). The sample consists of over 160 drivers with various characteristics (age group, experience, gender etc.). The measurements were conducted on 8 interchange ramp curves. The presented diagrams correlate either the driving or the differential radius with the critical geometric elements of the curves and highlight the significance of each. New equations established for direct calculation of the driving and the differential radius, which can contribute to the selection of the minimum radius, the speed limit in dry pavement conditions for each new interchange ramp and the differentiation of the current values when incorporated into the geometric road design guidelines. The comfort, tolerance, and safety limits of driving and differential radius are established depending on design radius, which complements the corresponding limits established for lateral acceleration and longitudinal deceleration in interchange ramps in previous research.

Keywords: interchanges, lateral acceleration, driving radius, design radius, geometric elements, geometric road design guidelines, speed, comfort limit, tolerance limit, safety limit

INTRODUCTION

Many studies have shown that the existing geometric road design is conservative (*Levinson, 2007, Neves, 2014, Xu et al, 2015, etc.*). While a safety threshold is desirable, it is a highly significant issue whether this should so profoundly influence geometric road design. The technological advancement of today's vehicles has modified the comfort, tolerance and safety limits of drivers. Speed measurements on interchange ramps (*Trakakis, Apostoleris & Psarianos, 2022, 2023 & 2024, Lytras et al., 2024, Jafarov & Zaluga 2020, De Jong, 2017)* have demonstrated that drivers consistently exceed the speed and lateral acceleration limits set by geometric road design guidelines, indicating more aggressive driving behavior.

The ability of drivers to choose their driving radius is a characteristic example of inconsistent design, which can lead to dangerous situations, especially on smaller path radii where drivers experience higher lateral acceleration than the design value, given the constant speed and superelevation. This risk steeply increases with higher speeds. In the other hand, driving larger radius than the design ones, means that the geometric design overestimates safety by increasing design costs unnecessarily.

This study analyzes this issue to encourage geometric design guidelines to be modified and consider it in corresponding manuals regarding the proper selection of the design speed or the minimum design radius within the concept of performance-based design. For this to happen, the correlation between the differential radius and the critical geometric elements of the curves place must be analyzed. In the following, this paper aims to provide the necessary data to support this task in the case of interchange ramp design.

PAST STUDIES

Road geometric design manuals use the global equation of motion (Equation 1) to calculate the minimum allowable horizontal radius, setting the design speed (V), the maximum superelevation (q), and the value of the provided lateral friction coefficient (f_R) they consider sufficient.

$$f_R = \frac{V^2}{127 \times R} - q \leftrightarrow R = \frac{V^2}{127 \times (f_R + q)} \quad (1)$$

Deviation Between Recorded Lateral Acceleration and Expected One

In previous studies by *Trakakis, Apostoleris & Psarianos, 2023*, on 5 interchange ramps (Figure 1) with 6 horizontal curves (over 650 measurements used) and by *Lytras et al., 2024* using existing measurements on a diamond interchange (Figure 2), discrepancy was observed between the unbalanced lateral acceleration experienced by the driver and the anticipated by design values based on Equation 1.

For the calculation, in the Equation 1 was given the constant value of the driver's speed within the curve (V), the curve centerline radius (R) and the curve's design superelevation (q). The results are presented in Figure 1.

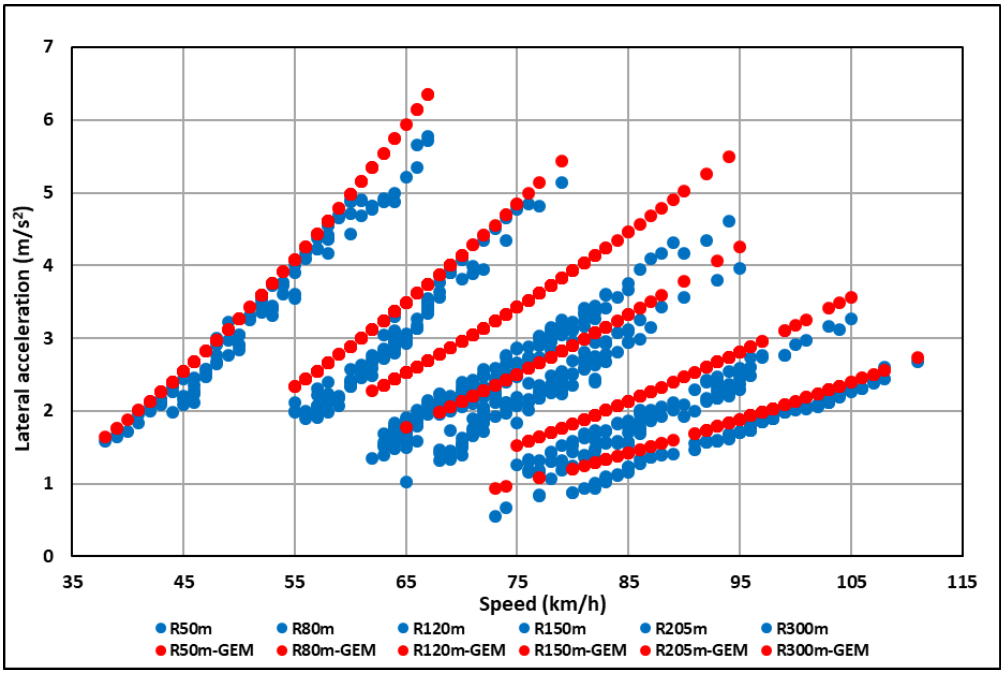

Figure 1 Correlation between lateral acceleration recorded and anticipated by design values (Trakakis Apostoleris & Psarianos, 2023)

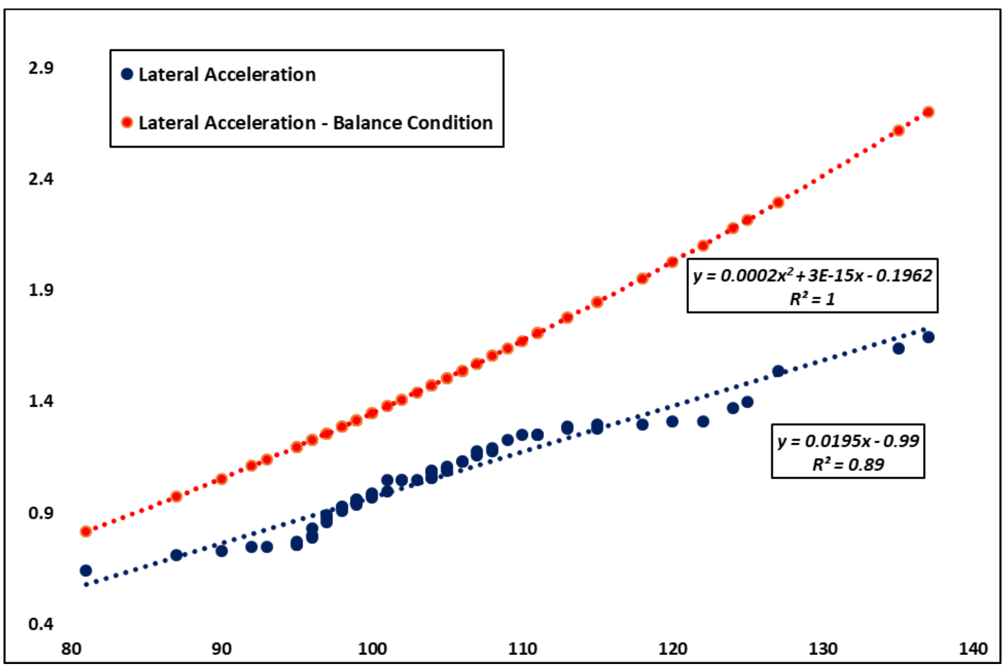

Figure 2 Correlation between lateral acceleration recorded and anticipated by design values (Lytras et al., 2024)

Difference Between Design Radius and Real Vehicle Path Radius

Aminfar et al., 2023 examined 5 couples of reversed curves with radii ranging from 155m to 590m, calculating the driving radius by taking horizontal coordinates of the path every 0.03sec. The driving radius

(Rdr) found larger than the design radius (Rdes), with the value directly depending on the length of the common tangent of reverse curves (d) and the speed (Vmc), according to Equation 2.

$$Rdr - Rdes = 188.64 - 1.61 \times d + 0.003 \times d^2 + 1.31 \times Vmc - 0.003 \times Vmc \times d \quad (2)$$

A study by *Das et al., 2014* was conducted on 8 horizontal curves with radii ranging from 202m to 1537m, on two-way roads with a road width ranging from 6m to 12m. The placement of the vehicle on the horizontal curve was calculated based on the distance of its front left wheel from the edge of the pavement. Researchers concluded (Figures 3 left and 4) that as the radius increases the vehicle is shifting towards the center.

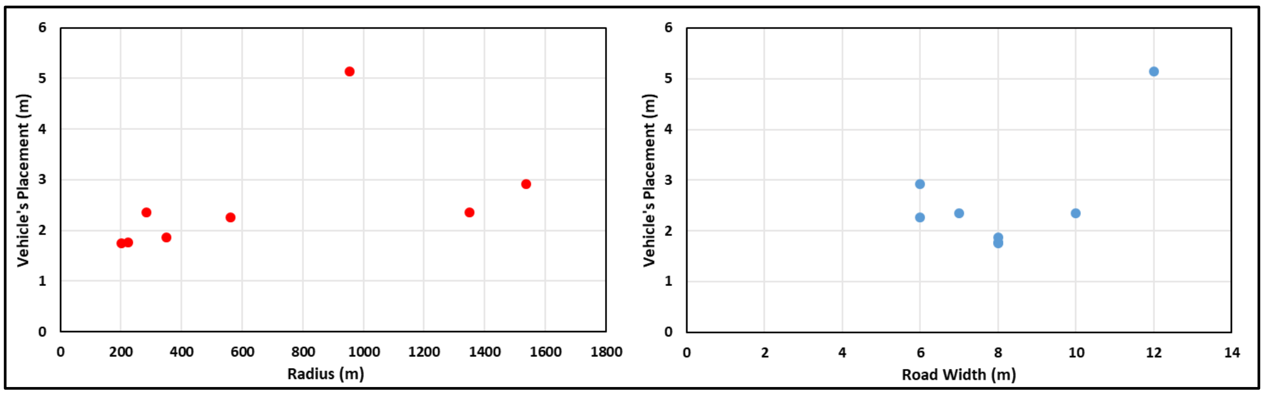

Figure 3 Radius and road width impact on vehicle's placement on horizontal curves (data from Das et al., 2014)

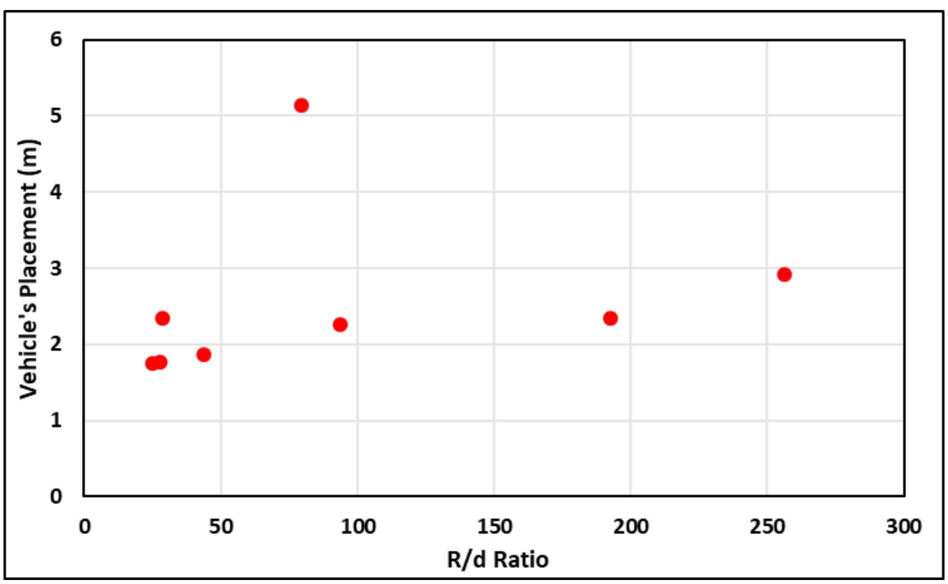

Figure 4 Ratio Radius / Road Width impact on vehicle's placement on horizontal curves (data from Das et al., 2014)

Maljkovic & Cvitanic, 2021 utilized 20 drivers for field measurements, using a GPS device, on a two-lane rural road with curve radii ranging from 80m to 315m, under free-flow conditions and on dry pavement. The vehicle's path radius (R) was estimated based on the length of the curve trajectory (L) and the degree of change in heading (Dc), according to Equation 3.

$$R = \frac{57{,}3 \times L}{Dc} \tag{3}$$

The methodology was based on calculating the differential radius (ΔR) using the critical path radii at the 15th percentile, according to Equation 4.

$$\Delta R = \frac{R - R15}{R} \times 100 \tag{4}$$

The study investigated the impact of the road curve's design radius (R), the curve length (L), the deflection angle (α) and the operating speed (V_{85}) on the curve (Figure 5). The coefficient of determination showed a stronger correlation between the differential radius and the curve length. The driving radius found 12% smaller or 25% larger than the design radius in curve radii larger or smaller than 150m respectively. Researchers concluded that drivers underestimate the actual curvature in smaller radii in search of more comfort.

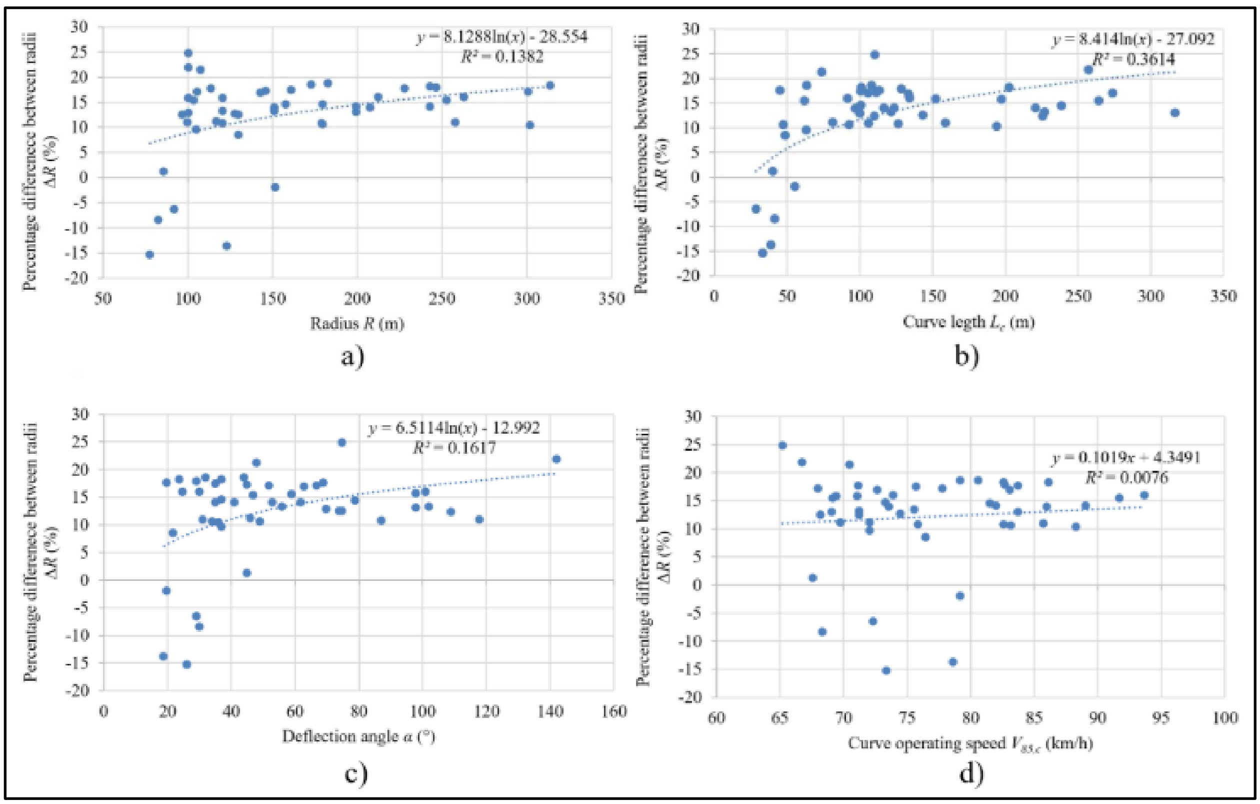

Figure 5 Individual scatter plots of percentage difference between radii versus geometric elements (Maljkovic & Cvitanic, 2021)

The authors propose that the differential radius be calculated depending on curve length based on Equation 5.

$$\Delta R\ (\%) = 8.41\ \times \ln(Lc) - 27.09 \tag{5}$$

The research of *Glennon et al., 1985*, showed that most drivers choose to drive on a smaller radius than the design radius (Figure 6). However, their assertion that drivers begin maneuvers and speed adjustment 3 seconds before entering the curve may have influenced the results of the vehicle's path radius.

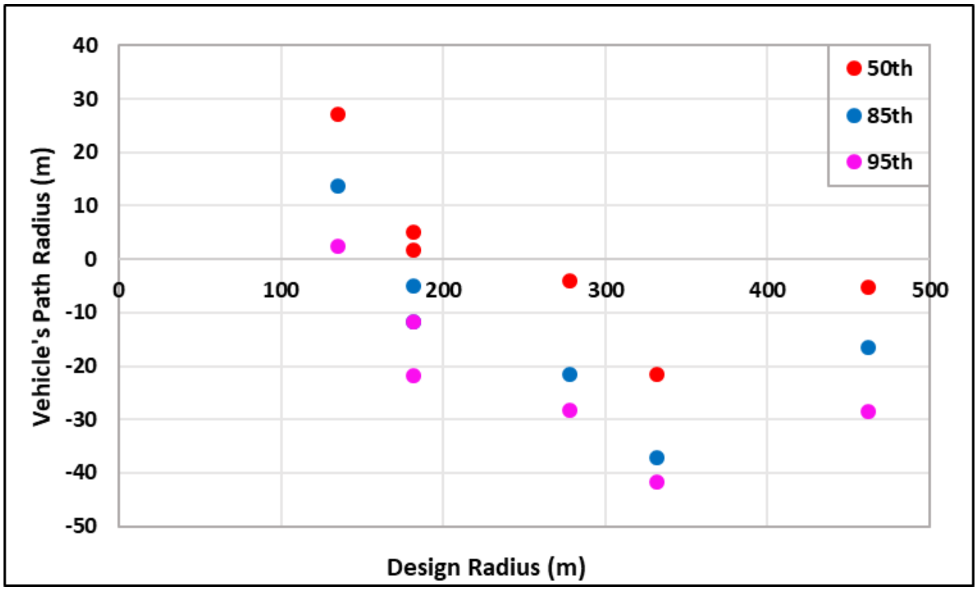

Figure 6 Vehicle's Path Radius depending on Design Radius (Glennon et al.,1985)

DATA COLLECTION

Method

To ensure unbiased measurements, given that the number of 8 curves is not a very large curve sample, a sufficient sample size was needed. A total of more than 160 drivers (74% male and 26% female) participated in the study, using their personal vehicles (Micro, Hatchback, Sedan, SUV and MPV types). Their driving experience ranged from 6 months to 35 years. The distribution of drivers' genders closely followed the research findings of the *International Transport Forum (ITF, 2020)*, which confirm that the percentage of male drivers worldwide ranges between 70% and 80%.

In total, the study examined 8 horizontal curves, with over 850 measurements taken, each curve tested by at least 105 drivers. The EU regulation for mandatory new car equipment from July 2024 includes intelligent speed assistance, attention warning in case of driver drowsiness or distraction, event data recorders as well as an emergency stop signal, lane keeping system, automated braking for vehicles, etc. The need to adapt the study to today's vehicles, with innovative active safety features and better maintenance standards imposed by modern regulations on vehicle manufacturers, led to two vehicle participation restrictions. No vehicles older than six years were included, and all vehicles had to have well-maintained tires and recent state-imposed regular inspections. The average vehicle age was 5.5 years, with a minimum of 2 years and a maximum of 7 years, and the tires were up to 1.5 years old and in good condition.

The most drivers (86%) used their own vehicle. To ensure familiarity with the vehicle, drivers not using their personal vehicles underwent training and test runs outside the study area. Drivers were required to have never driven the specific examined route before to test the most adverse scenario, i.e., unfamiliarity with the ramp's geometric elements.

A researcher accompanied each driver as a passenger in the front seat solely to operate the measuring equipment. The passenger did not provide any instructions, express comfort and safety feelings, or give route information within the curve. The passenger's role was to activate the equipment 1 km before entering the ramp (within the previous tangent) and deactivate it 1 km after the ramp’s end (at the following tangent).

All measurements were conducted on days with low traffic volumes (i.e. early weekend mornings or holidays), always maintaining a Level of Service A. All passages were on completely dry pavement, as side and tangential friction coefficients were also measured. The measuring procedure took place between 2020 and 2022. Measurements were suspended and resumed on subsequent days if rain started.

Measuring Equipment

This study required great precision to be conducted effectively. Since its foundation relates to lateral acceleration and speed, allowing for the calculation of the driving radius for a known superelevation based on Equation 1, equipment that measures lateral acceleration and speed with high accuracy and frequency was necessary. Therefore, the Vericom 4000RG (Figure 7) was selected, as in its various versions, has demonstrated its reliability in numerous similar studies (*Mavromatis et al., 2023, Aoun et al., 2017, Ruth and Brown, 2010, Hamernik et al., 2006, Eubanks et al., 1993, etc*.) and is widely used in the scientific community.

Vericom measures horizontal coordinates in the WGS '84 system, altitude, speed, and acceleration (in the X, Y, and Z axes, presenting the values as friction coefficient expressed as a percentage of gravitational acceleration) every 0.01 seconds. This way, the researcher can know the exact position (tangent, clothoid, arc) where any driver reaction occurred and evaluate it accordingly. Thus, speed within the curve combined with lateral acceleration resulted in no margin for error.

Vericom must be calibrated before use to establish the zero measurement in the 3D model. For this reason, the placement and calibration inside each vehicle were performed in enclosed garages where the longitudinal and lateral gradient values are approximately zero. Additionally, the Vericom recordings must be corrected for the longitudinal gradient, which inherently factors in the longitudinal acceleration.

Measurements were initially stored in the Vericom’s internal memory, then copied to a micro-SD card for transferring the data to the computer. Data processing was done through Profile 5, an application by Vericom Computers, which exported each measurement into a separate CSV file.

Figure 7 Vericom 4000RG

Selected Interchanges

To select the appropriate interchange ramps, the following conditions had to be met:

1. Interchange ramps with variations in design radius were selected. The curves examined have a radius between 39m and 300m with an average radius of 140m.
2. Different types of interchanges and ramps were selected to examine all types and achieve the desired variation in radii. Interchanges of trumpet type (Egaleo 1 & 2, Schistos – Skaramagas and Alimou Interchange) and three leg directional type (Syggrou Interchange) were selected. All the selected interchanges are in the Attiki prefecture of Greece. The types of the interchange ramps were loop (radius 39m and 50m), semi- directional (radius 120m and 150m), and directional (radius 80m, 175m, 205m, and 300m).
3. The road surface had to be well-maintained to ensure that driving behavior would not be affected and to record representative lateral acceleration values.
4. The maximum longitudinal gradient of interchange ramps should not exceed 7% on downgrades as required by the *RAA, 2008* guidelines or the maximum allowable values of the *AASHTO, 2018* guidelines, which differentiate the maximum grade for upgrades and downgrades based on the ramp design speed. For design speeds over 70 km/h, the maximum allowable grade is 5%, while for design speeds up to 30 km/h, it is 8%. This restriction, in this research, mainly concerns the increasing influence of the longitudinal gradient on speed. This restriction was also maintained for the tangents preceding the curves.
5. The superelevation of the curve should not exceed 7% and as much as possible 6% (within the guidelines margins i.e. *AASHTO,2018* or *RAA,2008)*.

The interchanges selected for investigation are sections of highways and are presented in Figure 8.

The speed limits are 30km/h for the 39m, 40 km/h for the 50m and 80m radius curves, 50 km/h for the 120m and 150m radius curves, 60km/h for the 205m radius curve and 80km/h for the 300m radius curve, based on the warning signs before the curves.

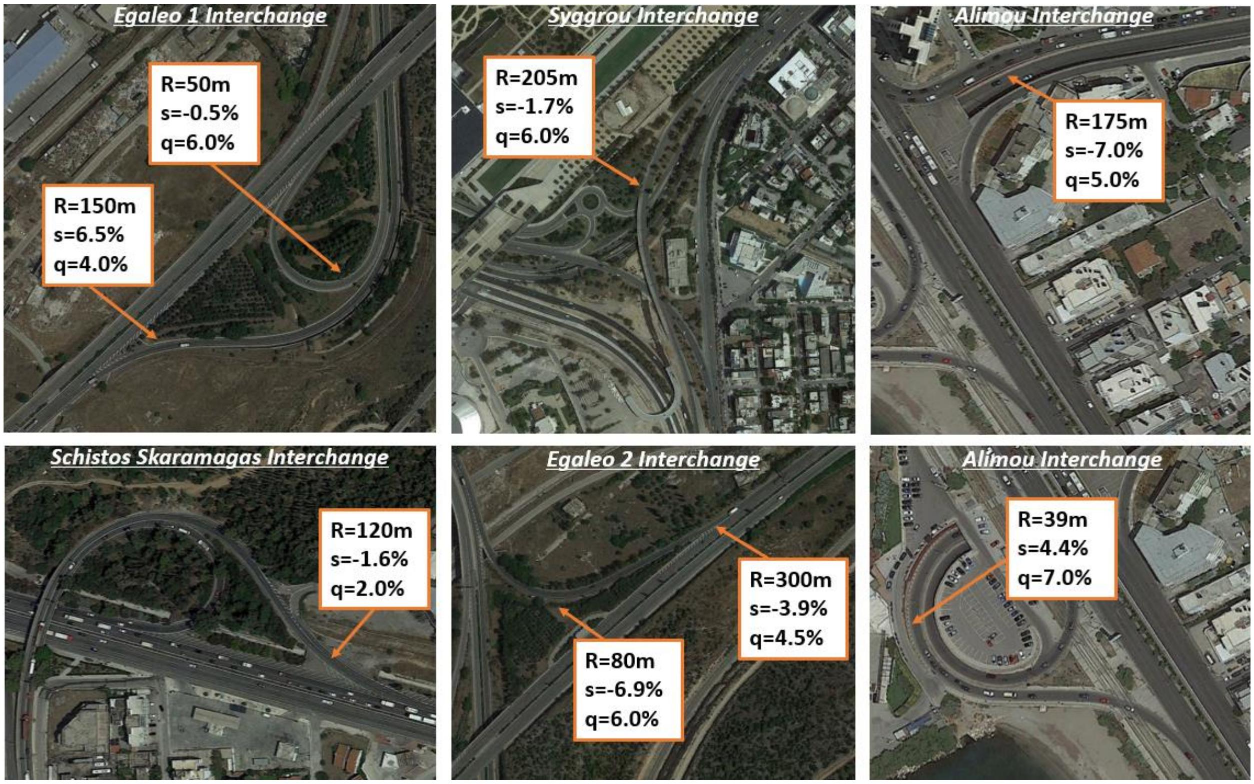

Figure 8 Selected interchange ramps (R, s, q are radius, gradient, superelevation respectively)

RESULTS

Lateral Acceleration and Design Radius

A key objective of the study is to explain the discrepancies (Figure 1) between the recorded lateral acceleration and the value derived from the geometric elements using Equation 1. The recorded values of lateral acceleration corresponding to the 85th percentile as a function of the radius of the examined interchange ramp curve are isolated and presented. It is noted that the radius is calculated at the median axis of the pavement.

Previous studies on interchange ramps (*Trakakis, Apostoleris & Psarianos, 2023 & 2024*) have demonstrated that the 85th percentile coincides with the safety threshold as perceived by the driver during traversal through interchange ramps and constitutes the critical factor of lateral acceleration. For the speed at which the lateral acceleration of the 85th percentile was recorded, the theoretical lateral acceleration is calculated based on Equation 1. The superelevation has been measured from available as-built plans in the study areas and inclinometers placed transversely on the axis. The results are presented in Figure 9.

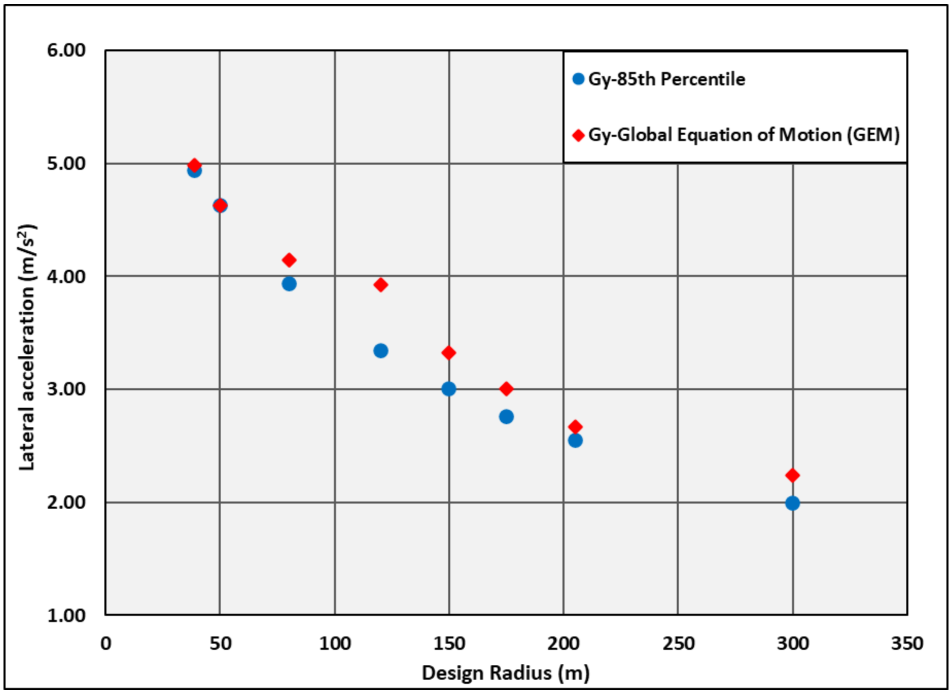

Figure 9 Correlation between the 85th percentile of lateral acceleration and the values anticipated by design (Equation 1) as a function of the curve radius

In Figure 9, the discrepancy between the recorded value and the expected value based on Equation 1 is immediately evident. Moreover, the design radius appears to influence the discrepancy between them. The recorded lateral acceleration is consistently lower than the equilibrium value, especially in radii greater than 80m. The largest discrepancies are found in curves with radii of 120m, 150m, 175m, and 300m with differences of 0.58 m/s^2, 0.32 m/s^2, 0.25 m/s^2, and 0.25 m/s^2, respectively. However, the design radius is not the only factor affecting this discrepancy.

To explain this discrepancy, Equation 1 must be used, given that the VERICOM 4000RG equipment has been tested on accurate trajectories and numerous studies and is reliable. In Equation 1, speed (V) is a constant with a specific value for each measurement. The superelevation (q) also takes a specific value, and it cannot be assumed that the vehicle's placement angle on the curve forms a compound inclination that significantly differs from the curve's superelevation. Therefore, the only remaining factor is the radius. This viewpoint had already formed when the researchers from the passenger seat observed different trajectories within the curve in most field measurements. However, this view was further supported by data from literature.

Driving Path Radius and Design Radius

To explain the deviations resulted, for each examined radius of the curve ramp, the driving radius values of the 15th, 50th, and 85th percentiles were recorded, as derived from Equation 1 using the lateral acceleration of the respective percentile, the speed corresponding to this value, and the superelevation. The driving radii were correlated with the design radii, as presented in Figures 10 and 11.

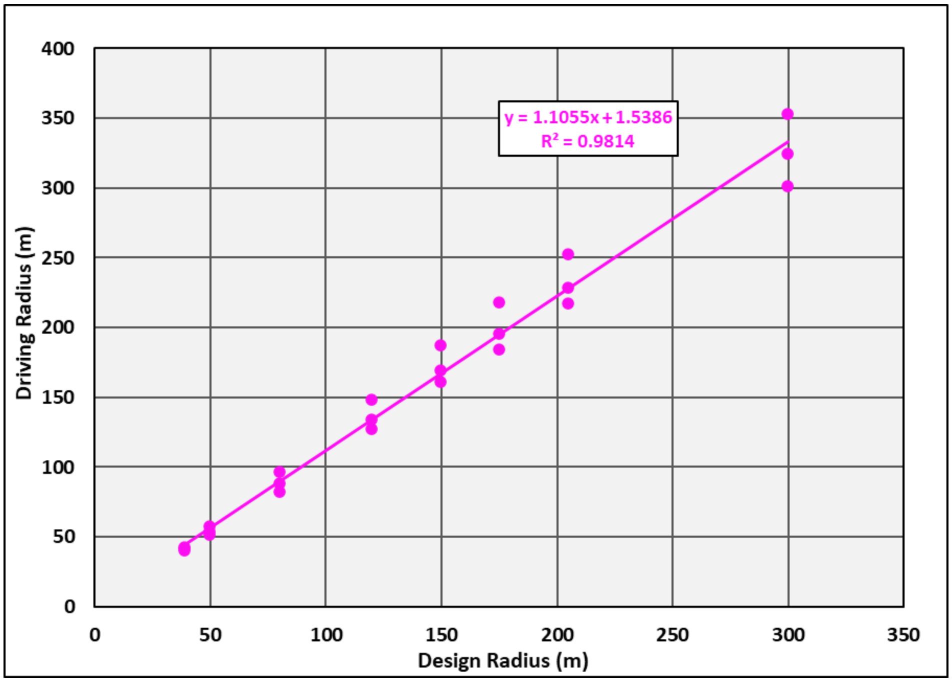

Figure 10 Correlation between Driving Path Radius and Design Radius in Interchange Ramps

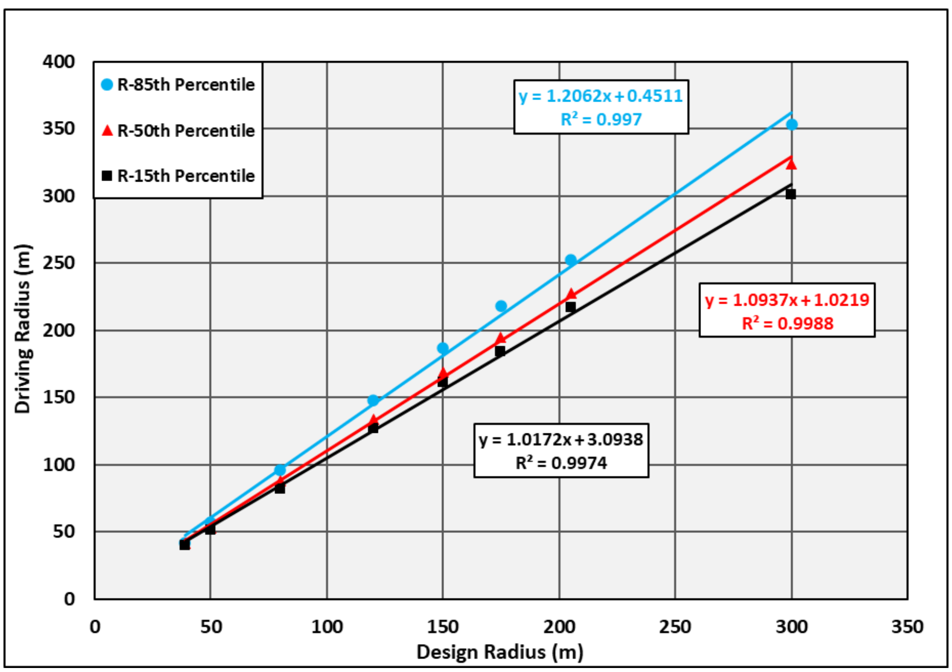

Figure 11 Correlation between Driving Radius Percentiles and Design Radius in Interchange Ramps

A very strong correlation between either the inherent driving radius or the percentiles and the design radius was observed, as the coefficient of determination is practically equal to one in each correlation. Also, the driving radius values corresponding to the 15th percentile are larger than the design radius values for radii up to 275m. Similarly, the driving radius values are even larger at the 50th and 85th percentiles as drivers choose to drive on larger radii. The highest rate of change appears to exist up to design radii of 175m, as will be shown in the following figures.

The inherent driving radii and corresponding for the 85th, 50th, and 15th percentiles are functions of the design radius through Equations 6 and 7, 8, and 9, respectively. Parameter Rd is the driving radius, R is the design radius and R^2 the coefficient of determination.

$$Rd\ (m) = 1.1055 \times R + 1.1356 \qquad R^2 = 0.9814 \tag{6}$$

$$Rd85\ (m) = 1.2062 \times R + 0.4511 \qquad R^2 = 0.9970 \tag{7}$$

$$Rd50\ (m) = 1.0937 \times R + 1.0219 \qquad R^2 = 0.9988 \tag{8}$$

$$Rd15\ (m) = 1.0172 \times R + 3.0938 \qquad R^2 = 0.9974 \tag{9}$$

Differential Radius and Design Radius

To better understand Figures 10 and 11, Figure 12 and Table 1 are provided in combination, which illustrates the differential radius values for each design radius, the driving radii as derived from Equation 1, and the rate of change of the differential radius. The rate of change is typically presented following the methodology of *Maljkovic & Cvitanic, 2021*. Still, it is not adopted in this study since there is no strong correlation between the rate of change of differential radius (ΔR %) and the design radius derived from the results of this research.

TABLE 1 Driving Radius and Differential Radius Depending on Design Radius

R (m)	Rd_{85} (m)	ΔR_{85} (m)	ΔR_{85} (%)	Rd_{50} (m)	ΔR_{50} (m)	ΔR_{50} (%)	Rd_{15} (m)	ΔR_{15} (m)	ΔR_{15} (%)
39	42	3	8	41	2	5	40	1	3
50	57	7	14	53	3	6	51	1	2
80	96	16	20	88	8	10	82	2	3
120	148	28	23	134	14	12	127	7	6
150	187	37	25	169	19	13	161	11	7
175	218	43	25	195	20	11	184	9	5
205	252	47	23	228	23	11	217	12	6
300	353	53	18	324	24	8	301	1	0

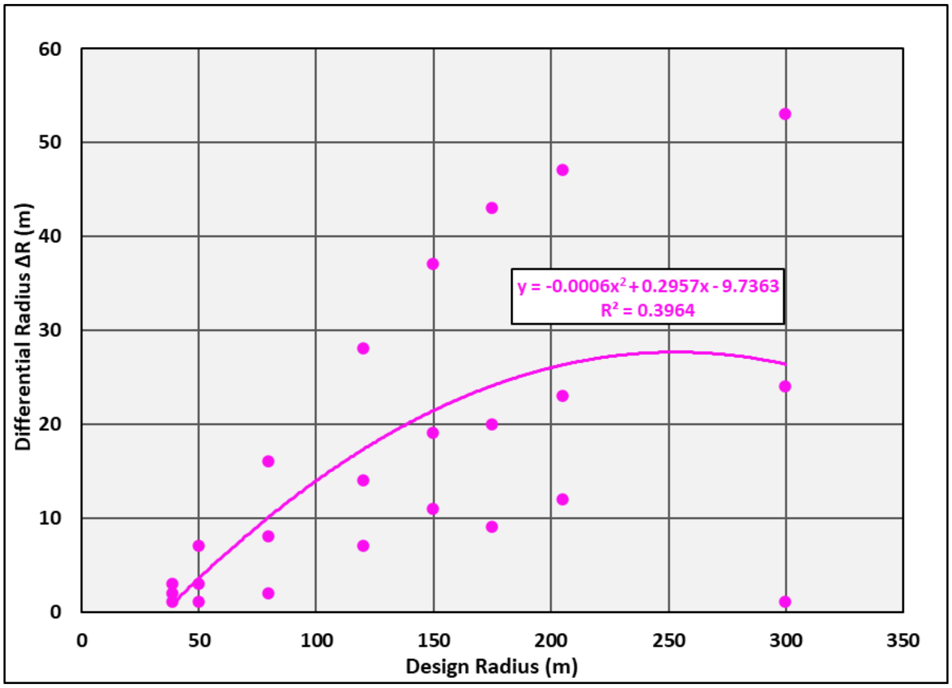

Figure 12 Correlation between Differential Radius and Design Radius in Interchange Ramps

$$\Delta R\ (\%) = \frac{Rdriving - Rdesign}{Rdesign} \times 100 \qquad (10)$$

Where:
R (m) is the Design Radius of the curve,
$Rd_{15,50,85}$ (m) is the Driving Radius for each percentile,
ΔR (m) is the Mathematical Differential Radius between driving and design radius &
ΔR (%) is the Differential Radius Rate of Change (relative error) resulting from Equation 10.

Figure 12 and Table 1 show a correlation between the values of the differential radius and the design radius. At the same time, it is observed that the differential radius value remains positive up to the curve with the maximum measured radius (300m). However, the inflection point of the differential radius appears at a radius of 250m. This means that positive differential radius values will be maintained for curves with radii up to 525m. This is logical since radii greater than 500m, especially with small deflection angles, do not differ in drivers' perception from tangents at interchanges (*Lytras et al., 2024*). For the rate of change of the differential radius as a function of the design radius, no significant correlation was found in contradiction with the conclusions drawn by *Maljkovic & Cvitanic, 2021* (Figure 5a), and therefore it is not further analyzed.

The correlation between differential and design radii is much stronger when analyzed in individual percentiles, as shown in Figure 13, judging by the high coefficient of determination values. The findings of this study suggest that drivers position themselves in such a way that they follow a new trajectory of a larger radius, directly influenced by the design radius value. This occurs progressively up to radii of 300m for the 85th percentile, up to 260m for the 50th percentile, and up to 200m for the 15th percentile, based on the mathematical value of the differential radius in Figure 13.

According to the equations, the mathematical value of the differential radius for the 85th and 50th percentiles will be zero at a radius of approximately 530m, and for the 15th percentile at a radius of approximately 450m. This result perfectly matches the overall diagram (Figure 12), which predicts a zero-differential radius at a design radius of 525m. Therefore, Figures 10,11,15 and Equations 6 to 9 are limited to radii of up to 300m. Also, the use of Figures 12,13, 14, and Equations 11 to 16 is limited to radii up to 525m for the inherent driving radius and 85th and 50th percentiles and 450m for the 15th percentile.

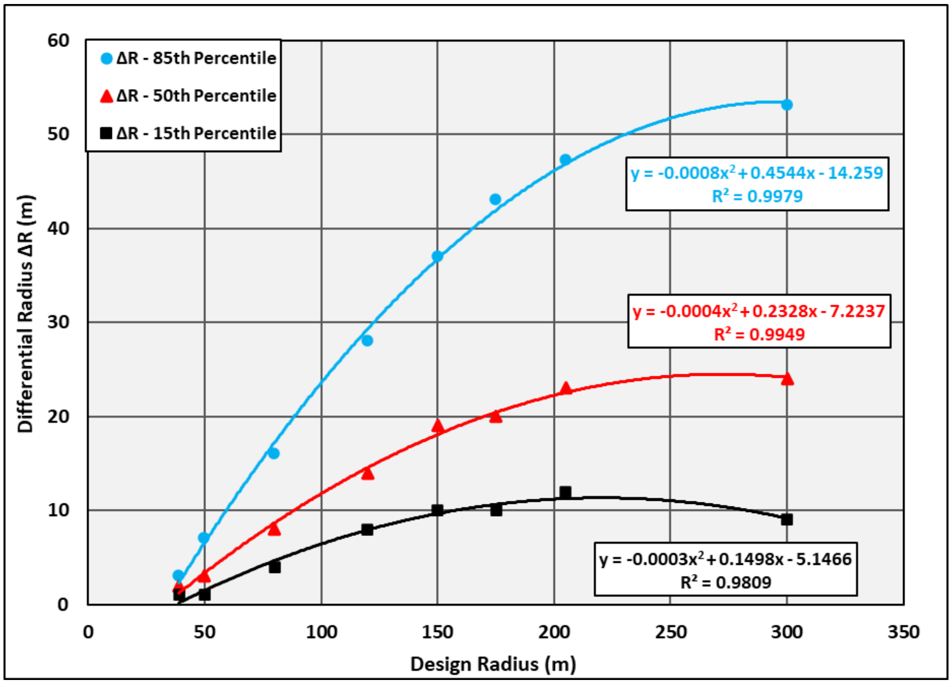

Figure 13 Correlation between Mathematical Differential Radius and Design Radius in Interchange Ramps

A second-degree polynomial relationship best describes the correlation between the individual percentiles of the differential radius and the design radius. For the 85th, 50th and 15th percentiles, Equations 11, 12, and 13 respectively are derived.

$$\Delta R85\ (m) = -0.0008 \times R^2 + 0.4544 \times R - 14.259$$

$$R^2 = 0.9979 \tag{11}$$

$$\Delta R50\ (m) = -0.0004 \times R^2 + 0.2328 \times R - 7.2237$$

$$R^2 = 0.9949 \tag{12}$$

$$\Delta R15\ (m) = -0.0003 \times R^2 + 0.1498 \times R - 5.1466$$

$$R^2 = 0.9809 \tag{13}$$

The coefficient of determination for the 85th percentile could have been even higher, approaching the value 1, if there had been less deviation between the differential radius recorded for the curve with a design radius of 175m and that predicted by Equation 11. This deviation is possibly due to the small deflection angle of the alignment in that specific curve, as explained later in this study.

Furthermore, for all three percentiles, $\Delta R_{85,50,15}$ deviations from the trend line are observed in the curves with radii of 50m and 150m, for the 85th and 50th percentiles in the curve with a radius of 120m, and for the 85th percentile in the curve with a radius of 175m. The reason lies in the geometric elements. The curves with radii of 50m and 150m have a road width of 4m, larger than all other curves except the one with a radius of 39m. The curve with a radius of 120m has 2 lanes (1 more than 6 of the remaining 7 curves), while the curve with a radius of 175m is the only one with two opposing directions without a physical or structural separation between the two directions.

Hence, it is deemed appropriate for the calculation of the differential radius to be primarily depended on the design radius, but also secondarily on the lane width (b), the number of lanes in the same direction (N) and the number of directions on undivided pavements (d).

Concerning the values of b, N, and d (Table 3) and Figure 13, three equations were created for the calculation of the mathematical value of differential radius (ΔR) as a function of design radius (R), lane width (b), number of lanes (N) in the same direction (mostly one and, in some cases, two), and number of directions (d) on undivided pavements for interchange ramps. Equations 14, 15, and 16 concern the differential radius for the 85th, 50th, and 15th percentiles, respectively."

$$\Delta R85\ (m) = -0.0008 \times R^2 + 0.46 \times R + 1.6 \times b + 0.55 \times N \times d - 21.41 \qquad (14)$$

$$\Delta R50\ (m) = -0.0004 \times R^2 + 0.23 \times R + 1.6 \times b + 0.55 \times N \times d - 14.15 \qquad (15)$$

$$\Delta R15\ (m) = -0.0003 \times R^2 + 0.15 \times R + 1.6 \times b + 0.55 \times N \times d - 12.35 \qquad (16)$$

Critical Values of Driving & Differential Radius as a Function of Design Radius

The 85th, 50th, and 15th percentiles presented as the safety, tolerance and comfort limit / threshold values respectively, in studies of lateral acceleration and longitudinal deceleration (*Trakakis, Apostoleris & Psarianos, 2023 & 2024*). However, in the case of the differential radius, these conditions are reversed. The 85th percentile corresponds to the comfort limit / threshold value, the 50th percentile remains the tolerance limit / threshold value, and the 15th percentile becomes the safety limit / threshold value. This happens because lateral acceleration decreases with increasing radius (Equation 1). The larger radius the road users drive, the more comfort they seek within the curve.

Therefore, Figure 14 is the modified Figure 13 and constitutes a consolidated diagram classifying as comfort, tolerant or safe the differential radius value depending on the design radius in interchange ramps. Similarly, Figure 15 is the modified Figure 11, where the limit/threshold values for comfort, tolerance, and safety are directly calculated based on the driving radius. Now, alongside lateral acceleration and longitudinal deceleration values, new threshold values have been established for both differential and driving radii based on driving behavior in interchange ramps. Hence, the calculation of the comfort, tolerance, and safety limit values can take place utilizing Equations 7, 8 and 9 in the cases where the driving radius is directly sought as a function of the design radius. In cases where the differential radius is the scope of work, then Equations 11 and 14 are recommended for the direct calculation of the comfort limit, Equations 12 and 15 for the tolerance limit, and Equations 13 and 16 for the safety limit. This method represents a first approach to the issue in an effort to distinguish between road safety and operational criteria, which will be supported by even more data in future research.

The difference between the results derived from the models for the driving and the differential radius is not significant. However, it is recommended to choose the differential radius as a study criterion since its calculation includes elements of the ramp's cross-section, but also because it is judged to be an appropriate way of expressing and evaluating the results.

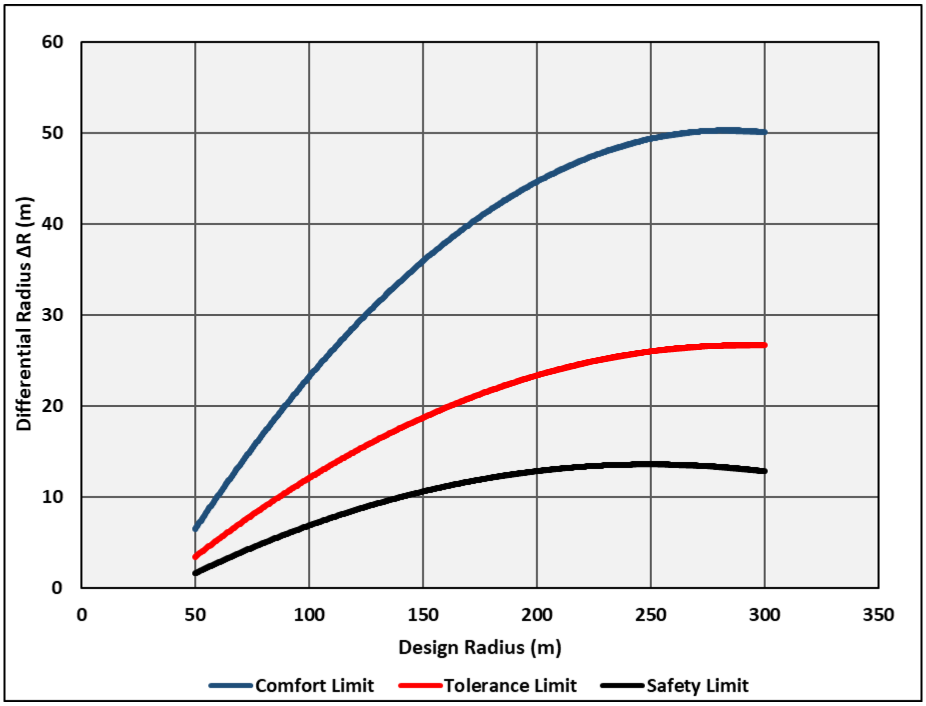

Figure 14 Mathematical Differential Radius Critical Values and Design Radius in Interchange Ramps

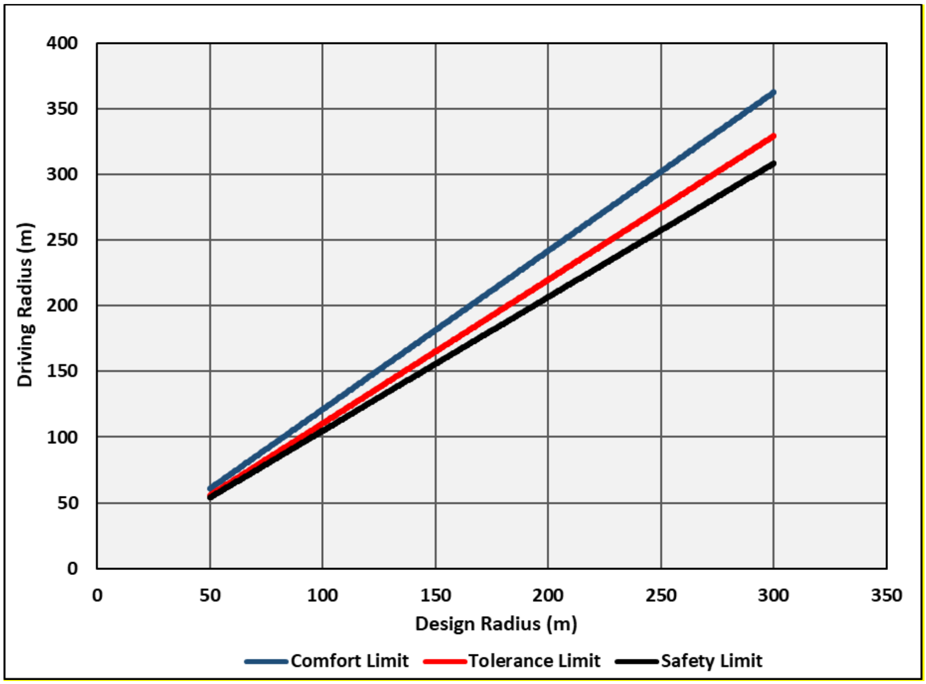

Figure 15 Driving Radius Critical Values and Design Radius in Interchange Ramps

The models presented through Figures 14 and 15 offer standard values as a basis for the critical driving & differential radius in a curve of interchange ramp depending on the design radius. It appears that the 15th percentile/safety limit almost approaches the design radius, especially for the driving radius factor.

TABLE 2 Expected Critical Values of Driving & Differential Radius Depending on Design Ramp Radius in Interchange Ramps

Design Radius (m)	Driving Radius (m)			Differential Radius (m)		
	Comfort Limit (R_{85})	Tolerance Limit (R_{50})	Safety Limit (R_{15})	Comfort Limit (ΔR_{85})	Tolerance Limit (ΔR_{50})	Safety Limit (ΔR_{15})
50	61	56	54	6	3	2
75	91	83	79	15	8	4
100	121	110	105	23	12	7
125	151	138	130	30	16	9
150	181	165	156	36	19	11
175	212	192	181	41	21	12
200	242	220	207	45	23	13
225	272	247	232	47	25	13
250	302	274	257	49	26	14
275	332	302	283	50	27	13
300	362	329	308	50	27	13

Differential Radius and Basic Geometric Elements

In addition to the design radius studied in the previous figures and the superelevation analysed through lateral acceleration and design radius, additional geometric elements of each curve's horizontal and vertical alignment in the interchange ramp were examined. In Table 3, included critical measured geometric elements are included for each value of the design radius of the ramp curve.

TABLE 3 Basic Geometric Elements of the Curves of the Examined Interchanges

R (m)	L (m)	s (%)	γ (grades)	q (%)	CCR (grads/km)	Rd_{85} (m)	Rd_{50} (m)	Rd_{15} (m)	b (m)	N	d
39	108	4.4	174	7%	1611	42	41	40	4.5	1	1
50	105	-0.5	300	6%	2857	57	53	51	4	1	1
80	155	-6.9	114	6%	735	96	88	82	3.25	1	1
120	70	-1.6	45	2%	643	148	134	127	3.25	2	1
150	100	6.5	48	4%	480	187	169	161	4	1	1
175	45	-7.0	18	5%	400	218	195	184	3	1	2
205	185	-1.7	73	6%	395	252	228	217	3.25	2	1
300	52	-3.9	10	4.5%	192	353	324	301	3.25	1	1

Where:
R (m) is the design radius of the curve,

L (m) is the length of the design curve of the examined ramp,
s (%) is the road gradient,
γ (grades) is the deflection angle (1 grade=0.9 degrees),
q (%) is the superelevation of the road,
CCR is the curvature change rate given by the Equation $CCR\ (\frac{grad}{km}) = \frac{\gamma}{L}$, (17)
$Rd_{15,50,85}$ (m) is the driving radius for each percentile,
b is the road width for the examined direction,
N is the number of lanes in the ramp in the same direction &
d is the number of directions in undivided ramps (1 or 2).

Curve Length

For each examined curve, the design length was measured and correlated with the differential radius, as shown in Figure 16. The calculated length pertains to the entire curve, including the entry and exit clothoids.

Although the curve length was considered by *Maljkovic & Cvitanic, 2021* to be the most critical factor affecting the differential radius (Figure 5b & Equation 5), this is not confirmed by the present study. Even when the measurements are divided into individual percentiles, the coefficient of determination remains very low, and in a generalized set, it is even lower.

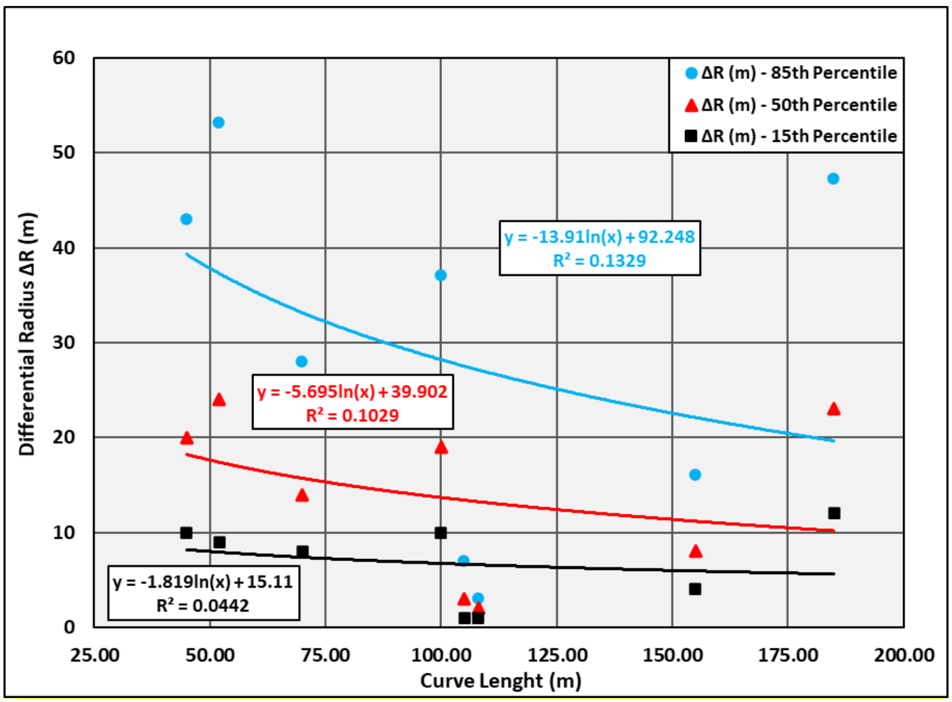

Figure 16 Correlation between Differential Radius and Curve Length in Interchange Ramps

Road Gradient

The longitudinal road gradient significantly affects driving behavior, mainly regarding the speed. For each curve examined, the longitudinal gradient was correlated with the differential radius. The observation from Figure 17 indicates that even in the detailed analyses across percentiles, there is no strong correlation ($R^2 \approx 0.10$) between the longitudinal road gradient and the differential radius.

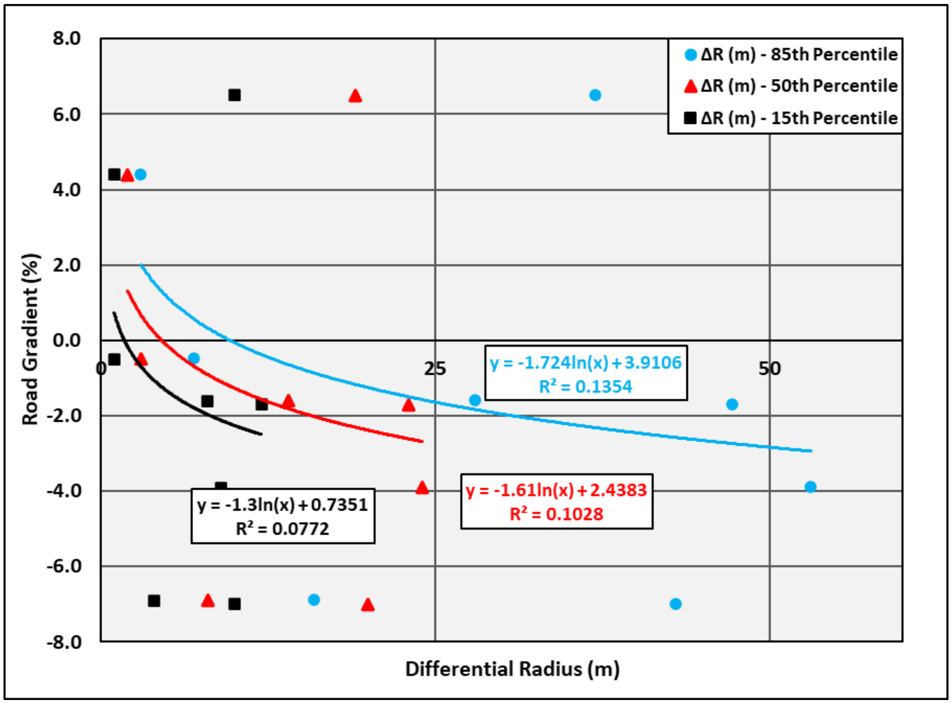

Figure 17 Correlation between Differential Radius and Road Gradient in Interchange Ramps

Deflection Angle

The deflection angle is a highly significant factor influencing driving behavior. Greek geometric design guidelines (*OMOE-X, 2001*) base the selection of the clothoid parameter "A" on the central angle (α), which is directly related to the deflection angle (γ). Similarly, critical parameters in the German guidelines *RAA, 2008* (such as the transition from tangent to curve without clothoid) and *RAL, 2012* (combination of horizontal and vertical alignment) are determined based on the deflection angle. The correlation of the deflection angle of each examined curve in combination with the differential radius (Figure 18) demonstrated that road radii on interchange ramps are directly affected by the deflection angle.

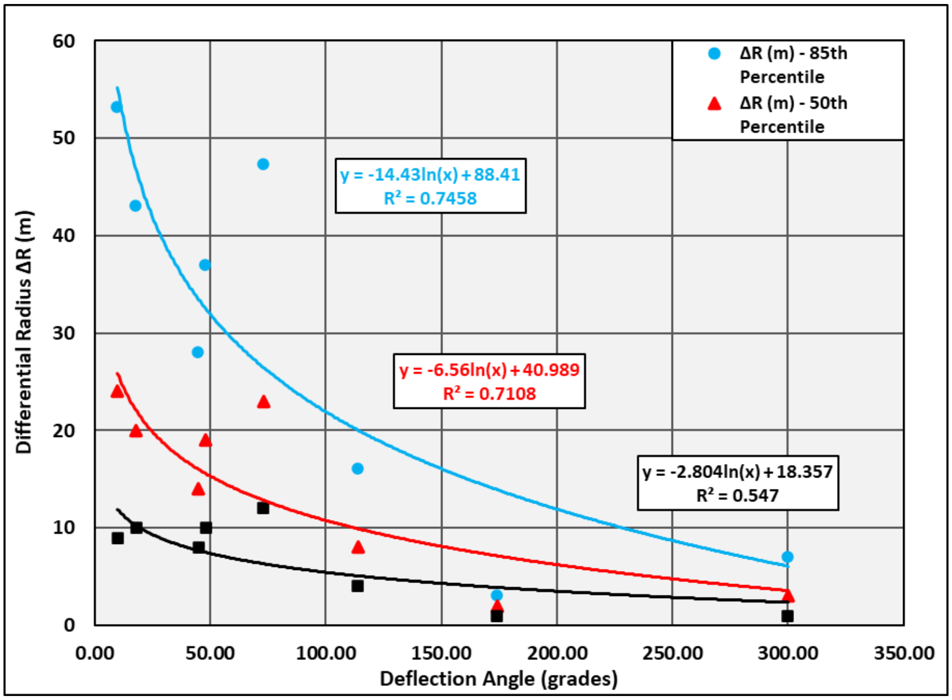

Figure 18 Correlation between Differential Radius and Deflection Angle in Interchange Ramps

On curves with a small deflection angle, drivers choose a larger driving radius than the design one, as the differential radius approaches higher values. Increasing the deflection angle decreases the differential radius, meaning that the driving radius approaches the design radius more closely.

Based on Figure 13, the driving radius of the 175m radius curve deviates from the trendline more than the other radii on the 85th percentile. This is explained by the relatively small deflection angle (γ=18grades) for that specific curve. A small change in direction combined with a moderate to large design radius value (typical values for interchange ramps) allows drivers to choose larger driving radii.

Another example could be a curve with a small deflection angle (γ=10grades) and a design radius of 300m, where the differential radius measures 353m, 323m, and 301m for the 85th, 50th, and 15th percentiles, respectively. However, in this specific curve, the radius value induces the most significant impact.

Curvature Change Rate (CCR)

Figure 19 includes only the CCR for the 85th and 50th percentiles, as the values for the 15th percentile were not as reliable, mainly due to the combination of the correlation between the deflection angle and curve length. For the 85th percentile particularly, and for the 50th subsequently, the coefficient of determination (R^2) is quite high, and the approach of the driving radius to the design radius in large CCR and correspondingly the large differential radii in small CCR is reasonably explained. Therefore, the differential radius could be directly explained by the CCR in interchange ramps, where the curve length does not vary as much among curves with different radii, as it does in geometric design in the main road network.

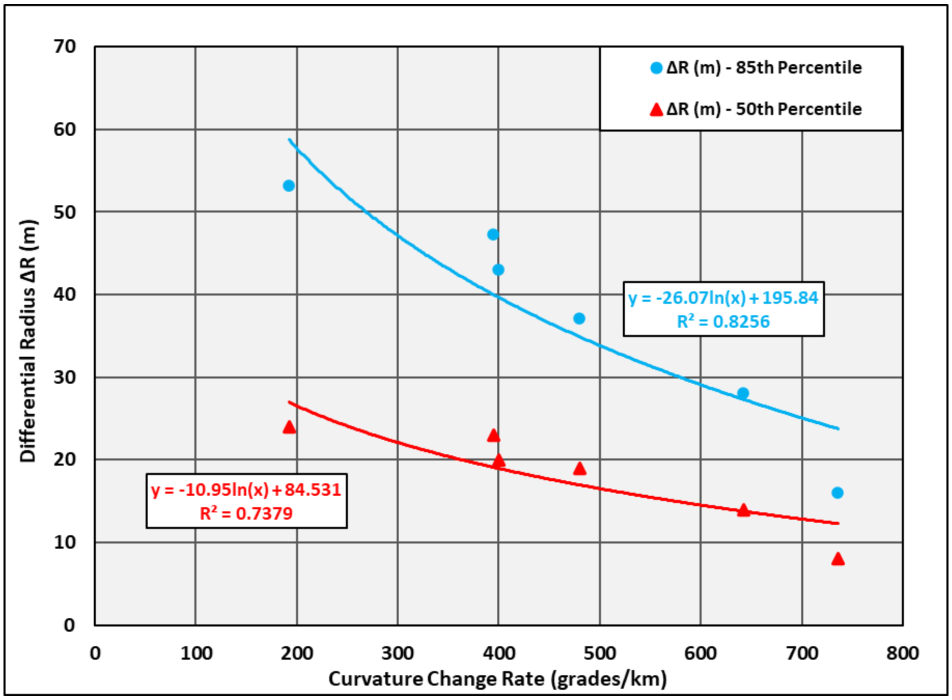

Figure 19 Correlation between Differential Radius and Curvature Change Rate in Interchange Ramps

CONCLUCIONS

The difference observed between lateral acceleration and its theoretical value in interchange ramps is due to the driving radius. Road users regularly choose to drive larger radii in more strained paths comfortable than the design radii, positioning their vehicle on the curve to receive the lateral acceleration they feel comfortable. A driving radius that approaches the design value means that drivers drive at the limits they perceive their driving task as safe.

Figures 10 and 11 can now directly result in the consistently larger driving radius (compared to the design one), and in combination with Figure 15, the established comfort tolerance and safety limits as perceived by drivers based on their vehicle trajectories can be estimated.

Analyzing the differential radius in individual percentiles (15th, 50th, and 85th) reveals a strong correlation with the design radius. The 15th, 50th, and 85th percentiles are established as the limits of safety, tolerance, and comfort of the differential radius according to this study, complementing the above limits for the mathematical value of the design radius and those established for lateral acceleration and longitudinal deceleration in previous research (*Trakakis, Apostoleris, and Psarianos 2023, and 2024*).

The deviations in lateral acceleration and, consequently, in the actual radius are preferably expressed utilizing the mathematical value of the differential radius (ΔR) since its usage range in interchange ramps reaches up to radii of 525m. Radii greater than 525m are treated as tangents by drivers, especially at small deflection angles, and it is not deemed appropriate to include them in this study's model.

Equations 14, 15, and 16 are integral equations for calculating the differential radius in interchange ramps, considering the design radius as well as critical cross-sectional elements such as the lane width, the number of lanes in the same direction and the number of directions on single carriageways. Following this methodology, the calculation of the differential radius is obtained with the highest possible reliability, based on the corresponding coefficients of determination.

The correlation between the differential radius and basic geometric elements showed a strong linked relationship only with the design radius, the deflection angle and the curvature change rate (CCR). The total length of the curve and the longitudinal slope did not seem to affect the differential radius. Superelevation was not examined separately since it is included in Equation 1 for calculating the differential radius.

The study's conclusions agree with the study by *Aminfar et al. 2023* in the increase of the differential radius along with the increase of the design one, given that the driving radius is always larger than the design one. In contrast, they completely disagree with the findings of *Maljkovic & Cvitanic, 2021and Glennon, J.C., et al., 1985,* who in most cases find a smaller driving radius compared to the design one.

Maljkovic & Cvitanic, 2021 agree on a larger driving radius only for curves with radii up to 150m. However, the ΔR (%) index (Equation 5 as a percentage value) they recommend as an evaluation factor of the results proves to be statistically insignificant based on the findings of the present study, which considers the absolute value ΔR (m) as a key factor. Also, they consider the length of the curve as the most critical parameter for the differential radius and not significant at all for the deflection angle, in contrast to the outcome of the present research.

However, the measurements are a key factor in determining results, and the abovementioned studies took place on the main road network, not at interchanges like the present research. Therefore, it may be concluded that driving along an interchange ramp is a different task than one on an open highway, and the geometric design of ramps should consider it accordingly.

Both the figures, tables, and equations are proposed to be considered properly in the geometric road design manuals especially in the case of design exception procedures allowing designers to assess accordingly the constant larger driving radius and the corresponding lower lateral acceleration drivers seek when traversing interchange ramps. Within a performance-based design concept, the minimum recommended design radii values by design policies can be reduced in some challenging environments without safety concerns since drivers tend to drive larger radii than constructed. Finally, the deflection angle can now be incorporated in the selection process of horizontal radii as a secondary influencing factor after speed and the coefficients of tangential and side friction.

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