Speed Impact on Interchange Ramps

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ABSTRACT

The primary scope is to conduct a study that investigates the speed impact on different types of interchange ramps (7 ramps of loop, semi-directional, and directional types were examined). The data were derived from real field measurements involving 160 drivers with various characteristics (age, experience and gender). The recordings were made using tested and trusted equipment (time-lapse of 0.01 sec) attached to the vehicle. An additional objective is to establish threshold/limit values for comfort, tolerance, and safety for speed on interchange ramps depending on the curve radius. Speeds within the curve are isolated, divided into the 15th, 50th, and 85th percentiles and then compared with values derived from literature models for driver comfort, tolerance, safety and with the threshold/limit safety values listed in geometric design manuals. The results indicate that many literature threshold values are aggressive, as the increasing deviation from the measured speeds of this study is significant. In contrast, the applied models in the geometric design guidelines for calculating the minimum radius based on speed are conservative. In conclusion, the speeds corresponding to the 15th, 50th, and 85th percentiles of this study are proposed in the road geometric design guidelines as the thresholds/limits of comfort, tolerance, and safety depending on radius, respectively. Thus, the method for selecting the speed limits in dry pavement and calculating the minimum radius can be modified, considering the corresponding threshold/limit values of lateral acceleration proposed by researchers in previous studies. Therefore, geometric design in interchanges can become more economical, especially in expropriation conditions.

Keywords: speed, interchange ramps, threshold/limit values, comfort, tolerance, safety, geometric design manuals, guidelines models, literature models

INTRODUCTION

The V_{85} increases by 0.5 km/h per year in Greece (*Lamm, Psarianos & Cafiso, 2002*) and drivers tend to exceed the speed limit up to 12% of their total driving time (*Yanis et al., 2017*). These values are likely even higher in modern vehicles and are expected to increase further with the next generation of vehicles. This is due to the EU regulation for mandatory new car equipment starting in July 2024, which includes intelligent speed assistance, attention warning systems for driver drowsiness or distraction, event data recorders, emergency stop signals, lane-keeping systems, automated braking for vehicles, and more. Drivers tend to drive at higher speeds when they feel that their vehicle provides them with safety. (Lytras et al., 2024).

In a previous study by authors (*Trakakis, Apostoleris and Psarianos, 2022*), it was found that vehicles circulating on interchange ramps were released 72% after 2008 and 45% after 2016, collecting data within the years 2019 and 2020. Plenty of the geometric design guidelines (*OMOE-X, 2001, RAA, 2008, RAL, 2012 etc*.) were established in previous decades and do not even consider the ABS (Anti-lock Braking System) and ESC (Electronic Stability Control) in the calculation of the critical design values (tangential and side friction coefficients, minimum curve radius, speed limit, utilization factor, superelevation and stopping sight distances). Hence, the threshold and limit values recommended for comfort, tolerance, and safety do not align with the capabilities of modern vehicles.

Updating design manuals based on the concept of performance-based design and establishing critical speed values on interchange ramps, which describe driver comfort, tolerance, and safety as perceived by today's drivers, is imperative. The key condition is the establishment of variable values depending on the curve radius rather than absolute ones.

This study shows that the limits set by geometric design manuals are increasingly exceeded as the design radius increases. Additionally, the threshold values (independent of radius) set by literature models cannot adequately describe driving behavior on interchange ramps. The variable values are safer, as the comfort or safety speed can be directly estimated for each design radius. In contrast, the absolute values set specific thresholds regardless of the geometric elements of the curve and mainly the way drivers behave on interchanges. By following the variable values, the minimum design radius can be reduced more on roads of lower design speed and less on higher. Conversely, the allowable speed limits can be increased more in curves with smaller radii compared to those with larger radii in dry pavement conditions and to distinguish them from those corresponding to wet pavement.

PAST STUDIES

Speed as a Function of Design Radius

Figure 1 includes speed models derived by measurements in interchanges. *De Jong, 2017* models were established by taking measurements on 16 curves of interchange ramps (radii ranging between 70m and 395m) in the Netherlands. Data were collected either via a smartphone app (Equation 1) or by a helicopter equipped with a camera (Equation 2). The *Jafarov and Zaluga, 2020* model (Equation 3) was developed using measurements from 18 interchange ramps in Moscow, utilizing a laboratory vehicle equipped with a GPS recorder and two cameras. All the ramps were of the flyover type and had two lanes, with curve radii ranging from 30m to 270m, superelevation in the curve at 2.0%, and longitudinal gradients up to 5.5% (ascending ramps) and 5.0% (descending ramps).

Xu et al., 2018 models (Equations 4 & 5 for ascending and descending ramps respectively) were derived from measurements on helical ramps in China, with radii ranging from 27m to 60m. These measurements were taken using either an AHR system (consisting of an IMU, a 3D accelerometer, and a gyroscope) or a Laser Doppler Tachometer.

$$V85 = 29.607 \times \ln(R) - 61.964 \qquad R^2 = 0.877 \tag{1}$$

$$V85 = 27.943 \times \ln(R) - 55.106 \qquad R^2 = 0.794 \tag{2}$$

$$V85 = 20.162 \times \ln(R) - 30.163 \qquad R^2 = 0.983 \tag{3}$$

$$V85 = 21.803 \times \ln(R) - 43.175 \qquad R^2 = 0.940 \tag{4}$$

$$V85 = 28.494 \times \ln(R) - 68.198 \qquad R^2 = 0.962 \tag{5}$$

Where:

V_{85} (km/h) is the operating speed,
R (m) is the design radius of the curve &
R^2 is the coefficient of determination.

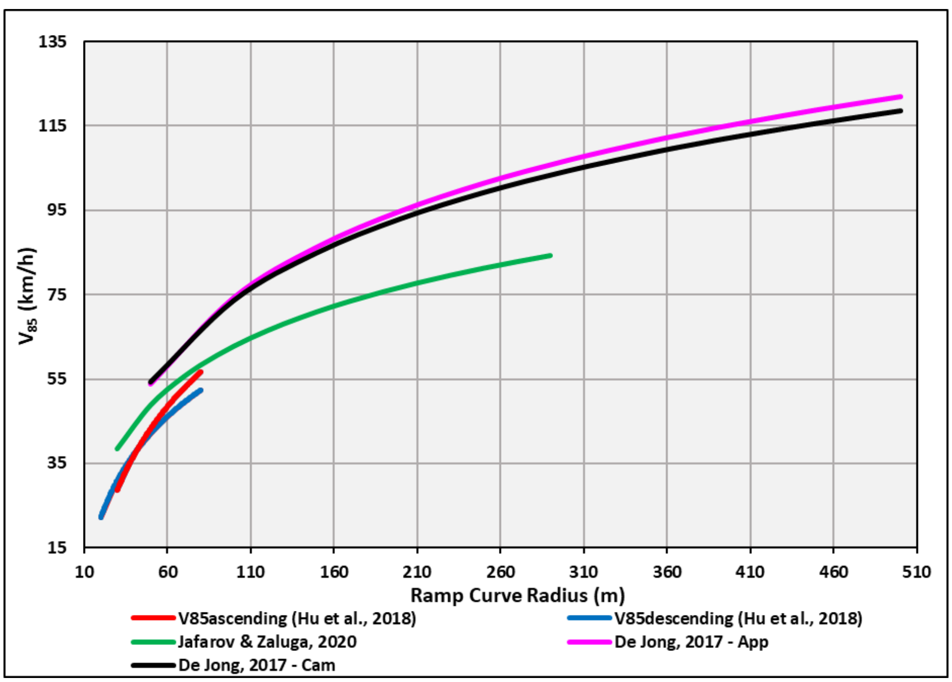

Figure 1 V_{85} depending on radius based on previous studies on interchange ramps

Literature models for calculating operating speed as a function of radius on main carriageways are presented in Figure 2. Equations 6, and 7 correspond to the models established by *Lippold, 1997* (universal function) and *Marchionna & Perco, 2008* (measuring curves with radii between 100m and 635m), respectively. Equations 8 and 9 correspond to the models of *Kanellaidis et al., 1990* and *Bird & Hashim, 2005* respectively. Coefficients of determination are noted only for those studies where they were reported in the comprehensive study by *Hassan et al., 2011*.

$$V85 = 18.2222 \times \ln(R) - 4.880 \tag{6}$$

$$V85 = 118.11 - \frac{510.56}{\sqrt{R}} \tag{7}$$

$$R^2 = 0.58$$

$$V85 = 129.88 - \frac{623.1}{\sqrt{R}} \tag{8}$$

$$V85 = 104.379 - \frac{4698.216}{R} \tag{9}$$

$$R^2 = 0.79$$

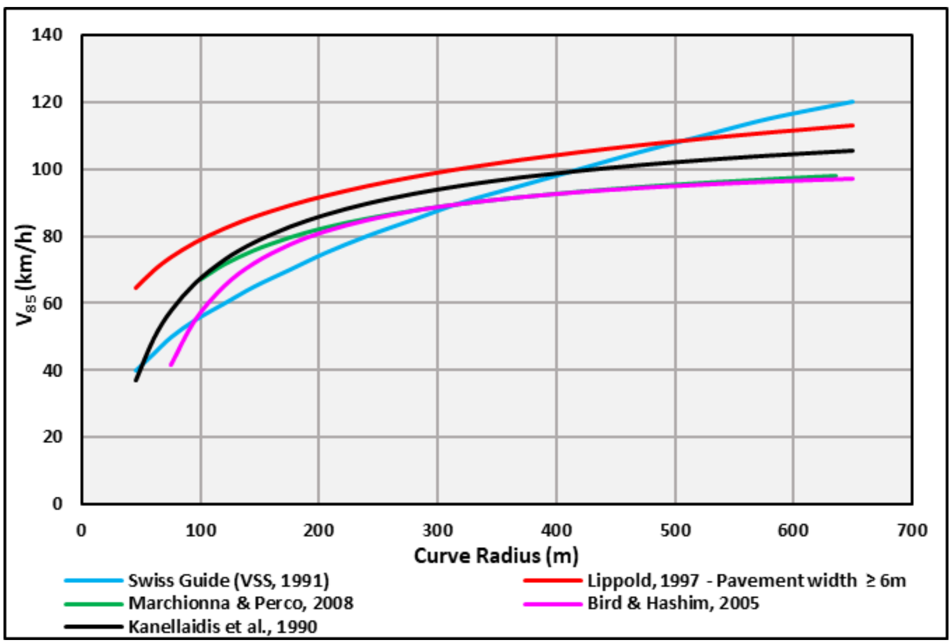

Figure 2 V_{85} depending on radius based on previous studies in main carriageways

The study by *Vos et al., 2022* on 99 freeway sections in the Netherlands and a total of 153 curves was based on determining speed at 4 breakpoints (BPs). The BPs are the positions around the curve start and end where drivers deviate from a constant speed value (*Montella et al., 2015* and *Vos et al., 2021*). BPs 2 & 3 (Figure 3) correspond to a few meters on either side of the curve's midpoint, where the speed remains constant. The V_{85} at BPs 2 & 3 is calculated as a function of the radius and a coefficient dependent on the number of lanes, based on Equations 10 and 11.

$$V85bp_2 = 28 \times \ln(R) + 7 \times n - 58 \qquad R^2 = 0.961 \tag{10}$$

$$V85bp_3 = 27 \times \ln(R) + 7 \times n - 51 \qquad R^2 = 0.919 \tag{11}$$

Where:
V_{85bp} (km/h) is the operating speed in breakpoints 2 & 3,
R (m) is the design radius of the curve,
n is the distinction of having 1 or more lanes (value 0 corresponds to 1 lane and value 1 to more lanes) &
R^2 is the coefficient of determination.

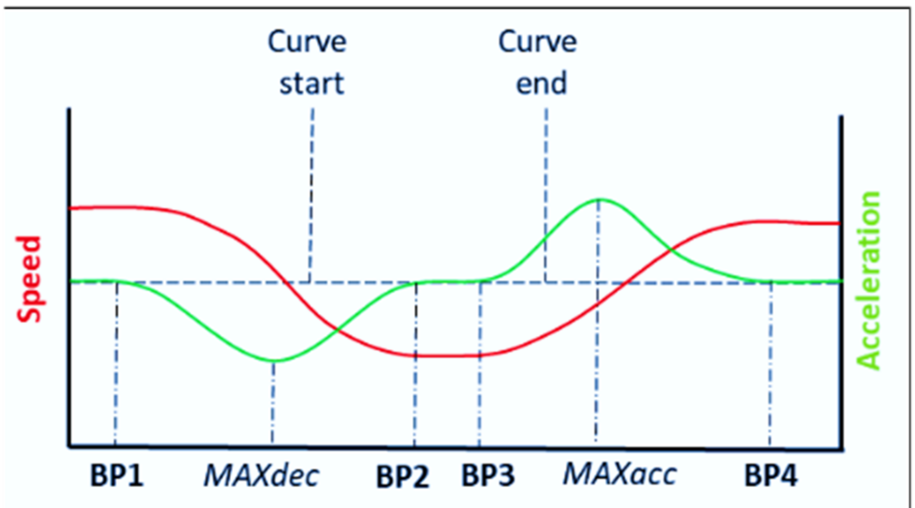

Figure 3 Speed and acceleration profiles, showing the positions of the breakpoints and maximum deceleration and acceleration based on the curve start and end (Vos et al., 2022)

Lateral Acceleration Threshold Values and Speed

Lateral acceleration is related to speed based on the global equation of motion (Equation 12).

$$f_R = \frac{V^2}{127 \times R} - q \leftrightarrow V = \sqrt{127 \times R \times (f_R + q)} \tag{12}$$

Where:
V (km/h) is speed,
R (m) is the design radius of the curve,
f_R is the side friction coefficient, which is converted to unbalanced lateral acceleration by multiplying with the acceleration due to gravity (g=9.81 m/s^2) &
q is the design superelevation of curve.

McGee et al., 1984, Felipe, 1996, Schofield, 2001, and *Xu et al., 2015* establish comfort limits of 1.96 m/s², 3.92 m/s², 2.45 m/s², and 1.80 m/s², respectively. *McGee et al., 1984, Felipe, 1996,* and *Levinson, 2007* determine safety limits of 2.94 m/s², 3.92 m/s², and 7.42 m/s², respectively. *McGee et al., 1984* define a stability limit of 6.87 m/s², the *Geotab Institute, 2011* specifies a harsh limit of 4.76 m/s², *Neves, 2014* identifies hard and extreme lateral acceleration limits of 2.94 m/s² and 4.42 m/s² respectively, and *Xu et al., 2015* determine medium comfort and discomfort limits of 3.60 m/s² and 5.00 m/s² respectively.

The *OMOE-X, 2001, RAA, 2008, RAL, 2012,* and *AASHTO, 2018* guidelines have established specific values (Table 1) for the tangential or the side friction coefficients for specific speed values on wet pavement. *OMOE-X, 2001, RAA, 2008,* and *RAL, 2012* calculate the side friction coefficient as a percentage of the tangential friction coefficient (derived from traction measurements on wet pavements and related to speed through Equation 13) based on the utilization factor, established by *Lamm, 1984* (Equation 14).

$$f_T = 0.59 - 4.85 \times 10^{-3} \times V + 1.51 \times 10^{-5} \times V^2 \quad (13)$$

$$f_R = 0.925 \times f_T \times n \quad (14)$$

Where:

f_T is the tangential friction coefficient,
V is the design speed,
f_R is the side friction coefficient,
n is the utilization factor, and its values vary depending on the curve's superelevation (n=40% for q_{max}=7%, & n=10% for q_{min}=2.5% according to *OMOE-X, 2001* for main carriageways designed on mountainous relief and n=50% for q_{max}=6% & n=30% for q_{min} =2.5% according to *RAA, 2008* for interchange ramps)

TABLE 1 Tangential and side friction coefficients set by guidelines

Speed (km/h)	$F_{tangential,OMOE-X}$	$F_{tangential,RAA}$	$F_{side, OMOE-X}$ (*)	$F_{side,RAA}$ (*)	$F_{side,AASHTO}$
50	0.385	0.38	0.14	0.18	0.28
60	0.353	0.36	0.13	0.17	0.23
70	0.324	0.34	0.12	0.16	0.19
80	0.299	0.32	0.11	0.15	0.17
90	0.276	0.3	0.10	0.14	0.15
100	0.256	0.29	0.09	0.13	0.14
110	0.239	0.28	0.09	0.13	0.13
120	0.225	0.27	0.08	0.12	0.12
130	0.215	0.25	0.08	0.12	0.11

(*) Indicative values for maximum superelevation (q) derived from Equation 14.

3. METHOD

Structure of Measuring Procedure

The initial step was the search for interchange ramps of different types and with different geometric elements (Figure 4). Loop, semi-directional, and directional ramp types on highways in Attiki, Greece, were examined. A crucial factor was to select curves with different design radius (R) and distributed in such a way that the results reflect a wider range of radius (50m-500m) to create reliable radius ramp profiles.

The maximum longitudinal gradient (s) 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.

In *Green Book, 7th Edition 2018* it is mentioned that for design speeds over 70 km/h or up to 30 km/h, the maximum allowable gradient is 5% or 8% respectively. This restriction is adhered to in this research to avoid high and biased speed values that do not correspond to the fundamental geometric elements (primarily radius and superelevation) of the curves. The superelevation (q) of the curve should not exceed 7% and preferably should be kept at 6% (within the margins set by *AASHTO, 2018* or *RAA, 2008* guidelines).

The measurements were fulfilled on days with low traffic volumes (i.e. early weekend mornings or holidays) between 2020 and 2023. Ideal weather conditions, specifically dry pavement, were sought during the field measurements for this research, since during rainy conditions, driving behavior tends to be notably conservative. The recording for the vehicle was started 1km before the ramp and only when the vehicle immediately in front was at a considerable distance and when the vehicle immediately behind was at a distance such that there was no possibility of overtaking the examined vehicle and ultimately obstructing it. Approximately 500m distance in either direction was sufficient for the application of this restriction. All the participant drivers characterized their passage unhindered by external factors.

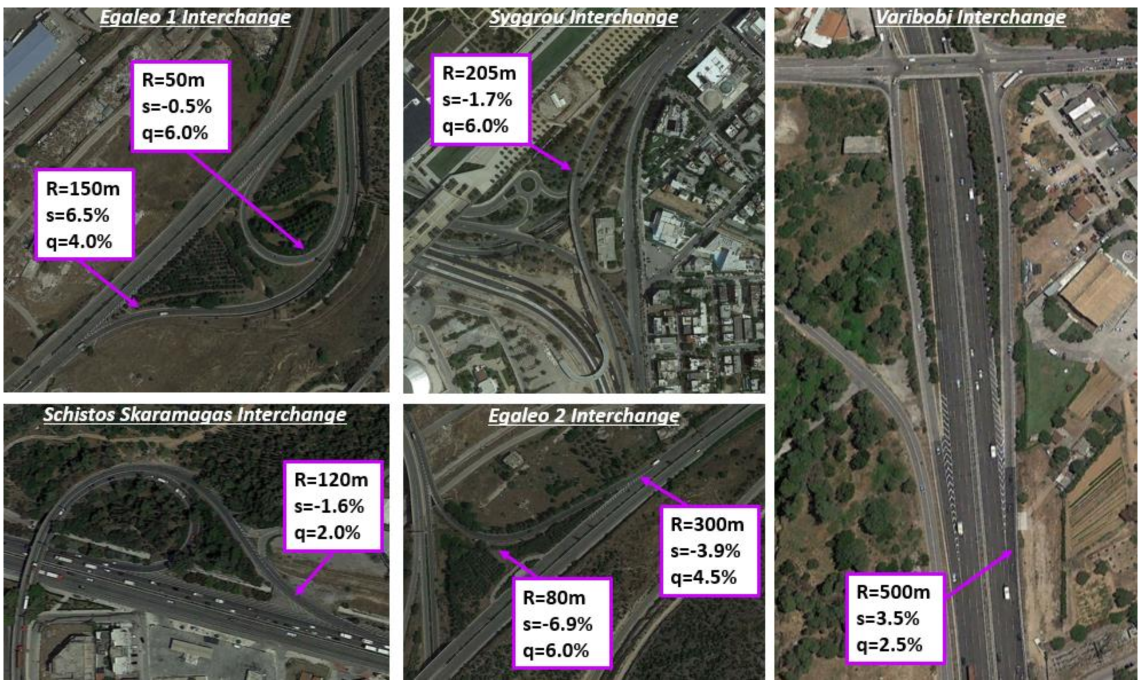

Figure 4 Selected interchanges

Since the total number of curves examined was not large (7 in total), the reliability of the study needed to be ensured by involving a large sample of drivers with varying characteristics, reflecting the actual diversity found in a road network. This approach would allow the influence of the design radius on driving behavior to be adequately assessed by recording a range of speed values for the same radius.

In this study, 160 drivers with different characteristics (age group, driving experience, gender) and various types of vehicles (micro, hatchback, sedan, SUV and MPV) participated. Specifically, the drivers were between 18 and 65 years old, had driving experience ranging from 6 months to 35 years, and were 80% male and 20% female. No vehicle manufactured before 2014 was used. The maximum and average vehicle ages were 7 and 5 years, respectively.

Despite the sample of men being four times that of women, measurements are not biased. According to the *International Transport Forum (ITF), 2020*, male drivers constitute 70-80% of the total drivers. Only drivers who declared that they had not previously driven on the specific road sections participated, to examine the least safe scenario, i.e., a driver unfamiliar with the road network. In total, 751 measurements were used to extract the results.

After each measurement, the drivers were asked whether they considered the passage to be comfortable, safe, or something in between. The responses were added to each driver's individual profile.

Measuring Equipment

This study necessitates precise determination of the application position of each speed value within the curve. Therefore, the Vericom 4000RG (Figure 5) was selected. It functions as both an accelerometer and speedometer and measures horizontal coordinates in the WGS 84 system and altitude every 0.01 second. This way, the speed at each position (tangent, clothoids, arc) could be reliably determined, and the longitudinal gradient at each position could be derived. Vericom has been adequately utilized in many transportation research studies (*Mavromatis et al., 2023; Hamernik et al., 2006; Eubanks et al., 1993*, etc.). It measures without a margin of error, provided it has been calibrated at a point of zero longitudinal and lateral gradient. The placement inside each vehicle and the calibration was performed in enclosed garages where inclinometers confirmed zero gradients.

Vericom was positioned inside the vehicle in a location that did not obstruct the driver's view and could be easily operated by one of the researchers seated in the front passenger seat. The researcher would activate the Vericom when a measurement was to begin and deactivate it after the measurement was completed. Typically, the device was placed either at the side window of the front right seat or at the front right part of the windshield.

The data recorded by the Vericom 4000RG was transferred to a computer using MicroSD cards and imported into the Profile 5 application provided by Vericom Computers Company. Using the "Save as" command in the basic menu, each recording was exported as a csv file and then opened in Excel application, where it was saved as an xlsx file. The final layout included separate columns for each measured parameter (speed, acceleration, coordinates, etc.).

Figure 5 Vericom 4000RG

RESULTS

Based on the horizontal coordinates occurred by Vericom's recordings, the vehicle's movement along the curve was identified, and the constant speed value within the arc was isolated. This speed value was identified approximately between the second and third quarters of the arc, symmetrically around its midpoint. That occurred values used for each subsequent analysis.

Correlation Between Critical Speed Values and Ramp Curve Radius

For each participating driver, the consistent speed value within the curve was isolated. The aggregate speed measurements of each curve were divided into specific percentiles (15th, 50th, and 85th).

The values of each percentile were examined in relation to the design radius of the curve (Figure 6 and Table 2). Using a logarithmic function (Equations 15, 16, and 17), strong correlations were observed between the critical speed values and the design radius based on the coefficient of determination (R^2) and the total of 751 measurements.

$$V85 = 22.022 \times \ln(R) - 40.304 \qquad (15)$$
$$R^2 = 0.993$$

$$V85 = 23.177 \times \ln(R) - 38.419 \qquad (16)$$
$$R^2 = 0.994$$

$$V85 = 23.956 \times \ln(R) - 34.920 \qquad (17)$$
$$R^2 = 0.993$$

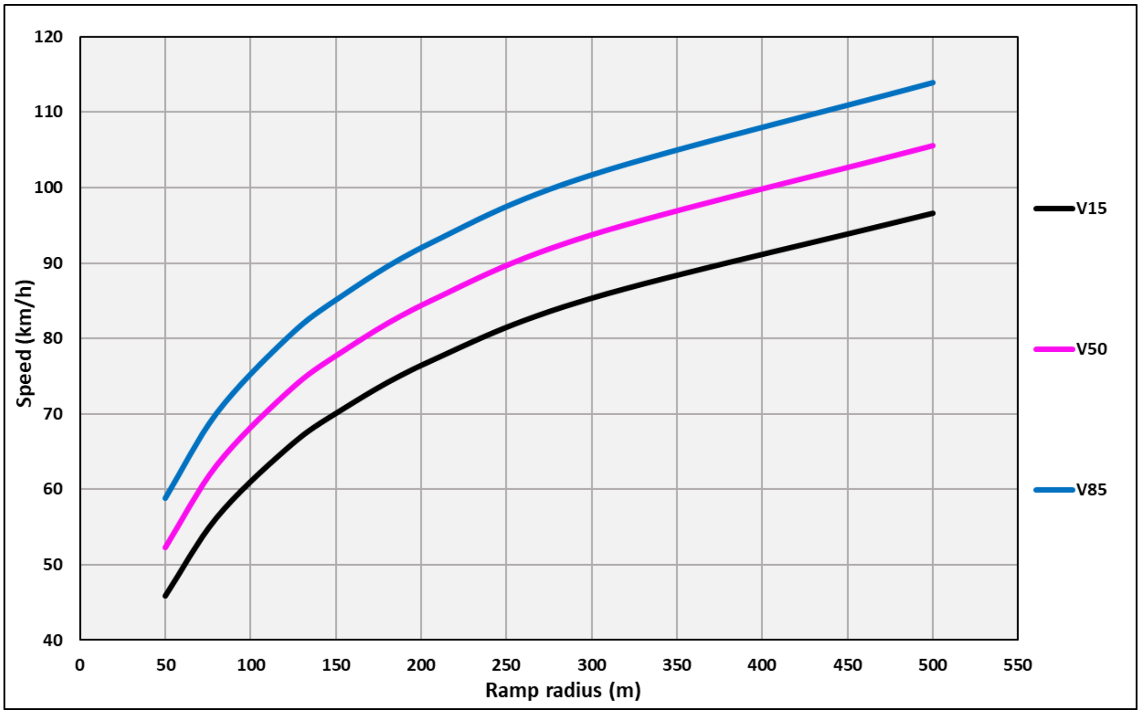

Figure 6 Critical speed values as a function of design radius in interchange ramps

TABLE 2 Critical speed Values Depending on Curve Radius in Interchange Ramps

Limit/Threshold Type	Ramp Curve Radius (m)						
	50	80	120	150	205	300	500
V_{15}	46	56	65	70	77	85	97
V_{50}	52	63	73	78	85	94	106
V_{85}	59	70	80	85	93	102	114

Figure 6 highlights the consistent pattern observed in the rate of change of speed as a function of radius for each critical speed value (15th, 50th, and 85th percentiles). Driving behavior appears to be categorized into three groups based on curvature. The first pertains to small radii (up to 100m), where speed seems to increase quite sharply with the increase in radius. The second concerns small to medium radii (larger than 100m up to 250m), where speed increases sharply but less so compared to smaller radii. The third corresponds to medium to large radii (larger than 250m up to 500m), where the function of critical speed values and radius becomes essentially linear.

For radii up to 100m, the difference between V_{15} and V_{50}, and between V_{15} and V_{85}, is approximately 7 km/h and 14 km/h, respectively. For radii greater than 100m and up to 250m, V_{85} is on average greater than V_{50} and V_{15} by 7 km/h and 16 km/h, respectively. For radii greater than 250m and up to 500m, V_{85} is on average greater than V_{50} and V_{15} by 8 km/h and 17 km/h, respectively.

Comparison Between Critical Speed Values of this Study and Threshold Values from the Literature Depending on Design Radius

In this chapter, the speed threshold values obtained from Equation 12 (using the lateral acceleration threshold values derived from the literature, along with the radius and superelevation values of the curves examined in this research) are compared with the critical values resulting from this research, as shown in Figures 7-10 and Table 3.

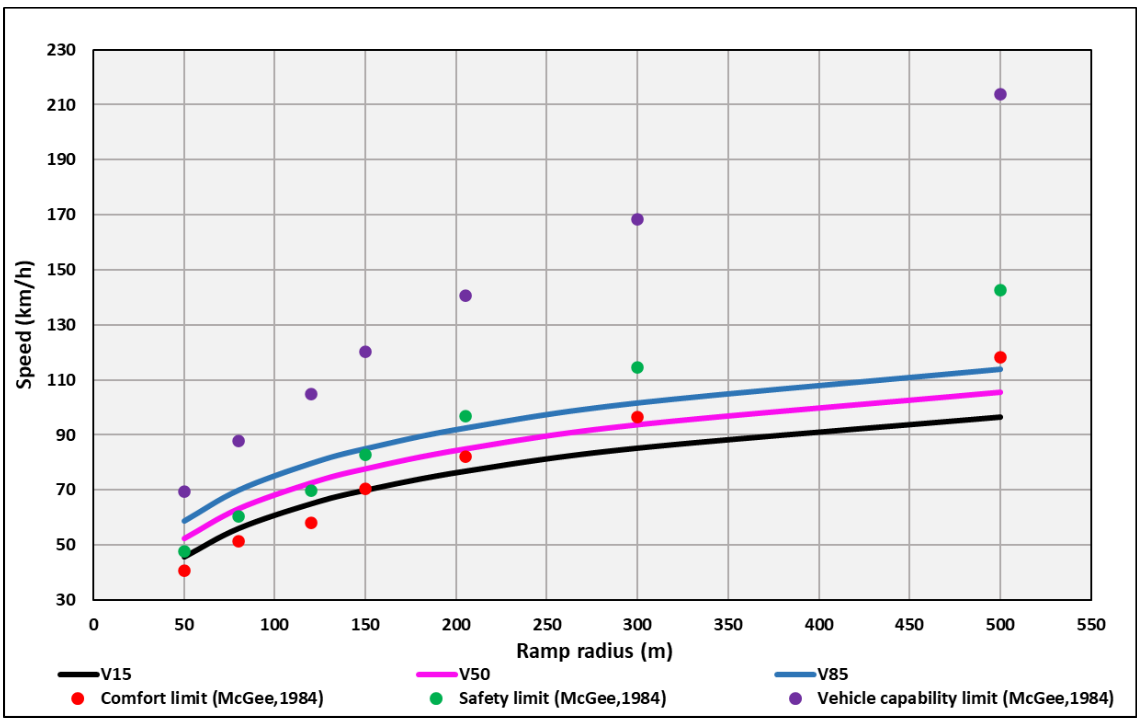

Figure 7 Critical speed values of this study and thresholds set by McGee

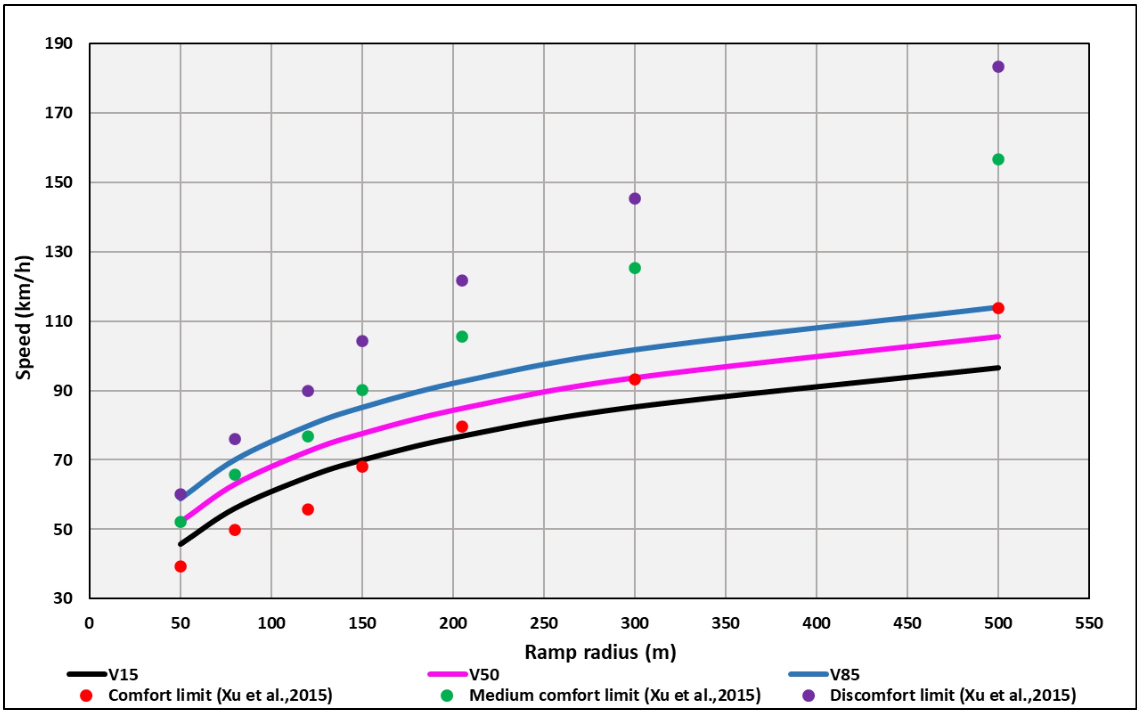

Figure 8 Critical speed values of this study and thresholds set by Xu et al

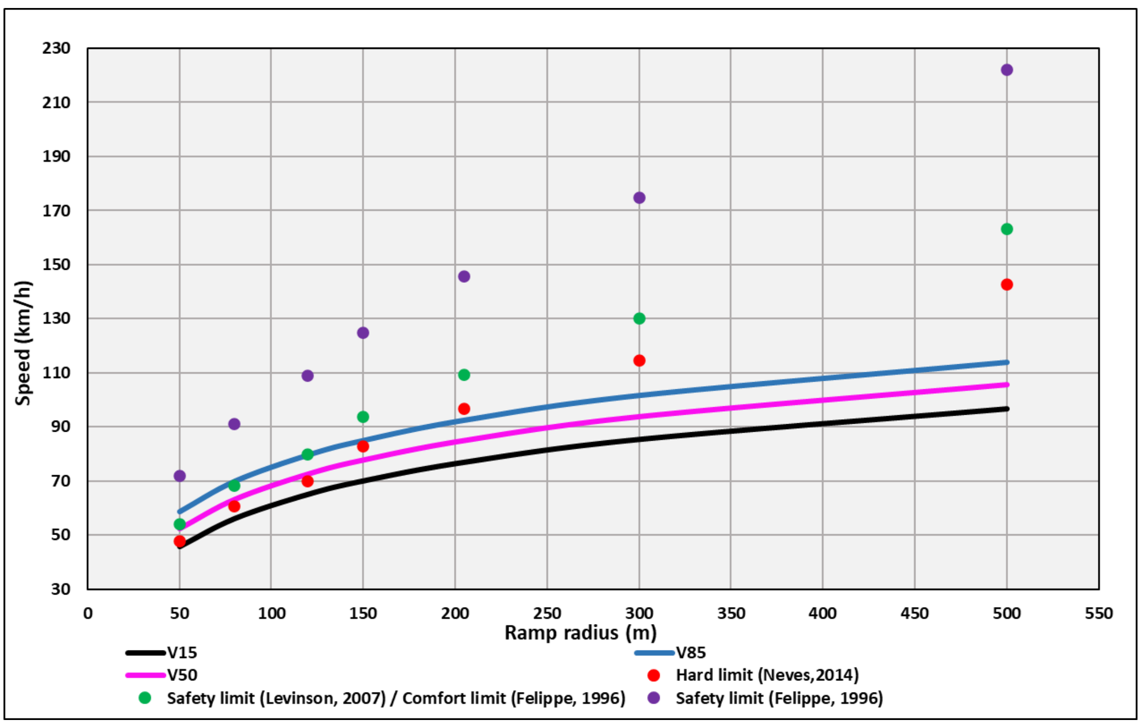

Figure 9 Critical speed values of this study and thresholds set by Felipe, Levinson and Neves

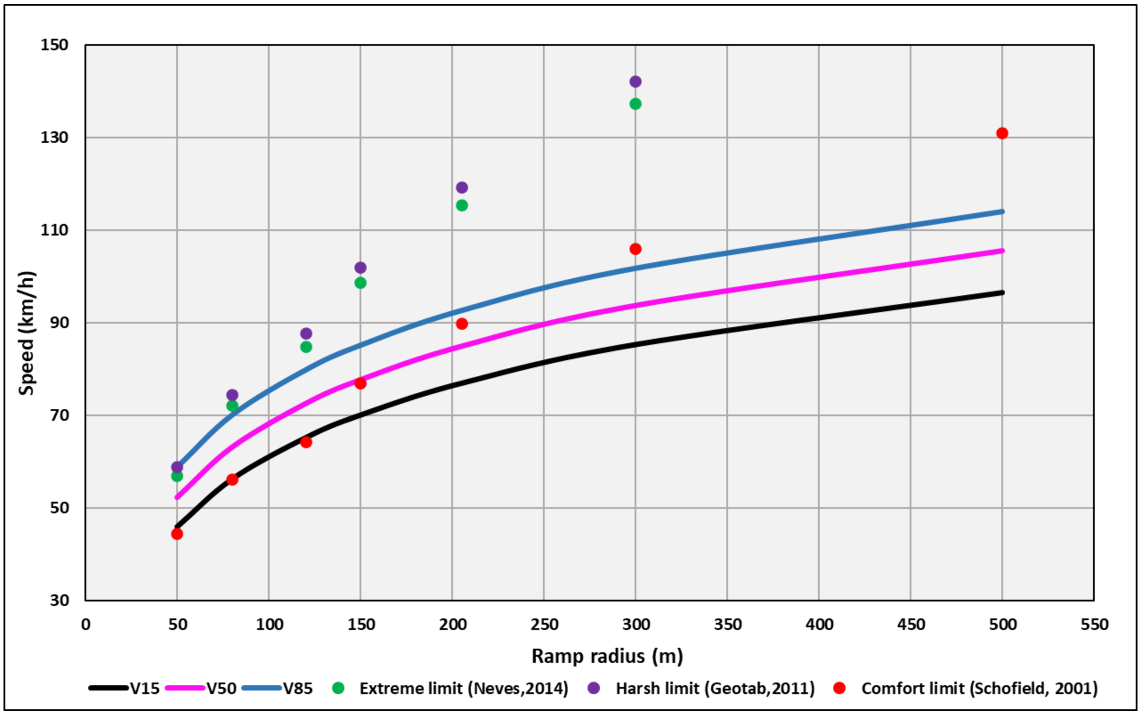

Figure 10 Critical speed values of this study and thresholds set by Schofield, Geotab Inc, and Neves

TABLE 3 Speed threshold / limit values of literature models depending on ramp radius

Limit/Threshold Type	Reference	Ramp Curve Radius (m)						
		50	80	120	150	205	300	500
Comfort	McGee, 1984	41	51	58	70	82	97	118
Comfort	Felipe, 1996	54	68	80	94	109	130	163
Comfort	Schofield, 2001	44	56	64	77	90	106	131
Comfort	Xu et al., 2015	39	50	56	68	80	93	114
Medium Comfort		52	66	77	90	105	125	157
Discomfort		60	76	90	104	122	145	183
Safety	McGee, 1984	48	60	70	83	97	115	143
Safety	Feliipe, 1996	72	91	109	125	146	175	222
Safety	Levinson, 2007	54	68	80	94	109	130	163
Harsh	Geotab Inc., 2011	59	74	88	102	119	142	179
Hard	Neves, 2014	48	60	70	83	97	115	143
Extreme		57	72	85	99	115	137	173
Vehicle capability	McGee, 1984	69	88	105	120	141	168	214

The V_{15} values of this study align with the comfort threshold of *Schofield, 2001* and approach or exceed the safety threshold of *McGee et al., 1984* respectively for radii up to 120m. The V_{50} values correspond to the medium comfort threshold of *Xu et al., 2015* for radii up to 120m and the hard limit of *Neves, 2014* for radii up to 150m. Additionally, V_{50} aligns with the comfort threshold of *McGee, 1984* and *Xu et al., 2015* for radii from 200m to 300m. The V_{85} values approach the comfort thresholds of *Felipe, 1996*, safety of *Levinson et al., 2007*, extreme of *Neves, 2014*, and harsh of *Geotab Inc., 2011* for radii up to 120m, the medium comfort threshold of *Xu et al., 2015* for radii up to 150m, the safety and hard thresholds of *McGee et al., 1984* and *Neves, 2014* respectively for radii from 150m to 200m, the comfort threshold of *McGee et al., 1984* for radii from 300m to 500m, and equal the comfort threshold of *Xu et al., 2015* for a radius of 500m.

Comfort, Tolerance and Safety Limit Values Depending on Ramp Curve Radius

In previous studies by the researchers (*Trakakis, Apostoleris, and Psarianos, 2023 and 2024*), the 15th, 50th, and 85th percentiles were established as thresholds for comfort, tolerance, and safety respectively of lateral acceleration and longitudinal deceleration on interchange ramps. This assumption was based on how drivers perceive comfort, tolerance, and safety when traversing an interchange ramp, according to their responses to questionnaires given after the measurements.

The absolute threshold values of lateral acceleration and speed, established by studies in main carriageways, do not correspond to interchange ramps, as shown by the analysis above (Figures 7-10 and Table 3). Therefore, the researchers' method, which was effectively applied in investigations of threshold values for comfort, tolerance, and safety in lateral acceleration and longitudinal deceleration (*Trakakis, Apostoleris, and Psarianos, 2023 & 2024*), is also applied in this study. Consequently, the critical speed values are appropriately matched with the threshold values that describe driving behavior.

The 15th percentile (V_{15}) and the 85th percentile (V_{85}) were found to be quite compatible with the thresholds of comfort and safety, respectively. The speed at the 50th percentile (V_{50}) approached the drivers' responses for an intermediate sensation between comfort and safety, for which the term "tolerable speed" was used. Intermediate percentiles were established as assessment areas for the degree of aggressiveness or conservativeness of driving behavior based on speed on interchange ramps. In this way (Figure 11), comfort, tolerance, and safety speeds can now be directly estimated on interchange ramps, and corresponding standard values can be established (Table 4).

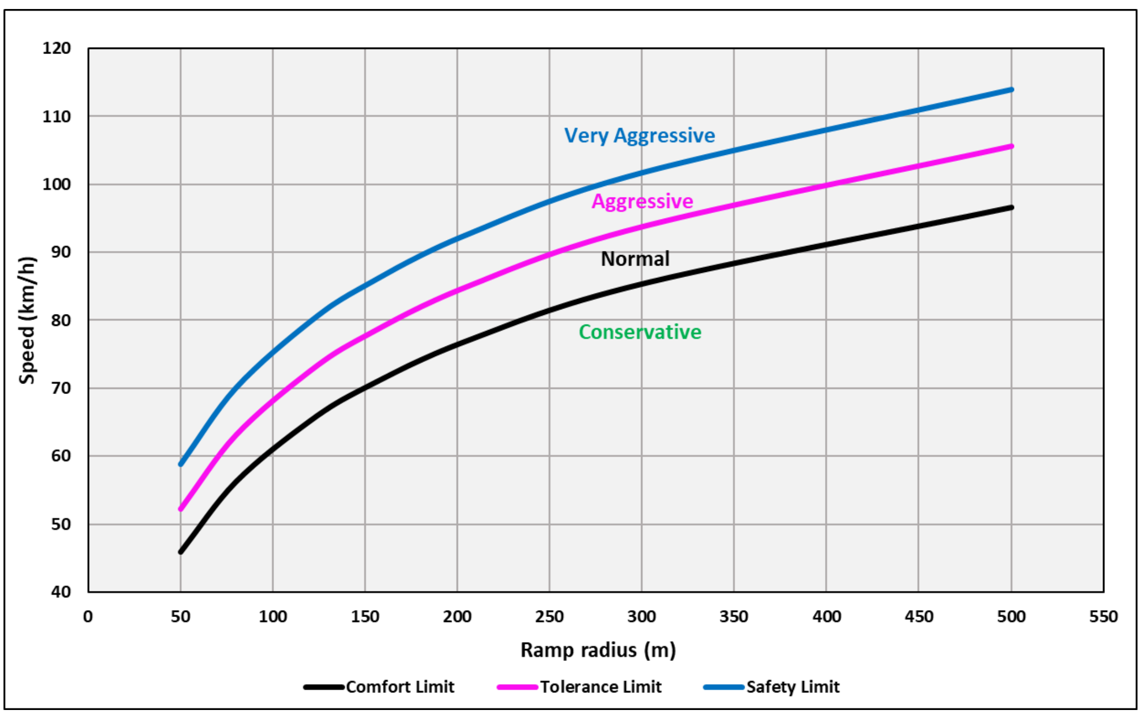

Figure 11 Characterization of driving behavior based on the correlation between speed and ramp curve radius for each examined interchange

TABLE 4 Speed Threshold/Limit Values Depending on Curve Radius in Interchange Ramps

Threshold / R (m)	50	100	150	200	250	300	350	400	450	500
Comfort Limit	46	61	70	76	81	85	89	92	94	97
Tolerance Limit	52	68	78	84	90	94	97	100	103	106
Safety Limit	59	75	85	92	97	102	105	109	111	114

Comparison Between Critical Speed Values of this Study and Speed Values Derived from Literature Models Depending on Design Radius

In this chapter the models established by this research are compared with those used for calculating the operating speed (V_{85}) as a function of radius, derived from previous studies on main carriageways and interchange ramps.

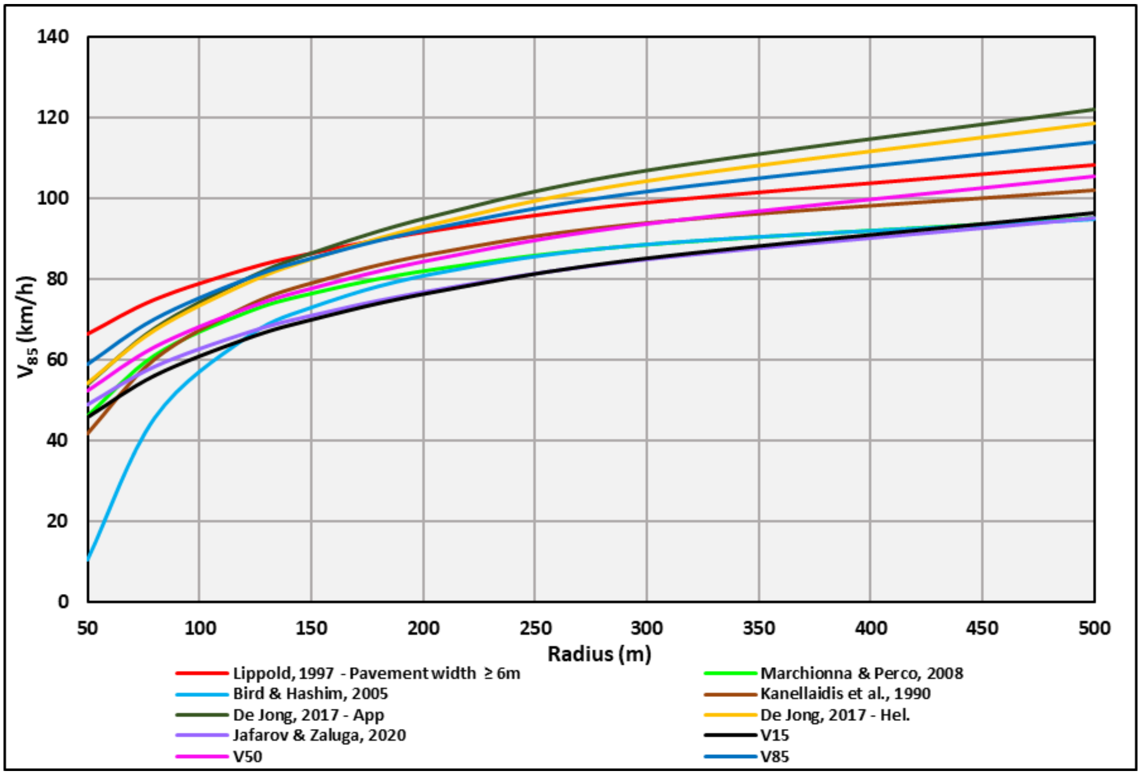

Figure 12 Speed values derived from literature models and critical speed values of this research as a function of radius

Figure 12 confirms that the increase in rate of change alongside the design radius observed in the present research, is consistent with the findings of previous studies (*Kanellaidis, 1990*, *Marchionna & Perco, 2008*, and *De Jong, 2017).*

TABLE 5 Speed values derived from literature models based on the radius values examined in this research

Curve Radius (m)	Speed (km/h) estimation model						
	Lippold, 1997	Kanellaidis et al., 1990	Bird & Hashim, 2005	Marchionna & Perco, 2008	De Jong, 2017 - App	De Jong, 2017 – Hel.	Jafarov & Zaluga, 2020
50	66	42	10	46	54	54	49
80	75	60	46	61	68	67	58
120	82	73	65	72	80	79	66
150	86	79	73	76	86	85	71
205	92	86	81	82	96	94	77
300	99	94	89	89	107	104	85
500	108	102	95	95	122	119	95

Figure 12 and Table 5 show that the V_{15} of this study coincides with the V_{85} of the model by *Jafarov and Zaluga, 2020*. Additionally, for radii up to 60m, it exceeds the V_{85} value of the model by *Kanellaidis et al., 1990*, while for larger radii, it is up to 9 km/h lower than the values of the abovementioned model. For radii of 350m to 500m, the V_{15} coincides with the V_{85} of the models by *Bird and Hashim, 2005* and *Marchionna & Perco, 2008*. The V_{50} of this research for radii of 100m and larger coincides with the V_{85} of the model by *Kanellaidis et al., 1990*, while for radii between 80m and 175m, it approaches the model by *Marchionna & Perco, 2008*. The V_{85} from this research's data approaches the V_{85} values derived from models 1 and 2 of *De Jong, 2017* for radii up to 200m and 300m, respectively, while for radii of 120m to 300m, it approaches the V_{85} of the model by *Lippold, 1997*.

Comparison between Critical Speed Values and Values Anticipated by Design Guidelines

Table 6 and Figure 13, in combination, illustrate the differentiations between measured speed values and values anticipated by design guidelines by inputting the geometric characteristics of each ramp into Equation 12.

TABLE 6 Threshold speed values anticipated by geometric design guidelines and values established by this research depending on ramp curve radius

Threshold / R (m)	50	80	120	150	205	300	500
OMOE-X, 2001	36	44	32	47	66	67	59
RAA, 2008	41	50	46	58	75	80	83
AASHTO, 2018	43	52	57	66	74	83	94
Comfort Limit (V_{15})	46	56	65	70	77	85	97
Tolerance Limit (V_{50})	52	63	73	78	85	94	106
Safety Limit (V_{85})	59	70	80	85	93	102	114

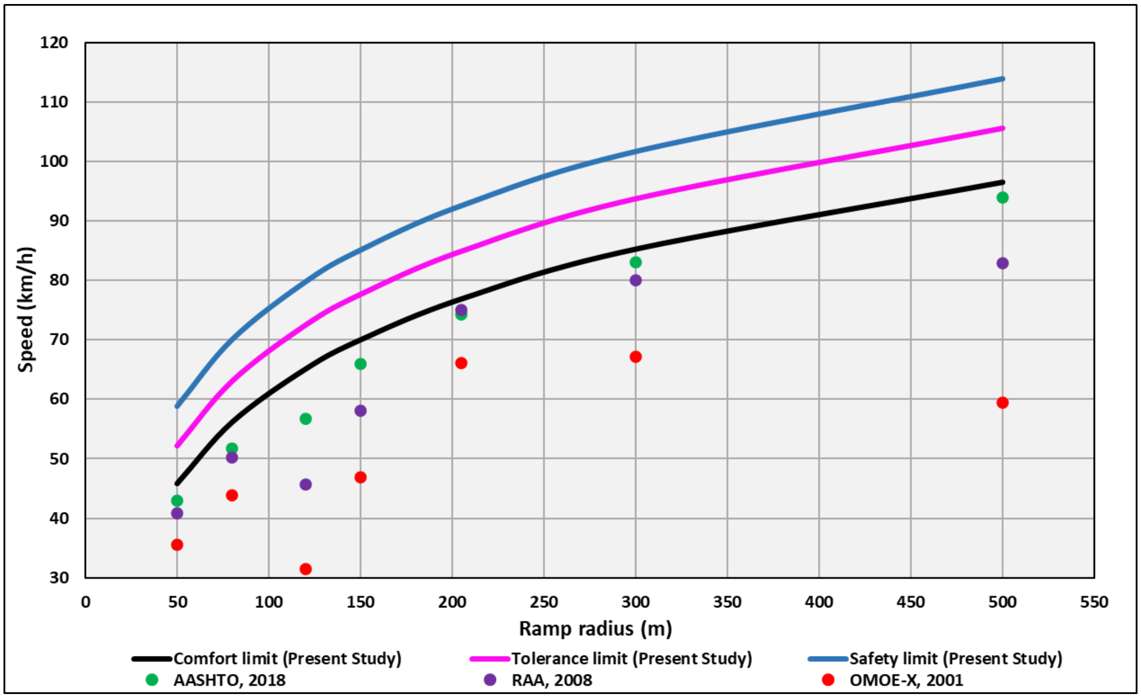

Figure 13 Threshold speed values established by this research and values anticipated by geometric design guidelines as a function of ramp curve radius

More conservative speed values are provided by the Greek *OMOE-X, 2001* because they use the smallest utilization factor (n) compared to the *RAA, 2008* for each value of common superelevation. Similarly, the highest speeds are derived from the *Green Book* (*AASHTO, 2018*), where the utilization factor for calculating the side friction coefficient does not decrease with the reduction of superelevation.

CONCLUSIONS

This study proposes modifications to the way geometric design guidelines currently address interchange ramp curves. Modifications should account for the technological capabilities of more modern vehicles, using parameters for vehicles from at least the 2010s rather than those from the 1980s and 1990s, as is currently the case in existing manuals. The functional speed measurements from this study revealed an increase in V_{85} values for Greek drivers by up to 17 km/h compared to the study by *Kanellaidis et al*., 1990.

The assumption by *Vos et al., 2022*, regarding speed stabilization at the midpoint of the horizontal curve (Figure 3) of main carriageways does not align with driving behavior on interchange ramps. In over 80% of the 751 measurements collected from 160 drivers, it was observed that drivers begin braking approximately halfway through the deceleration lane and continue until about a quarter of the way through the interchange ramp curve. Their speed stabilizes in the second and third quarters of the curve.

Most of the threshold/limit values for lateral acceleration (and consequently, the corresponding speed values) that have been added to the literature over time for assessing driver comfort and safety on horizontal curves do not match the findings of this study. Notable examples include the safety limit by *McGee et al., 1984*, and the comfort limit by *Schofield, 2001* for radii of 205m and 300m respectively or larger, the medium comfort and discomfort limits set by *Xu et al., 2015* for radii greater than or equal to 205m and 120m respectively, and the safety and extreme speed limits by *Geotab Inc., 2011* and *Neves, 2014* respectively for radii of 120m and above. Additionally, the comfort and safety limits by *Felipe, 1996* for radii greater than 80m, and the safety limit by *Levinson et al., 2007* for radii of 150m and above, as well as the hard limit set by *Neves, 2004* for radii of 205m and above, are not applicable to interchange ramps. Significant deviation is observed for the comfort values established by *McGee, 1984*, and *Xu et al., 2015* for a radius of 500m

The above findings highlight the need for establishing threshold values that reliably describe driving behavior on interchange ramps and are not dependent on studies where data were collected on main carriageways. On main carriageways, drivers frequently encounter curves. The *OMOE-X, 2001* guidelines allow for maximum tangent with a constant longitudinal gradient up to 20×Ve (design speed in km/h), while the *RAA, 2008* and *RAL, 2012* permit maximum tangent length of 2000m and 1500m respectively. Therefore, absolute values of comfort, tolerance, and safety are significant on main carriageways, as it is undesirable for drivers to constantly experience discomfort on curved paths, even under dry pavement conditions where the safety margin is large.

In contrast, interchange ramps are road sections that appear at least every 4km (*RAA, 2008*) on the road network, and typically the same driver uses 1 or 2 exit ramps per 100 km on rural or urban highways, respectively. Studies by *Trakakis, Apostoleris, and Psarianos, 2023 and 2024* have shown that drivers perceive comfort, tolerance, and safety differently on interchange ramps. A value of lateral acceleration might indeed cause discomfort to the driver, but the length of the ramp and mainly the frequency of driving a ramp during a whole corridor (compared to curves on main carriageways) lead the driver to tolerate this discomfort or even consider an aggressive and steep passage as safe.

Therefore, the 15th, 50th, and 85th percentile speeds were correlated with the comfort, tolerance, and safety threshold/limit values. This approach was applied for two reasons. First, it had been effectively used in studies of lateral acceleration and longitudinal deceleration. Second, the questionnaires completed by drivers about how comfortable or safe they perceived their passage, combined with field measurements, showed a significant alignment of the comfort limit with speeds up to the 15th percentile and the safety limit with speeds corresponding to the 85th percentile or higher percentiles.

The threshold/limit values provided in road geometric design manuals are considerably more conservative compared to the speeds recorded in this study. The tangential and side friction coefficient values given in the manuals, although established for wet pavement conditions, do not align with the driving behavior of drivers with modern technology vehicles and will increasingly diverge from actual driving behavior in the near future. The permitted speed limits set for wet pavement conditions are universally exceeded by the 15th percentile (comfort limit) of the recorded speeds in this study. The exceedances range from 6 km/h to 20 km/h, indicating that drivers completely disregard speed limit signs when they can safely apply much higher speeds.

Therefore, the current allowable threshold values are not meaningful. Harmonizing driver behavior with speed limits could be achieved by adopting dual speed limits for interchange ramps depending on dry or wet pavement conditions. Additionally, applying a performance-based design concept to interchange ramps could make geometric design much more cost-effective (e.g., by reducing the minimum allowable curve radius and limiting expropriations) without compromising safety. The permissible speed limits for dry pavement of existing and new interchange ramps, along with design cost-effectiveness, is an interesting area for future investigation and is already being explored by the authors of this study.

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