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RESEARCH PAPER

Performance Comparison of Various Chicane Types: A Driving Simulator Study

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Abstract

Urban streets are becoming noisy, less safe and unattractive places due to high traffic volumes and vehicular speeds. Especially, high speeds causes many problems such as traffic accidents, noise, etc. To prevent these problems and negative effects of speeding, traffic calming measures have been widely used in many developed countries. In this study, the effectiveness of ten most common chicane types on speed limit compliance were examined by comparing and ranking chicanes according to their performance. For this purpose, a "Safety Index" was developed and an Ordinary Least Square Regression analysis was performed to identify safest chicane types for undivided two-lane and divided four-lane roads by using various parameters. Additionally, statistical tests were conducted to determine the most important driver characteristics of drivers before and inside the chicanes. For the analyses, all necessary data were obtained from the driving tests of 106 volunteers using a driving simulator. For the simulation scenarios, Akdeniz University's (Antalya/Turkey) campus roads were selected as a case area. The results showed that Chicane Types 2 (CT-2) and 7 (CT-7) have the highest Safety Index values (0.69 and 0.98) and they were found to be the most proper CTs for the undivided and divided roads, respectively. From the statistical tests, it was also found that education level, gender and driving license duration were found to be the statistically significant parameters on speed choice for the most proper chicane types. Additionally, it was concluded that the most important driver characteristics are determined as age (has a negative effect) and gender (to be male has a positive effect) of drivers before and inside the chicanes. All these findings show that the investigation of different CTs has a great potential to reduce speeds and ensure safety in urban minor roads to limit vehicle speeds.

Keywords Chicane · Driving simulator · Safety · Speed reduction · Traffic calming

1 Introduction

Road safety statistics indicate that the total number of deaths caused by traffic accidents have reached 1.35 million per year all over the world [1]. Also between 20 and 50 million people suffer non-fatal injuries with many incurring a disability as a result of their injury caused by the traffic accidents [1]. To classify the type and severity of these injuries, caused by the traffic accidents, a number of scales have been proposed by the researchers [2–5]. Current researches have also shown that high vehicle speeds and lack of road infrastructure are the critical parameters on deaths and injuries caused by traffic accidents [6–8]. If the average traffic speeds increase, crash risks, deaths and serious injury risks for pedestrians, cyclists and motorcyclists will be higher [9]. Previous studies found that the speed limits of urban street roads must be below 30 km/h to prevent the negative effect (traffic accident, traffic noise, etc.) of high interaction between motorized traffic, pedestrians, cyclists and moped riders [1, 6, 9]. Therefore, setting and enforcing suitable national speed limits has a key importance to prevent vulnerability of road users and to make urban roads safer and livable. Nowadays, many countries set various speed limits for highways, urban (residential or industrial) and rural roads

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to provide safer roads [1]. According to 2017 statistics of United Nations (UN), 98 countries (approximately half of the UN member countries) determined urban street limits as 50 km/h or below [10]. In addition to adjusting the speed limit, safer traffic systems can be provided by preventing complexity among pedestrians, cyclists and vehicles. For this reason, it is important for the local authorities to control and manage speeding by using Traffic Calming (TC) applications or speed management policies. TC applications are the best methodology to limit and control vehicle speeds as a famous speed control and management method. Because low vehicle speeds have a great importance to achieve safer traffic systems for pedestrians, cyclists and vehicles, TC applications have been widely used in many developed countries to prevent accidents and improve road safety by reducing the negative effects of excessive speeding [11–16]. They are also an important part of transportation planning of cities, and they have an ability to provide safety on streets or street networks by controlling traffic volumes and reducing vehicle speeds. Also, these applications can successfully reduce vehicle speeds by changing and controlling the speed of vehicles. According to Sanz [17], these applications have two main aims: to supply a reduction in accident frequency and severity and to improve safety for urban streets.

In the past decade, many standards and manuals have been proposed by the researches and transportation authorities about the TC applications for engineers and researchers about design and application [18–22]. In these standards and manuals, the most suitable application procedures about geometry and location selections and traffic flow ranges are given in detail. Several studies have been conducted to investigate and measure the effects of TC applications on urban roads, and a reduction was found to be about 60–70% in speeds and 18% in traffic accidents [23–27]. Additionally, it was found from the previous studies that the area-wide TC applications in urban roads have a significant potential to prevent or reduce traffic accidents [23, 24, 28].

Chicanes are one of the most important and effective traffic calming applications to limit and reduce vehicle speeds in urban and rural road sections. They are actively used in many countries (especially in developed countries) as an important traffic management and calming techniques to prevent excessive speeding problems [11–15, 29]. In literature, there are several documents (reports, design guides, etc.) regarding the chicane design and speed reduction applications. But unfortunately, there are no academic studies that directly examine and compare the effect of different chicane types (CTs) on speeding and safety. For this reason, a detailed investigation of the chicanes' performances has a great importance to fill in the gap in the literature.

Driving simulators may be the most proper method to measure the performance of TC applications (chicanes, half chicanes, chokers, gateways, slow points, lateral shifts, road narrowing, etc.). Because driving simulators have a significant and effective role to evaluate the relationship between drivers' behaviors, road properties and traffic safety. Simulators possess an ethical tool to measure these driver behaviors [30–32]. They also have many benefits such as cost and safety, easy data collection and easy control of experiments [33–41]. They are especially used to determine effective countermeasures. In a number of studies, the efficiency of TC applications has been evaluated with the help of driving simulator experiments [28, 39, 42–45]. For example, Molino et al. [13] examined and compared the speed reduction effectiveness of different TC applications (chicanes, bulb-outs, post-mounted delineators and the presence of parked cars) on rural roads. After they carried out a number of simulator tests, the speed reduction effectiveness of different TC applications was ranked (from best to worst) as follows: curb and gutter chicanes (14.5 km/h reduction), painted chicanes (9.7 km/h reduction) and parked cars (6.4 km/h reduction). In a similar work, [45] studied the effectiveness of TC applications in reduction of drivers' speeds along a road near Venice, Italy. Simulator experiments were conducted to investigate speed changes caused by various countermeasures (i.e. dragon's teeth markings, tall guideposts, spaced guideposts and narrowing guideposts). Results showed that all narrowing guideposts contribute to reduction of speeds by up to 2.7 km/h. Also, it was seen from these experiments that driving simulators are reliable devices to measure driver behaviors on dangerous road segments. Similarly, driving simulators were used to examine the effect of TC applications in the 1990s and 2000s [30–32, 42, 44, 46]. In the TRL driving simulator, driver speeds were obtained from before and after studies by analyzing simulated entrance of three real villages. It was found from the driving tests that real and simulated speeds were extensively comparable. In another study, Riemersma et al. [47] studied the effect of different TC applications (gateway, colored asphalt and median strip) by using a driving simulator in the Netherlands. In the study, first, simulator experiments were performed to measure approaching speed to the village of Weiteveen and then the real environment and simulator tests were compared. The comparison results showed that simulator experiments can be used effectively for the speed measurement and estimation of speed reduction. Daniels et al. [44] investigated road markings' effect on obedience to speed limits by using a driving simulator. For this purpose, both a driving simulator and real environment experiments were performed to measure additional road markings' effects on speed choice behaviors of drivers. In a different study, Godley et al. [42] evaluated the speeding countermeasures at three road segments (for stop sign intersegments, left curves and right curves) which included transverse rumble strips using an advanced simulator. They obtained close values and a high relation between simulator and real driving speeds. All these presented findings have shown that driving simulators can be used as an effective tool to evaluate the performance of different TC applications such a chicanes, half chicanes, chokers, gateways, etc.

In summary, it was seen from the previous studies that there is a limited number of studies on the speed reduction and safety performance evaluation of the chicanes. Current studies have some limitations because they have only focused on the evaluation of the speed reduction effectiveness. But in reality, there are various effective factors on speed reduction at chicanes such as geometry, driver characteristics and safety parameters. In this study, to determine the effect of these parameters, ten most common chicane types on speed limit compliance were examined by comparing and ranking them according to their effectiveness. For this purpose, a new "Safety Index (SI)" was developed and an Ordinary Least Square Regression (OLSR) analysis was performed to examine safest chicane types for undivided two-lane and divided four-lane roads using various parameters. After safety evaluation, statistical tests were conducted to determine the most important driver characteristics of drivers before and inside the chicanes. All study findings showed that the investigation of different CTs has a great potential to reduce speeds and supply safety in urban roads to limit vehicle speeds.

2 Method

2.1 The Participants

According to 2017 statistics of Turkish Statistical Institute (TUIK), 24.8% of drivers are females and 75.2% of drivers are males in Turkey [48]. For this reason, in the study, total 106 drivers (26 females and 80 males) participated in the driving simulator experiments ($\mu_{\text{drivers}} = 27.7$; SD 7.9; range 20–62 years) to reflect real gender proportion of the licensed Turkish drivers. All volunteers in the study had a valid driving license for the duration of 1–35 years ($\mu_{\text{license}} = 7.2$ years). Drivers from both inside and outside of the university were chosen as volunteers for the experiments. The selected drivers had never used a driving simulator before and they had driving experience in real urban minor roads for minimum 1 year. To conduct all driving tests, permission had been obtained from the university's ethics committee.

2.2 Driving Simulator Scenarios and Experiments

The topography and the geometric properties of the computer-animated roads were taken from the main arterials of Akdeniz University Campus (see Fig. 1). The landscape simulator was used based on the real landscape surroundings

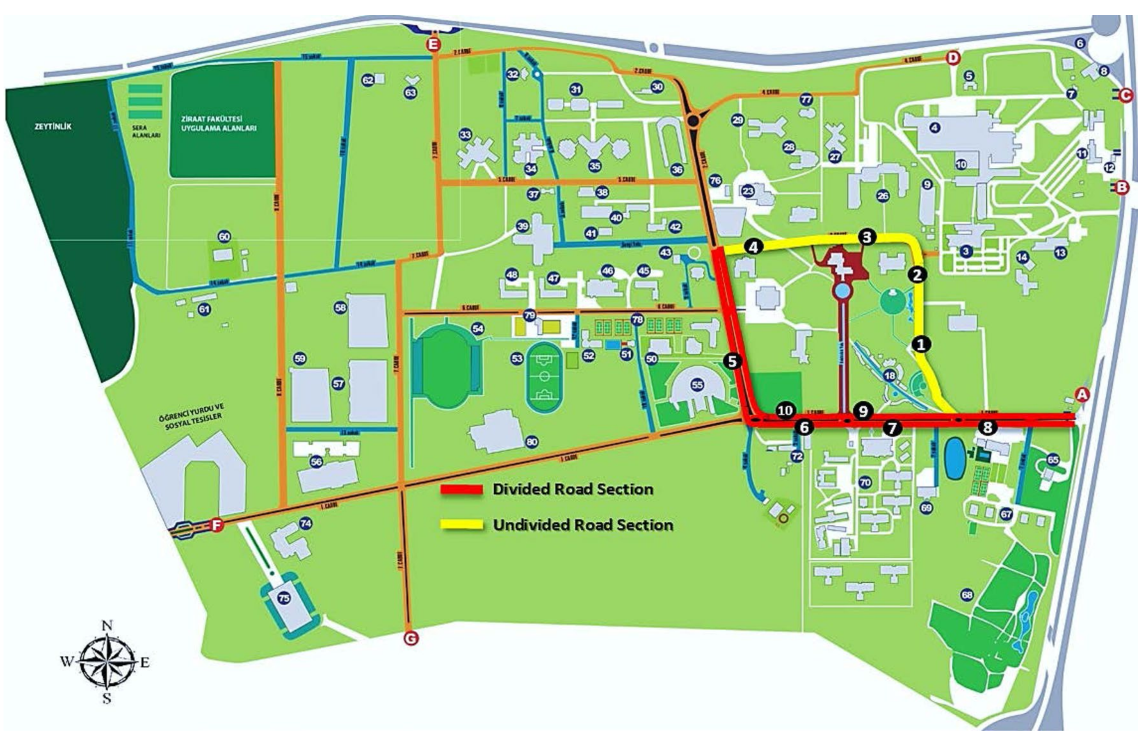

Fig. 1 The simulated route within the campus

which are urban areas characterized by many faculty buildings and trees. Various objects (such as bus stops, traffic signs, advertisement boards, trees and shoulders) were placed into the scenarios to mimic real campus environment. The simulated route (3.2 km) consisted of 2.25 km divided four-lane (two in each direction) and 0.95 km undivided two-lane (one in each direction) roads with a posted speed limit of 30 km/h. To give a real campus impression, real-world roadside photographs were taken along the route and superimposed with the software. Also, the real locations of the roadway and roadside objects were embedded accordingly.

In all experiments, the weather conditions were chosen as sunny and the traffic volumes were chosen as about 400 vehicles/h (average real traffic volume) obtained from the real-world observations in the campus during peak hours. Ten different and the most common CTs were implemented for the simulator study inspired from [11–19, 43, 46]. Geometric properties of the chicanes in question are given in Table 1 and the general design structures of the chicanes are shown in Fig. 2.

The system runs with a PC platform and integrates a visual system, a sound system and a simulator software. The simulator consists of a real Renault-Toros Car (a real car) cabin (with brake and gas pedals, a realistic steering wheel, a manual gear box and all manual controls) and a projection system. The speed, gear and engine RPM values were displayed on the screen to give a detailed driving information to drivers. The left, right and rear images of the simulation are displayed on three large screens, and the front image is displayed on a large wall (center screen) to supply a real driving atmosphere. Inside and outside views of the used driving simulator system are shown in Fig. 3.

To examine and evaluate the designed chicane scenarios, a new simulator software (AUDSIM Drive V1) was developed in collaboration with a commercial company. This software allows to control some parameters such as traffic

Table 1 The geometric properties of the chicane types

Chicane type “CT”	Road type “RT”	Lane number “N_L”	Overall lane width “W” (m)	Chicane island geometry	Effective lane width “W_E” (m)	Distance between islands (m)	Entry and exit angles of chicane island (°)	Total island number “N_I”
1	UD	1	4	Cornered	2.7	18	30–30	2
2	UD	1	4	Cornered	2.7	18	60–30	2
3	UD	1	4	Cornered	3.3	18	30–30	2
4	UD	1	4	Cornered	3.3	18	60–30	2
5	D	2	8	Cornered	5	18	45–45	2
6	D	2	8	Parabolic	3	18	45–45	2
7	D	2	8	Cornered	3	18	60–30	2
8	D	2	8	Cornered	3	18	45–45	2
9	D	2	8	Cornered	3	18	30–30	2
10	D	2	8	Cornered	3	18	45–45	3

UD undivided, *D* divided road segments

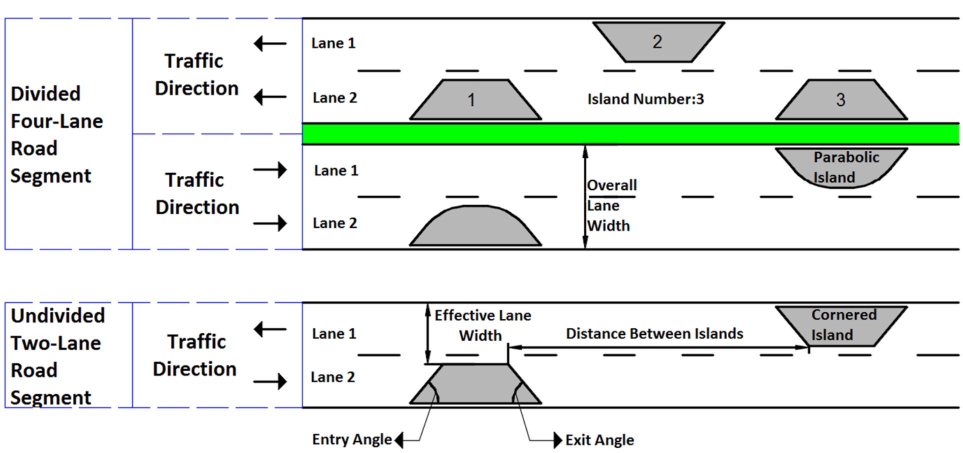

Fig. 2 Explanatory visual presentation of the chicane types and the geometric design properties

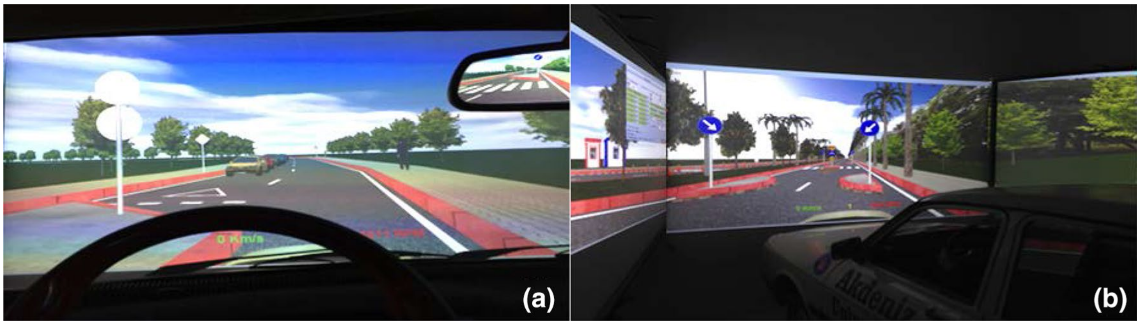

Fig. 3 **a** Inside and **b** outside views of the used driving simulator system

volume, acceleration and deceleration rates, and it records vehicle speeds and trajectories (location of vehicles on *x*, *y* and *z* axes in 3D) for one-second intervals. It also provides an interaction between the steering software, the sound system, the projection system, the steering wheel, the pedal and the gearshift lever. An immersive four-projector system displays the visual information on three large flat screens. The displays provide quality image views for the driving tests (1920 × 1080 pixels resolution refreshed at 120 Hz). The simulator software and the screens supply 270° viewing angle (see Fig. 4). The system also includes an in-vehicle camcorder to record the accidents (crash with a chicane island, sidewalk or another vehicle). During the tests, all participants were made aware of the presence of both audio and visual recordings, and warnings to draw attention of drivers to show the importance of driving tests.

The driving experiments were conducted in the Traffic Laboratory of Akdeniz University Engineering Faculty. Before the driving tests, basic training was given to drivers about the route and the system. Before starting the tests, all drivers drove the simulator (trial driving) on a neutral 1 km road (includes only two chicanes that they were not examined and analyzed in the scope of this study) to gain experience and learn driving a simulator. This training gave them a great opportunity to familiarize with the simulator including the gearshift, steering wheel and brake systems, visual and audio systems. After this training process, the drivers drove the simulator in real test one lap along a total 3.2 km route as shown in Fig. 5. In this lap, drivers met with ten different chicane types, and they saw each chicane only one time during the one lap test period.

2.3 Measurements

The driving performances of drivers were measured under two headings: (a) speeds of drivers (before and inside the chicanes) to measure the speed reduction (km/h) because of the applied chicanes, (b) traffic accidents (frequency and type) in entrance, inside and exit of the chicanes. Speeds of drivers were measured before 100 m from the chicanes and inside the chicanes. All speed data were recorded by AUD-SIM Drive V1 for every second. On the other hand, it was

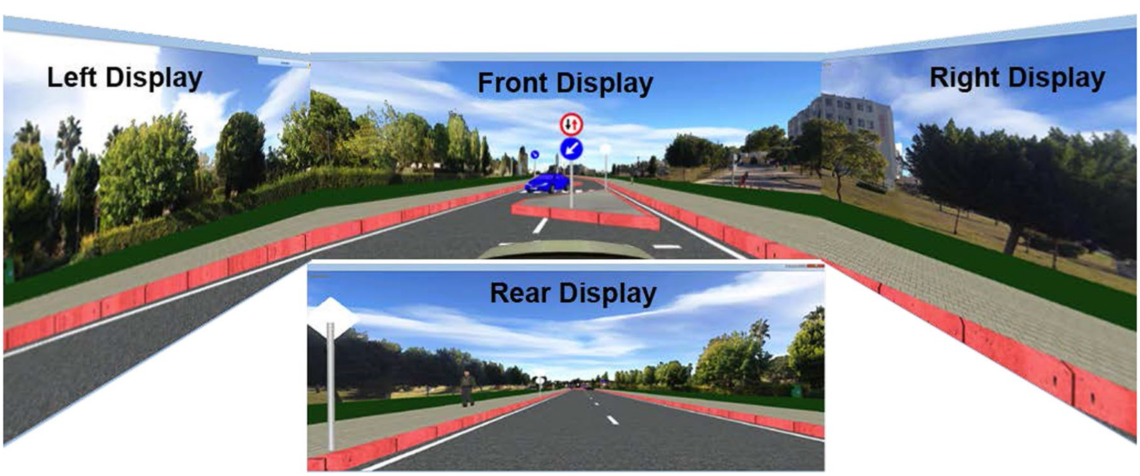

Fig. 4 A typical image from the drivers' perspective recorded by the in-vehicle camcorder

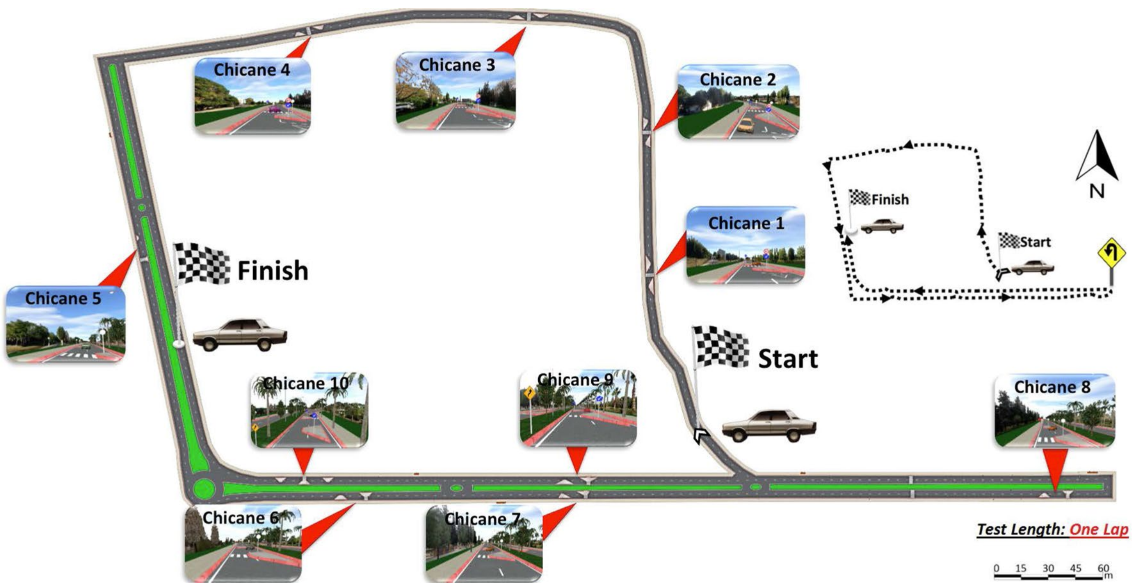

Fig. 5 The test route and the examined ten different chicane types

obtained from the simulator and real-world speed observations that drivers have tendency to drive with similar speeds in simulator after the chicanes (exit from the chicanes) compared with the real-world observations. This showed that there is no speed difference on vehicle speeds between the driving simulator and the real-world after the chicanes. For this reason, vehicle speeds after the chicanes were not examined and evaluated in the analysis.

To determine and observe the accidents, a warning system was attached to the software and all accidents were recorded by the software when one of the following conditions was met: (a) crash (hit) to sidewalk; (b) crash caused by excessive speed; (c) crash caused by the failure to yield the right of way. Three types of situations (crash with a chicane island, sidewalk or another vehicle) are defined as an accident and used in the analysis. The participants filled in a questionnaire survey after the simulator experience and hence qualitative (age and duration of driving license) and quantitative (education level, driver type and route familiarity of driver) variables were obtained. Additionally, opinions of drivers about the quality and performance of the software, the vehicle equipment and sound system (including 3D modelling and its reality level) and the ambiance of the simulator were determined from the questionnaire.

3 Analysis and Findings

3.1 Analysis of Speeds and Accidents

The mean spot speeds of the vehicles before and inside the chicanes were collected and analyzed to examine driving behaviors at different chicane types. For this purpose, a large amount of data were obtained from ten different chicane types. The calculated standard deviation, mean, minimum and maximum values of the vehicle speeds (km/h) before/inside the chicanes and the speed change ratio (speed reduction ratio) (see Eq. 1) for ten different CTs for all drivers are given in Table 2.

$$R_{\mathrm{SR}_i} = \frac{S_{\mathrm{BC}_i}}{S_{\mathrm{IC}_i}}, \quad (1)$$

where R_{SR_i} is the speed reduction ratio for CT *i*, S_{BC_i} is the speed before the CT *i* (km/h) and S_{IC_i} is the speed inside the CT *i* (km/h).

Table 2 shows that the speeds before the chicanes are always higher than the speeds inside the chicanes. Also, it can be seen from the table that CT-2 has the highest mean spot speed difference (17.7 km/h) and the speed change ratio (1.79) for undivided roads. Similarly, CT-10 has the highest mean spot speed difference (22.8 km/h) and the speed change ratio (20.02) for divided roads. The distribution of mean spot speeds before and inside the chicanes is shown in Fig. 6. As can be seen from the figure, all CTs have a great impact on speeds except for CT-5. As expected, the results confirm that all chicanes have a positive effect on speed reductions.

To investigate the effect of ten different CTs on mean spot speeds, an ANOVA test was carried out. All of the mean spot speed data "before" and "inside" the chicanes for 106 drivers were determined for normality and homogeneity of variance before the ANOVA test. To check the homogeneity of variance, Bartlett's test was performed. It

Table 2 Descriptive statistics results for examined 10 chicane types

Chicane type "CT"	Road type "RT"	Speed before chicane "S_{BC}" (km/h)				Speed inside chicane "S_{IC}" (km/h)				Mean difference (km/h)	Speed reduction ratio "R_{SR}"
		Mean	SD	Min.	Max.	Mean	SD	Min.	Max.		
1	UD	35.7	12.4	11.2	73	21.2	11.1	4.0	68	14.5	1.68
2	UD	39.9	10.9	7.6	72	22.2	9.3	4.6	52	17.7	1.79
3	UD	31.7	12.5	7.7	71	23.8	10.4	5.4	71	7.9	1.33
4	UD	35.8	14.3	6.5	78	28.4	11.0	4.6	75	7.4	1.26
5	D	46.1	11.1	15.7	67	45.6	14.1	4.2	73	0.5	1.01
6	D	38.1	12.2	5.1	68	26.3	11.6	5.0	68	11.8	1.44
7	D	44.3	13.1	6	78	22.5	8.4	5.1	50	21.8	1.96
8	D	44.0	16.9	10.2	87	25.0	9.5	4.0	62	19	1.76
9	D	43.4	14.0	18.4	77.3	24.8	8.9	4.1	60	18.6	1.75
10	D	45.1	11.6	18.3	78	22.3	8.3	5.2	55.3	22.8	2.02

UD undivided, *D* divided roads

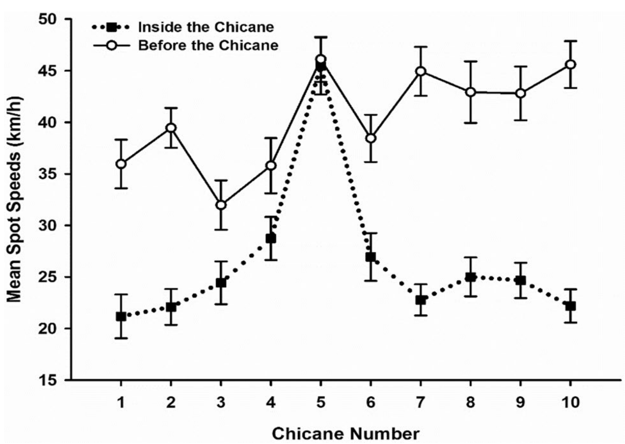

Fig. 6 The mean spot speeds of vehicles before and inside the chicanes. Vertical lines indicate confidence intervals (95% of the data distribution)

was calculated that $\chi^2 = 28.13$, $P = 0.001 < 0.01$ before the chicanes and $\chi^2 = 64.54$, $P = 0.000 < 0.01$ inside the chicanes for the speed data and it was found that homogeneity of variances is not significant at 0.01 significance level. Therefore, a nonparametric equivalent of the ANOVA "Kruskal–Wallis" test was performed to investigate whether there are significant differences between vehicle speeds before and inside chicanes. The results of Kruskal–Wallis test indicate that there are significant differences between vehicle speeds before ($\chi^2 = 121.39$ and $P = 0.001 < 0.01$) and inside the ten CTs ($\chi^2 = 241.61$ and $P = 0.000 < 0.01$) at 0.01 significance level. To determine the significant differences between the chicanes, Dunnet's T3 post hoc test was conducted as given in Table 3. Post hoc analysis indicated that there are significant differences between vehicle speeds before and inside the chicanes at 0.05 significance level. According to the Post hoc analysis, there are significant differences between CT-1 and CT-5, CT-4 and CT-5, CT-4 and CT-7, CT-5 and CT-3, CT-5 and CT-4, CT-5 and CT-6, CT-10 and CT-4, CT-10 and CT-6 for both situations (before and inside the chicanes).

Table 3 Dunnet's T3 post hoc test for speeds before and inside the chicanes for 10 chicane types

Significant difference between		Before the chicanes		Inside the chicanes	
Chicane type no.	Chicane type no.	Mean difference†	*P* value†	Mean difference†	*P* value†
CT-1	CT-5	− 7924	0.000	− 24,471	0.000
CT-4	CT-5	− 8115	0.000	− 16,874	0.000
CT-4	CT-7	− 9389	0.000	6036	0.000
CT-4	CT-10	− 9834	0.000	6663	0.000
CT-5	CT-3	11,967	0.000	21,206	0.000
CT-5	CT-4	8115	0.000	16,874	0.000
CT-5	CT-6	5292	0.039	18,700	0.000
CT-6	CT-10	− 7012	0.001	4837	0.036

†Significant at 0.05 level

According to mean spot speeds and mean rank values, vehicles have the highest speeds inside the CT-5 ($\mu = 45.6$; rank sum = 96,790.5) and the lowest speeds inside the CT-1 ($\mu = 21.2$; rank sum = 40,768.59). On the other hand, vehicles have the highest speeds before the CT-5 ($\mu = 46.1$; rank sum = 70,711) and the lowest speeds before the CT-3 ($\mu = 31.7$; rank sum = 36,025.5). The results showed that the mean spot speed inside the CT-5 (the highest) was 24.4 km/h higher than the mean spot speed inside the CT-1 (the lowest). Similarly, the mean spot speed before the CT-5 (the highest) was 14.4 km/h higher than the mean spot speed inside the CT-3 (the lowest). It means that CT-5 is less effective to decrease speeds before and inside of the examined chicanes.

A Multivariate Analysis of Variance (MANOVA) was also conducted to determine the influence of different driver characteristics such as age (year), duration of driving license (year), gender (1 = male and 0 = female), education level (1 = primary school, 2 = high school, 3 = undergraduate and 4 = postgraduate), driver types (1 = calm, 2 = less aggressive and 3 = aggressive driver) and route familiarity of driver (1 = yes and 0 = no) on vehicle speeds (km/hr) before and inside the chicanes. The MANOVA results showed that driver characteristics have a significant effect ($F_{(1.68)} = 5.36$, $p < 0.05$, Roy's largest root = 0.563) on speeds as given in Table 4.

As shown in Table 4, the age of drivers has a negative and strong effect on vehicle speeds before the chicanes for CT-1, 5, 8, 9 and 10, and inside the chicanes for CT-4, 5 and 10. The education levels of drivers have a positive effect on speeds before the chicanes for CT-9 and 10, and inside the chicanes for CT-2, 4 and 7. Also to be male has a positive effect on vehicle speeds before the chicanes for CT-5, 8 and 10, and inside the chicanes for CT-2, 5, 7 and 10. The duration of driving license of drivers has not any effect on speeds before all chicanes. On the other hand, it has a negative effect for inside CT-2, 3 and 5, and positive effect only for inside the CT-7. The route familiarity of drivers has an effect (positive) only before the CT-9 and inside the CT-4. However, it was obtained from the MANOVA test that the driver types have no effect on vehicle speeds before and inside the chicanes.

As a part of the evaluation of various CTs, the accident data were obtained from the researchers by observing the simulation replays of each participant. To investigate potential safety differences between the chicanes, they compared with each other using a "Safety Value (SV)" formula as given in Eq. (2).

$$\mathrm{SV}_i = 1 - \frac{\mathrm{TA}_i}{\sum_{i=1}^{n} \mathrm{TA}}, \tag{2}$$

where SV_i is the safety value for CT i, TA_i is the total accident number for CT i and $\sum_{i=1}^{n} \mathrm{TA}$ is the total accident number for all CT.

Table 5 presents the safety evaluation for each CT. The table reveals that CT-3 has the highest safety value (SV = 1) for undivided roads. It means that CT-3 is safer than other types for undivided roads. Similarly, CT-5, CT-6 and CT-7 have the highest safety value (SV = 1) and safer than other types for divided roads. But, mean spot speeds inside CT-5 were obtained as 45.6 km/h > 30 km/h (speed limit). Therefore, it was considered as an unsafe chicane.

3.2 Ranking of the Chicanes

In this study, a new evaluation "Safety Index (SI)" formula (see Eq. 6) was developed to be able to compare and rank various chicanes using mean spot speeds, safety values and speed reduction ratios. Min–Max normalization technique was used as one of the most common normalization techniques to scale mean spot speed, safety value (SV) and speed reduction

Table 4 MANOVA test results for driver characteristics on vehicle speeds

Dependent variables	Independent variables	Before chicanes Chicane type (+/− effect)	Inside the chicanes Chicane type (+/− effect)	Significance level
Speed (km/h)	Age	1, 5, 8, 9, 10 (−)	4, 5, 10 (−)	b
	Duration of driving license	–	2, 3, 5 (−), 7 (+)	c
	Gender (male)	5, 8, 10 (+)	2, 5, 7, 10 (+)	b
	Education level (high school)	9, 10 (+)	2, 4, 7 (+)	c
	Education level (undergraduate)	9, 10 (+)	2, 4, 7 (+)	c
	Education level (postgraduate)	9, 10 (+)	2, 4, 7 (+)	c
	Driver type (less aggressive)	–	–	b
	Driver type (aggressive)	–	–	b
	Route familiarity of driver	9 (+)	4 (+)	b

†a: Significant at 0.01 level, b: significant at 0.05 level, c: significant at 0.10 level

Table 5 Accident statistics of driving simulator experiments

Accident reasons	Chicane type (CT)										Total (∑)
	1	2	3	4	5	6	7	8	9	10	
Crash with sidewalk	14	4	–	–	–	–	–	1	3	5	27
Crash caused by excessive speed	–	1	–	1	–	–	–	–	–	–	2
Crash caused by the failure to yield the right of way	–	1	–	–	–	–	–	–	1	1	3
Total (∑)	14	6	0	1	0	0	0	1	4	6	32
Ratio	0.43	0.19	0	0.03	0	0	0	0.03	0.13	0.19	1
Safety value (SV)	0.57	0.81	1	0.97	1	1	1	0.97	0.87	0.81	–

ratio data. The technique does not introduce any potential bias into the data. In the study, the range is defined as [0, 1] to rank mean spot speeds, safety values and speed reduction ratios using Eqs. (3–6), respectively.

$$\mathrm{SNC}_i' = 1 - \frac{\bar{v} - \min(\bar{v})}{\max(\bar{v}) - \min(\bar{v})}, \quad (3)$$

$$\mathrm{SVNC}_i' = \frac{\mathrm{SV} - \min(\mathrm{SV})}{\max(\mathrm{SV}) - \min(\mathrm{SV})} \quad (4)$$

$$\mathrm{SRRNC}_i' = \frac{\mathrm{SRR} - \min(\mathrm{SRR})}{\max(\mathrm{SRR}) - \min(\mathrm{SRR})}, \quad (5)$$

$$\mathrm{SI}_i = \frac{(\mathrm{SVNC}_i' + \mathrm{SNC}_i' + \mathrm{SRRNC}_i')}{3}, \quad (6)$$

where SI_i is the Safety Index for CT *i*, SVNC_i' is the safety value normalization coefficient for CT *i*, SV is the safety value, SNC_i' is the speed normalization coefficient for CT *i*, $\bar{v}$ is the mean spot speed (km/h), SRRNC_i' is the speed reduction ratio normalization coefficient for CT *i* and SRR is the speed reduction ratio.

In Eq. (3), mean spot speeds inside the chicanes were normalized. According to this formula, lower mean spot speeds take higher values between 0 and 1 because if a chicane has a lower mean spot speed inside the chicanes, it has good speed reduction effectiveness. In Eqs. (4) and (5), lower safety and speed reduction ratio values take lower values between 0 and 1, because higher values represent better performance. All results for mean spot speed, safety value and speed reduction ratio evaluations and safety index are summarized in Table 6. In the table, ten different chicane types were ranked according to their safety index (see Eq. 6) from the highest to the lowest value for divided and undivided roads, separately. From the results, CT-2 and CT-7 are found to be the most optimum chicane types for undivided and divided roads, respectively (see Fig. 7).

Table 6 Ranking of different chicane types by using speed, safety and speed reduction ratio evaluations

Road type	Chicane type	Speed evaluation	Safety evaluation	Speed reduction ratio evaluation	Safety Index (SI)	Rank number (RN)
		SNC	SVNC	SRRNC		
Undivided	1	10.00	0.00	0.79	0.60	2
	2	0.86	0.21	10.00	0.69	1
	3	0.64	10.00	0.13	0.59	3
	4	0.00	0.92	0.00	0.31	4
Divided	5	0.00	10.00	0.00	0.33	6
	6	0.83	10.00	0.43	0.75	3
	7	0.99	10.00	0.94	0.98	1
	8	0.88	0.81	0.74	0.81	2
	9	0.89	0.31	0.73	0.65	5
	10	10.00	0.00	10.00	0.67	4

RN 1 shows the most optimum, RN 4 shows the least optimum CT for undivided roads

RN 1 shows the most optimum, RN 6 shows the least optimum CT for divided roads

Fig. 7 The most optimum chicane types **a** CT-2 for undivided, **b** CT-7 for divided roads

3.3 Modelling of Optimum Chicane Types

To understand the relationship between vehicle speeds and driver characteristics for CT-2 (the most proper CT for undivided roads) and CT-7 (the most proper CT for divided roads), an Ordinary Least Square Regression (OLSR) analysis was performed. Speeds of 106 drivers were taken as dependent variables and driver characteristics gender, education level, duration of driving license, driver profile and route familiarity were taken as independent variables. The dependent and independent variables of the analysis are summarized in Table 7.

To determine the most effective parameters of vehicle speeds for CT-2 (for undivided roads) and 7 (for divided roads) a regression model was used. It contains qualitative and quantitative variables and names as Analysis of Covariance (ANCOVA) model. The equation of ANCOVA model can be estimated as given below:

$$\begin{aligned} V_c = {} & \alpha_0 + \alpha_1\text{Gender} + \alpha_2\text{Education\_2} + \alpha_3\text{Education\_3} \\ & + \alpha_4\text{Education\_4} + \alpha_5\text{Driver\_Type\_2} + \alpha_6\text{Driver\_Type\_3} \\ & + \alpha_7\text{Route\_Familiarity\_of\_Driver} \\ & + \beta_1\text{Age} + \beta_2\text{DoDL} + u, \end{aligned} \tag{7}$$

where α_0 is a constant term, α_i is the dummy variables ($i \neq 0$), β_j is the coefficients of the variables in the model ($j = 1,\ldots, 2$) and u is a disturbance term.

To predict the coefficient of Eq. (7), An Ordinary Least Square (OLS) estimator was used. According to the OLRS model, multicollinearity, heteroscedasticity and model specification error problems were examined using diagnostic tests and results are given in Table 8 for CT-2 and CT-7. After checking multicollinearity, heteroscedasticity and model specification error problems, it was assumed that disturbances are distributed normally because of the big sample size (106 drivers) based on the Central Limit Theorem (CLT). As seen in Table 8, the proposed model was found significant for CT-2 ($F = 1.89$, $P = 0.062 < 0.10$) and CT-7 ($F = 5.13$, $P = 0.000 < 0.01$).

According to the modelling results, three types of driver properties have significant coefficients and positive effects on vehicle speeds for CT-2 (coef. = 7.842, $P = 0.055$ for Education 2; coef. = 4.245, $P = 0.068$ for Education 3 and coef. = 7.142, $P = 0.058$ Education 4). Among them, Education 2 (high school) variable has the highest and positive coefficient. That is, the drivers who have high school level education tend to drive faster inside CT-2 than other

Table 7 Dependent and independent variables of OLSR model for CT-2 and CT-7

V_c	Vehicle speeds inside chicanes
Covariates	
Age	Age (years)
DoDL	Duration of driving license (years)
Dummy variables	
Gender	(If driver is female: 1, otherwise: 0)
Education 2	(If driver has the education level as high school: 1, otherwise: 0)
Education 3	(If driver has the education level as university (undergraduate): 1, otherwise: 0)
Education 4	(If driver has the education level as M.Sc. or Ph.D. (graduate): 1, otherwise: 0)
Driver type 2	(If driver is less aggressive driver: 1, otherwise: 0)
Driver type 3	(If driver is aggressive driver: 1, otherwise: 0)
Route familiarity of driver	(If driver has route familiarity: 1, otherwise: 0)

Table 8 OLSR model results for vehicle speeds

Variables	CT-2				CT-7			
	Coefficient	St. E.	*t*	*P* value	Coefficient	St. E.	t	*P* value
Dep. variable: V_c								
Cons.	41.341[c]	21.41	1.93	0.056	10.250[c]	5.40	1.90	0.060
Gender	− 120.034[a]	4.42	− 0.63	0.008	− 3.525[b]	1.65	− 2.14	0.035
Education 2	7.842[c]	4.12	1.92	0.055	20.554[a]	60.05	3.40	0.001
Education 3	4.245[c]	2.86	1.82	0.068	11.557[b]	5.53	20.09	0.039
Education 4	7.142[c]	40.05	1.90	0.058	11.393[b]	5.68	20.00	0.047
Driver type 2	4.862	18.32	0.27	0.791	− 0.720	1.58	− 0.46	0.650
Driver type 3	− 0.456	0.72	− 0.63	0.529	− 1.138	2.75	− 0.41	0.680
Route familiarity of driver	2.869	4.72	0.61	0.545	− 5.632	3.99	− 1.41	0.161
Age	− 0.0861	0.60	− 0.14	0.886	− 0.156	0.19	− 0.84	0.400
DoDL	− 0.548[c]	0.31	− 1.78	0.077	0.247[c]	0.15	1.67	0.098
Max. VIF	2.4 (no multicollinearity problem)				5.1 (no multicollinearity problem)			
White test	$P = 0.678 > 0.10$ (no heteroscedasticity problem)				$P = 0.851 > 0.10$ (no heteroscedasticity problem)			
Shapiro–Wilk *W* normality test	$P = 0.059 > 0.05$ (disturbances are normally distributed)				$P = 0.125 > 0.10$ (disturbances are normally distributed)			
Ramsey reset test	$P = 0.636 > 0.10$ (no model specification error problem)				$P = 0.115 > 0.10$ (no model specification error problem)			

[a]Significant at 0.01 level, [b]significant at 0.10 level, [c]significant at 0.05 level

drivers. On the other hand, the drivers who have university degree drive slower than other drivers. Gender of the drivers and duration of driving licenses have also a negative and significant coefficient in the model (coef. = − 120.034, $P = 0.008$). It means that being female has a negative effect on speeds. Duration of the driving license and gender (female) variables have a positive effect on driving at low speeds in comparison to other variables for CT-2. In the model for CT-2, the dummy variables for Driver Type 2 (less aggressive driver), Driver Type 3 (aggressive driver), Route Familiarity of Driver and quantitative variable (age) have no significant effect on the vehicle speeds. It means that they did not affect speed choice behavior of the drivers inside the CT-2 significantly.

For CT-7, all four types of driver properties have significant and positive effects on vehicle speeds for CT-7 (coef. = 20.554, $P = 0.001$ for Education 2; coef. = 11.557, $P = 0.039$ for Education 3; coef. = 11.393, $P = 0.047$ for Education 4 and coef. = 0.247, $P = 0.098$ for duration of driving license). It expresses that drivers who have these characteristics tend to drive faster inside the CT-7. Among them, the highest and positive coefficient belongs to variable Education 2 (high school), the same as CT-2. It shows that the drivers who have the education level as high school, drive faster inside CT-7 than other drivers. However, the duration of driving license has less impact than other variables on speed inside CT-7. Gender of the driver has also significant coefficient in the model (coef. = −3.525, $P = 0.035$). It means that being female has negative effects on speeds. Female drivers are more willing to drive at low speeds in comparison to other type drivers for CT-7 as is the case with CT-2. Also in the model for CT-7, the dummy variables for Driver Type 2 (less aggressive), Driver Type 3 (aggressive), Route Familiarity of Driver and Age have no significant effect on the speed. In summary, it means that having these driver characteristics does not affect speed choice behavior of drivers for CT-7.

4 Conclusion and Discussion

This study aimed to investigate and evaluate ten most popular chicane types and their performances using a driving simulator. For this purpose first, chicanes were examined according to their speed reduction effectiveness and safety performances. Then all the chicanes were ranked according to their Safety Index (SI) value using driving simulator test data, because the real applications of ten different chicane types for testing on a divided and undivided urban minor roads have a high cost. Furthermore, some parameters are uncontrollable and not easy to measure from the field observations. For this reason in this study, the effects of chicanes on speed reduction have been investigated and statistically verified. Analysis results showed that there are significant differences between vehicle speeds before and inside of the chicanes. Also conducted Post hoc analysis revealed that there are significant differences between CT-1 and CT-5, CT-4 and CT-5, CT-4 and CT-7, CT-5 and CT-3, CT-5 and

CT-4, CT-5 and CT-6, CT-10 and CT-4, CT-10 and CT-6 for both situations (before and inside the chicanes). This result is very important to decide that drivers have different driving behaviors at before and inside different chicane types. These differences are also very important to conclude that chicanes have great impact on speed reduction. According to speed reduction comparisons, CT-2 for undivided roads and CT-10 for divided roads were found to be the most advantageous types. According to safety comparison (accident statistics) CT-3 for undivided roads and CT-5 and CT-7 for divided roads were found to be the safest chicanes because of the lowest accident ratio. However, in this study a new evaluation method, "Safety Index (SI)" which includes safety, speed and speed reduction parameters, was developed and used to compare performance of different chicanes with each other. According to SI comparisons, CT-2 and CT-7 were found to be the most optimum chicane types. This result shows that CT-2 and CT-7 are the most optimum chicane types for undivided and divided urban minor roads in Turkey because these chicanes indicate the maximum performance according to different performance evaluations tested by the Turkish drivers.

In the study, another important point was to determine the influence of different driver characteristics on driving before and inside the chicanes. For this purpose, a MANOVA test was conducted, and it was found that the most important and effective driver characteristics are age (has a negative effect) and gender (to be male has a positive effect) of drivers before and inside the chicanes, respectively. Also, an Ordinary Least Square Regression (OLSR) model was used to examine the effects of chicanes on speed choice of drivers inside the CT-2 and CT-7 (optimum chicane types). It was found that drivers' education levels (high school, university, graduate) have a significant and positive effect on drivers' speed choice for both CTs. It means that those drivers with low education levels have more tendency to drive faster than other drivers inside the chicanes. However, it was obtained from the results that being a female driver has a negative and significant effect on driving faster inside CT-2 and CT-7. It indicates that both CTs have a great impact on female drivers for driving slower. Female drivers are more willing to drive at low speeds in comparison to other types of drivers inside the CT-2 and CT-7. Additionally, duration of driving license (longer years) has a significant effect for both chicanes. But, this variable has a negative effect for CT-2 and positive effect for CT-7. It can be concluded that drivers with a longer driving license have more tendency to drive slower for CT-2 and drive faster for CT-7. Therefore, it can be remarked that duration of driving license is the key parameter on drivers' speed choice behavior at chicanes. Study results showed that the systematic investigation of different chicane types have a great potential to reduce speed and supply safety in urban minor roads. For this reason, the detailed investigation of different chicane types has a great importance to determine the most optimum type(s) according to different parameters such as traffic, road and driver.

In summary, the general findings of this study help better understand the potential benefits of different chicane types. Additionally, the results can be helpful for transportation authorities to apply suggested chicane types at urban minor roads to reduce vehicular speeds and traffic accidents as a traffic calming application. For broader coverage of results, various limitations need to be tackled in future studies. For example, the results of the study are obtained from the analysis of the most used ten different chicane types. Additional research may provide better understanding using more chicane types.

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