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Investigation of the Pothole-Designed 3D Pedestrian Crossing to Improve Pedestrian Safety

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Abstract

Every year, approximately 1.19 million people lose their lives in traffic accidents, and more than half of the fatalities are among pedestrians, motorcyclists, and cyclists. Pedestrian accidents are especially attributed to drivers not prioritizing pedestrians and not slowing down at pedestrian crossings. Pedestrians are vulnerable road users and increasing speed may change the result of a crash. Therefore, this study aims to provide visual appeal and encourage drivers to reduce speed with a new pothole-designed 3D pedestrian crossing. The study was implemented on the Başkent University Campus. The vehicle speeds were obtained before and after the 3D pedestrian crossing implementation during morning, noon, and evening peak hours. In conclusion, after implementing the 3D pedestrian crossing, it was observed that the average speed of private vehicles decreased by approximately 44%, service vehicle speeds decreased by 47%, and all vehicle speeds decreased by 46%. The independent t-test showed a statistically significant difference between the before and after average speeds of installing the new 3D pedestrian crossing.

1. Introduction

Traffic accidents are one of the significant causes of death worldwide and continue to take lives every day. In 2023, the World Health Organization (WHO) published a report on road safety, stating that injuries resulting from traffic accidents are the leading cause of death in children and young people aged 5 to 29. At the same time, approximately 1.19 million people lose their lives in traffic accidents every year, and more than half of the fatalities are among pedestrians, motorcyclists, and cyclists. As a result of the investigation of driver behavior at pedestrian crossings in terms of giving pedestrians the first right of way, pedestrians represent 23% of all fatalities [1].

Pedestrians are vulnerable road users and are exposed to severe injuries and fatalities due to collisions with vehicles. Particularly at pedestrian crossing areas where pedestrians often engage in crossing activities, vehicle crossings are usually regulated with horizontal and vertical markings and signalization. Conscious drivers tend to slow down and give way to pedestrians as traffic laws require, but if they do not take due care, they can cause pedestrian accidents that may result in death. Since pedestrians do not have a protective barrier around them, they face a force greater than they can tolerate in the event of a crash. Almost all fatalities in pedestrian crashes (98%) are pedestrians themselves [2]. As speed increases, the severity of an accident also increases. Therefore, speed is a critical and reducible parameter to minimize the consequences of a crash.

On the other hand, designing safe, accessible, and remarkable pedestrian facilities is vital to decrease pedestrian crashes. Existing traditional pedestrian crossings in areas with a high density of pedestrians may be insufficient to ensure pedestrian safety. To increase safety at pedestrian crossings and warn pedestrians and drivers, it is possible to implement different applications such as speed bumps [3], smart pedestrian crossing applications [4], and raised pedestrian crossings [5]. These applications may have advantages or disadvantages depending on their benefit-cost

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analysis and environmental impacts [6]. 3D pedestrian crossing designs, which have been applied in recent years, are innovative and low-cost approaches that aim to increase pedestrian safety by enhancing their visual appeal to encourage pedestrians to use these areas when crossing the street and raising driver awareness when approaching pedestrian crossings, resulting in speed reduction [7–9].

The limited effectiveness and, in some cases, inadequate safety of traditional pedestrian crossings encourage the search for new solutions [10]. 3D crossings offer significant advantages not only in terms of aesthetics but also in terms of pedestrian safety. They are essential for attracting drivers' attention and increasing awareness of pedestrian crossings. They are typically constructed in urban areas with high pedestrian activity, such as school areas and shopping districts. However, their applications in university campuses with high pedestrian density have not been encountered. When the literature was reviewed, only a report of the application at the University of Arkansas was found, but no scientific studies were found [11].

University campuses have high pedestrian demand and mobility. It is crucial to control vehicular speed at 30 km/hr to provide better safety for vulnerable road users in these locations [12]. This study was conducted on the Başkent University Campus, which has pedestrian prioritization and employs a low-speed limit (<30 km/hr) policy. On campus, vehicle speeds are generally controlled with speed bumps before pedestrian crossings. However, although speed bumps effectively reduce vehicle speeds, they have significant negative impacts, including increased wear and tear on vehicles, delays for emergency vehicles, increased noise and air pollution, and aesthetic concerns [13,14]. However, in some places at the Başkent University Campus, there are only conventional crossings, one of which is at the Engineering Faculty's student entrance. Therefore, this location was chosen to implement the newly designed 3D pedestrian crossing to analyze vehicle speeds before and after its installation. In the literature, there are different types of 3D pedestrian crossing drawings, which give the impression of a high platform against the approaching vehicle with a 3D visual illusion, except for one study to the best of our knowledge [9].

This paper aims to investigate the effectiveness of a new and unique 3D pedestrian crossing based on a pothole design in controlling speed. A radar speed gun was used, and speeds were manually recorded for the approach of the existing study location (conventional pedestrian crossing) before and after the 3D pedestrian crossing replacement. The impact of 3D pedestrian crossing was measured in terms of differences in speed distribution between before and after cases by comparing average speeds and analyzing the speed profiles of morning, afternoon, and evening peak hours.

2. The Road Safety Perspective of 3D Pedestrian Crossing

Excessive speed and poor driver perception abilities may cause traffic accidents. Providing sufficient visibility can help drivers improve road safety. Simple solutions can be implemented when the budget is insufficient for expensive traffic infrastructure [15]. In this context, today's cities' complex and dense traffic patterns require new solutions to enhance pedestrian safety and comfort. In this regard, the design of 3D pedestrian crossings has come to the fore as a more effective and attractive alternative to traditional pedestrian crossings.

Studies show that traditional marked crossings have little positive impact on pedestrian safety [16] and even increase pedestrian accident rates in some road environments [10]. In contrast to traditional crossings, innovative crossing designs have been found to have more positive effects on pedestrian collision risk and significantly improve pedestrian safety due to high visibility using larger painted areas [9, 17–19]. In this respect, 3D pedestrian crossings are low-cost solutions that positively affect driver awareness. It has been stated that they are effective in slowing down vehicle speeds as a driver behavior immediately after the application and even for a few weeks. Still they may lose their effect due to driver familiarity or faded paint [8, 20]. On the other hand, it is understood that the application area in terms of pedestrian safety is relatively new in the literature, open to development, and requires further research, as it helps to raise awareness with its design feature and is also a low-cost and environmentally friendly application.

3D crossings are a new generation of pedestrian crossings that are drawn flat on the road using optical illusions to create the perception of a three-dimensional crossing from the driver's perspective. They aim to improve pedestrian safety [8, 9, 21]. They offer significant advantages not only in terms of aesthetics but also in terms of pedestrian safety and traffic flow. Making pedestrian crossings more prominent attracts the attention of drivers and increases safety.

In recent years, 3D pedestrian crossings have been frequently implemented as pilot projects by local governments worldwide [20, 22–24]. When the applications are examined, they generally create the impression of a high platform, such as a speed bump, raised pedestrian crossing (see Figure 1-a) against the approaching vehicle with a 3D visual illusion [7, 15, 20]. These applications employ optical illusions by using different colors and angular drawings to create the impression of a three-dimensional effect from the viewpoint of drivers. Although the markings are painted flat on the surface, they give the illusion of a higher level of crossing. However, to the best of our knowledge (see Figure 1-b), there is one application that gives the impression of a downward slope to an approaching driver. [9]. On the other hand, scientific studies revealing their use's positive/negative effects in the literature are limited and do not form a consistent pattern. Therefore, each new study will provide valuable contributions to the literature.

Figure 1. 3D pedestrian crossings in different designs: a) the impression of a high platform [7], [15], [20] b) the impression of a downward slope [9]

3. Methodology

3.1. The Study Location and Drawing Pattern

An experimental study of road safety improvement was undertaken on the roadway inside the main campus at the student entrance of the Başkent University Faculty of Engineering. This location has a high level of pedestrian and staff activity, especially during academic terms. The roadway in the study area has two-by-two divided roads with only traditional pedestrian crossings for both directions. It is located at the back entrance of the Faculty of Engineering (Figure 2). In the campus area, speed bumps are used before the traditional pedestrian crossing to keep vehicle speeds down, except in the study location (Figure 3). The new building of the Faculty of Engineering has been in use for a year, and this area has recently experienced an increase in pedestrian density and vehicular activity. On weekdays during peak hours, many pedestrians, especially students and staff, cross the road to reach their destinations, such as faculty buildings, service vehicles, dormitories, and other lecture or dining facilities on campus. Therefore, there is a need for a new pedestrian crossing facility to improve upon the limitations of traditional pedestrian crossings in terms of speed reduction. Thus, it gives a chance to implement this new 3D pedestrian crossing facility in this location. This type of crossing has optical illusions to give the impression of a three-dimensional crossing from a vehicle driver's perspective. However, the crossing markings are painted on the level surface. It creates a gap between the visual perception of road users and the visual reality.

The drawing perspective technique was used for the 3D pedestrian crossing development. The one-point perspective (see Figure 4) was used in which the viewer's line of sight is perpendicular to the scene. The one-point perspective has a vanishing point on a horizontal line, and all parallel lines converge to this point [20, 21].

In this study, unlike typical 3D crossings that create a raised platform effect, a unique 3D pedestrian crossing was designed to give a downward slope effect, creating the perception of a pothole in the direction of traffic flow. The design was first drawn in the CAD environment. In the application area, it was considered to make an additional design by preserving the existing traditional pedestrian crossing. Because removing the existing pedestrian crossing would be both costly and damage the asphalt texture. For this reason, the new 3D design was planned to extend the existing crossing in the forward direction. When designing the new 3D pedestrian crossing, the fill color was chosen as a grey tone, which is distinguishable on the asphalt pavement, and black contour lines were used to provide depth perception and the pothole effect along the flowing direction (Figure 5). The dimensions of the new design were determined according to the existing pedestrian crossing and were drawn on both sides of the road (Figure 5-a). After the CAD design, the initial visual effect was tested by applying tape and black chalk on the road (Figure 5-b). And the final application was made on the roadway (Figure 5- c, d).

Since this was a special application, standard road marking patterns could not be used except for the white sections. During the application of each pedestrian crossing element, tape was applied to the surface; after the paint dried, the existing tapes were removed, and the tapes for the next step were placed. This process was repeated until all elements of the new pedestrian crossing design were completed.

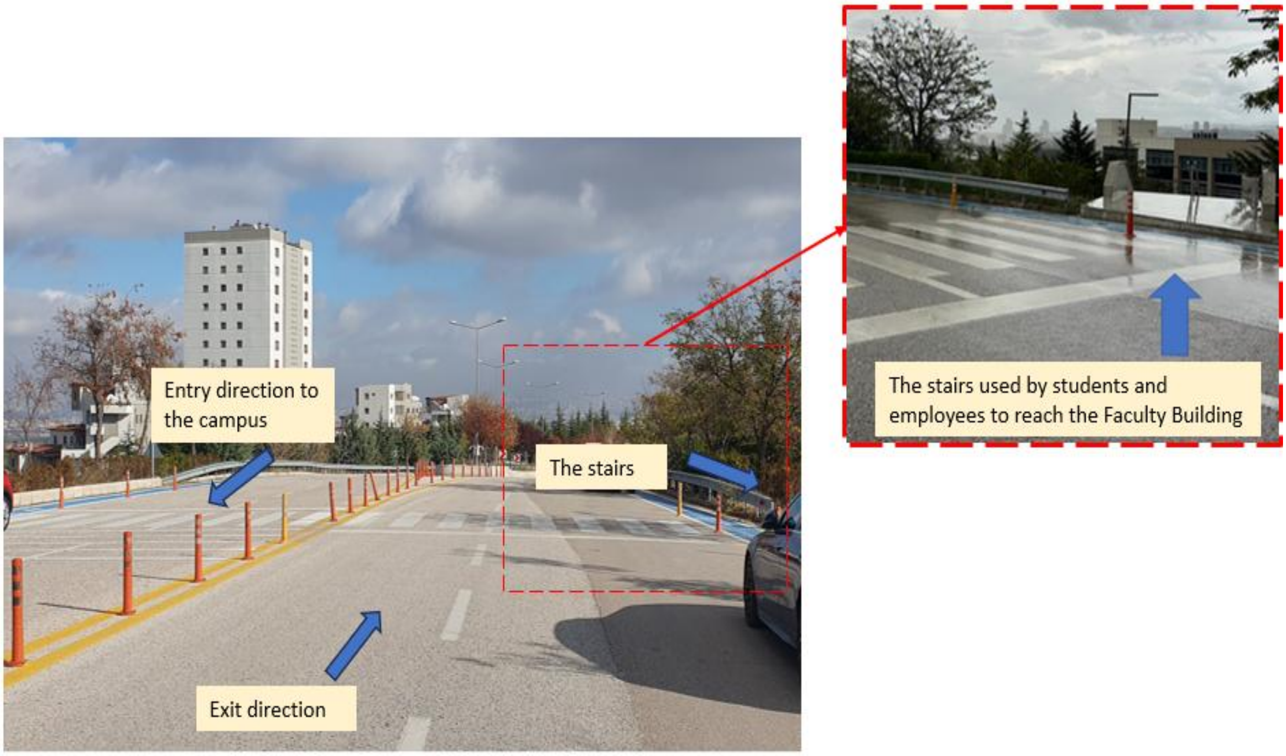

Figure 2. The roadway and the existing traditional pedestrian crossing in the study area

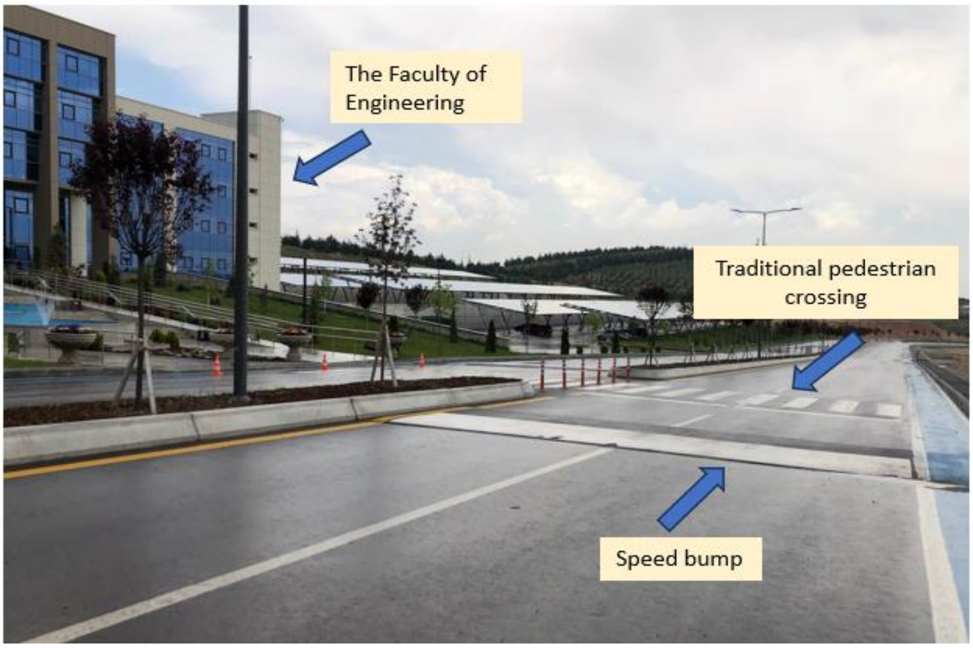

Figure 3. The speed bump application before the traditional pedestrian crossing in the Başkent University campus area

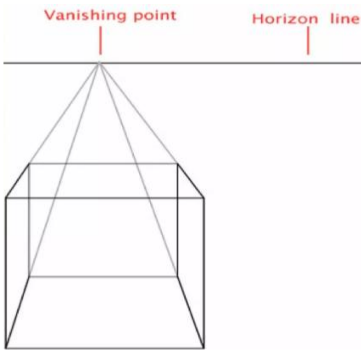

Figure 4. A drawing perspective technique with the vanishing point set at eye level

In the literature review, it has been noted that the studies conducted with 3D pedestrian crossings often lose their visual impact over time due to the fading of the paint in the long term, reducing the perception effect [8, 20]. This study used a double-component road marking paint to address this issue. This type of paint is both long-lasting and resistant to fading. This will allow for long-term investigation, although this has not yet been examined in this study. In addition, glass beads were used on the top side of the paint to increase its visibility in night-time conditions.

3.2 The Evaluation of 3D Pedestrian Crossing

3D pedestrian crossing designs, which have recently gained popularity, have been evaluated in only a few scientific studies. These limited studies have either examined the perceptions of drivers or pedestrians using surveys [7, 9] or concluded a statistical analysis of vehicle speed data captured by cameras [20]. Appropriate statistical test methods were selected based on data type, size, and research direction.

3.2.1 Speed Data Collection

Firstly, vehicle speed measurements were taken using a radar speed gun (Bushnell, Model 101911, accuracy: ±1.0 mph/kph [25]). This device provides manual speed data. Its operation requires a clear line of sight for accurate speed measurement, and it can be easily operated by a single individual [26]. The speed data were collected at the traditional pedestrian crossing within the study area during the morning (08:30-09:30), noon (12:00-13:00), and evening (16:30-17:30) peak hours. These time intervals were selected due to the high pedestrian and vehicle activity. Then, the same measurement was repeated after the 3D pedestrian crossing was installed. Speeds were recorded for service and private vehicles separately. In the mornings, the entrance direction to the campus is particularly active, while both directions are more active during lunchtime. On the other hand, the exit direction from the campus is more active in the evening. Five days of data were collected before and after installation. Table 1 shows the descriptive statistics of the data for total speeds and total flow over five days.

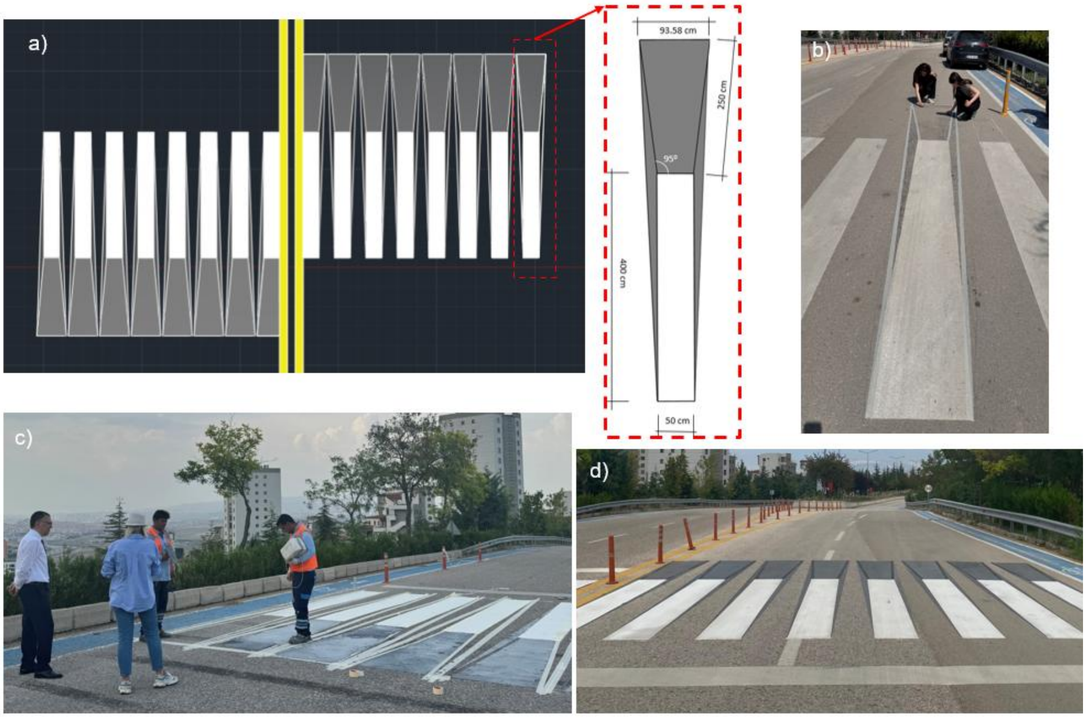

Figure 5. The new 3D pedestrian crossing design a) CAD drawing b) draft application using tape and black chalk c) on-site application process d) final view of the new design

Table 1. Descriptive statistics for before and after the installation of the new 3D pedestrian crossing

	Overall speed data in each period					
	08:30-09:30		12:30-13:30		16:30-17:30	
	Before	After	Before	After	Before	After
Flow	**150**	**63**	**150**	**55**	**148**	**67**
Min. Speed (km/h)	11	12	13	14	11	13
Max. speed (km/h)	81	50	83	50	78	47
Mode speed (km/h)	42	24	54	32	45	24
Mean speed (km/h)	43.38	24.64	46.98	26.94	45.71	25.03

3.2.2. Statistical Analysis of Vehicle Speeds

In this study, the research question is to determine how the 3D pedestrian crossing affects the visual awareness of vehicle drivers (measured by speed profiles). In other words, it examines whether there is a significant difference in the speed profiles between traditional and 3D pedestrian crossings. In this way, pedestrian safety can be assessed.

The study hypothesis is based on the assumption that the average speed at the 3D pedestrian crossing will be lower than the speed at the traditional pedestrian crossing. The null hypothesis (H_0) is that there is no change in average speed.

An independent t-test was used to determine whether there is a statistically significant difference between the two population means (before and after speeds). The test was conducted with a 95% confidence interval, and since the p-value was less than 0.05, the research hypothesis was accepted.

4. Results and Discussion

4.1 Before and After Vehicle Speeds

While the first measurements of the traditional pedestrian crossing were taken at the end of the university's spring semester, the 3D pedestrian crossing design measurements were conducted at the beginning of the summer school semester. There was no seasonal change (such as temperature, precipitation, or snow). Since the collected data was analyzed for short-term evaluation, measurements were taken in almost the same clear weather conditions. Therefore, this did not create a situation that would affect the speed variations. However, the initial traffic volume was lower than the subsequent vehicle volume (Table 1), as the semester had ended and most of the students had returned home. On the other hand, the values were similar within their respective periods when looking at the daily average values for the before and after periods. Accordingly, the 5-day average speed values in the initial period were 37.64 km/h for service vehicles, 47.66 km/h for private vehicles, and 45.17 km/h for all vehicles combined. Figure 6 displays the average speeds for service, private, and all vehicles before and after the installation for each day. When the after-installation period was checked, it was observed that vehicle speeds dropped significantly. While the average private vehicle speed during the after-installation period was around 25.22 km/h, it was 20.9 km/h for service vehicles. For all vehicles, the after-installation average speed was 24.22 km/h. In conclusion, after implementing the 3D pedestrian crossing, it was calculated that the average speed of private vehicles decreased by approximately 44%, service vehicle speeds decreased by 47%, and all vehicle speeds decreased by 46%. There seems to be a slight difference between the total reduction of private and service speeds. This may vary depending on the perception of the 3D effect in the forward direction due to the driver's eye level or seat height. To reach this judgment definitively, a survey study should be conducted, and it can be discussed how the 3D effect is perceived in vehicles of different dimensions, or more data must be collected.

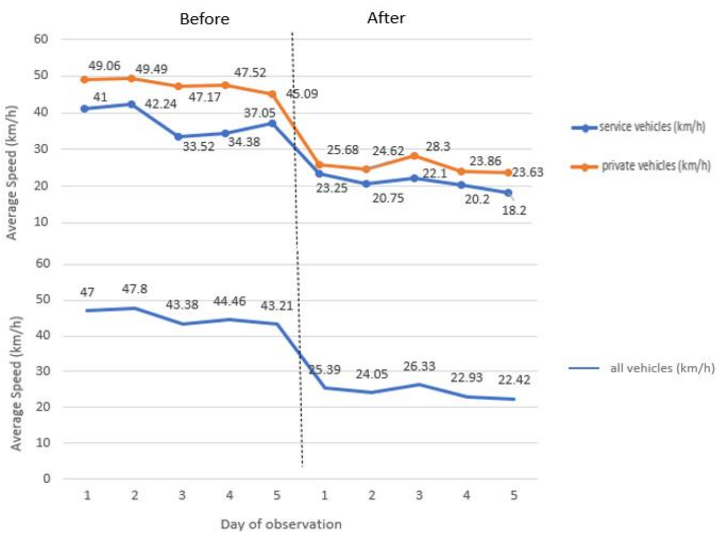

Figure 6. Average speed values of service, private, and all vehicles

The speeds for each vehicle type were recorded during morning, noon, and evening peak hours due to pedestrian activity (Table 2). In the initial period, while service vehicles showed the highest average speed (40.60 km/h) at the noon peak, the highest average speed for private cars was 48.44 km/h at the evening peak. In the after-installation period, the highest average speed of service vehicles was 25.32 km/h at the evening peak. The highest average speed for private vehicles was 27.80 km/h at the noon peak. Regarding all vehicle speeds (see Figure 7), the highest average speed in the initial period was observed in the evening, with midday speeds being the second highest, and the lowest speed was recorded in the morning. In the after-installation period, the highest average speeds were recorded at noon. Furthermore, a significant (approximately 45%) reduction in average speeds was generally observed after implementing the 3D pedestrian crossing.

Table 2. Average speeds for vehicle type versus time of day

	Average speed (km/h)					
	Morning		**Noon**		**Evening**	
	08.30-09.30		**12.00-13.00**		**16.30-17.30**	
Vehicle type	**Before**	**After**	**Before**	**After**	**Before**	**After**
Service vehicles	36.73	21. 25	40.60	23.80	36.56	25.32
Private cars	47.36	25.80	47.24	27.80	48.44	24.91

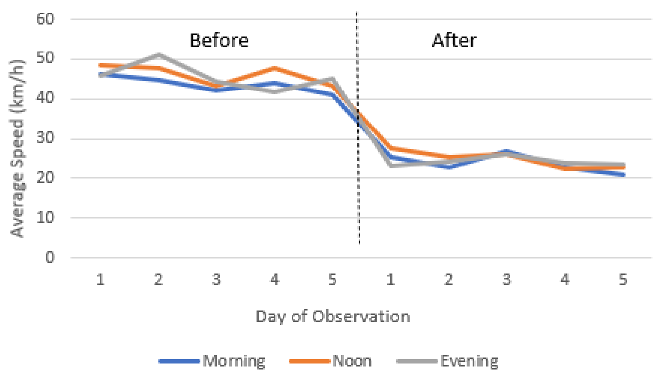

Figure 7. Average speeds of all vehicles for the morning, noon, and evening peak hours

4.2 Statistical Analysis Results

Before and after speeds covering all vehicles were analyzed using an independent samples t-test at a 95% confidence level ($p < .05$). Group statistics are shown in Table 3. There is nearly three times a higher difference between the standard deviations of the groups. Levene's test for equality of variances showed no homogeneity in the variances ($p<.000$). Therefore, the second row of Table 4 was used. The test results showed that there is a significant difference between the before-average speed and the after-average speed ($p<.000$). However, due to the lack of homogeneity, the Welch's t-test, which is an alternative test, was applied and confirmed the significance of the difference ($p<.000$). Thus, it was determined that there was a significant difference between the before and after average speed data (Table 5).

Table 3. Before and after group statistics

Speed	N	Mean	Std. Deviation	Std. Error
Before	448	45.19	15.571	0.736
After	185	24.03	5.463	0.403

Table 4. Independent t-test results

		Levene's test for equality of variances		t-test equality of means		
		F	Significance	t	df	sig.
Speed	Equal variances assumed	172.874	.000	17.975	629	.000
	Equal variances not assumed			25.205	617.953	.000

Table 5. Robust tests of equality of means

Speed	N	Mean	Std. Deviation	Std. Error
Before	448	45.19	15.571	0.736
After	185	24.03	5.463	0.403

5. Conclusions and Recommendations

Pedestrians are vulnerable road users, and almost all fatalities in pedestrian crashes are the pedestrians themselves. Therefore, one of the priorities for road safety is to prevent road accidents involving pedestrians.

As a traffic calming tool, the new and unique 3D pedestrian crossing was implemented in the campus area of Başkent University. This unique 3D design aimed to create a pothole effect on the road surface, and observations were collected during morning, noon, and evening peak hours due to students' and employees' activity. The speed data was obtained from service and private vehicles using a radar speed gun, separately. The effect of this 3D road crossing was then analyzed before and after the installation. The analysis showed a significant difference between the average speeds before and after installing the 3D pedestrian crossing. After implementing 3D pedestrian crossing, the average speed reduction was calculated to be approximately 44%, 47%, and 46% for private, service, and all vehicles, respectively. Additionally, the statistical tests showed a significant difference between the average speed before and after installing the new 3D pedestrian crossing.

This study has shown positive results in increasing pedestrian safety, especially at crossings with high pedestrian traffic. The design of the new pedestrian crossing has significantly reduced vehicle speeds in the initial evaluation period. The effect of the new 3D pedestrian crossing design appears to have enhanced driver awareness. Thus, such applications can contribute to pedestrian safety. However, the literature has adverse effects (such as driver familiarity, paint peeling) of these applications that need long-term investigation [20]. Therefore, long-term evaluation should be considered for future research. Additionally, driver and pedestrian awareness can be measured with the prepared questionnaires.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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