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Mohammed Taleb OBAIDAT[1]*, Bara' Wasfi AL-MISTAREHI[2], Aminah Naser ABU-YAMEEN[3]

THE EFFECTIVENESS OF AUTOMATED SPEED ENFORCEMENT CAMERA PROGRAM ON URBAN ROADS

Summary. The main purpose of this study was to consider the effectiveness of the Automated Speed Enforcement Cameras Program applied on the urban roads of Amman. The operating speed profiles along fixed speed camera segments were constructed in urban areas using continuous speed data collected by a GPS tracking technique to understand drivers' reactions to cameras. Operating speed profiles showed that drivers reduced their speed about 208 m upstream of speed cameras, then recovered their speed about 221 m downstream. Four regression models were developed to estimate the minimum speed at the speed camera (R^2=60.7%), the deceleration distance (R^2=68.1%), the acceleration distance (R^2=70.6%), and the maximum speed downstream of the speed camera (R^2=71.8%). The minimum speed at the speed camera is reduced as the speed limit decreases, the longitudinal street slope decreases, and the radius of the curve toward the speed camera increases. The existence of a traffic calming measure upstream of a speed camera increased the deceleration distance, and the existence of a traffic calming measure downstream of a speed camera decreased the maximum speed downstream. A before-and-after study using a paired samples t-test with a 95% confidence level showed that the number of crashes increased and the severity of crashes decreased (but with no statistical significance) after speed camera installation.

1. INTRODUCTION

Road safety is a very important measure needed to prevent road users from being killed or injured. Obaidat and Ramadan [1] mentioned that traffic crashes were ranked by the Jordan crash statistics as the leading cause of death. This measure is related to three elements: the road infrastructure, the driver, and the vehicle. According to the Jordan Traffic Institute [2], 98% of traffic crashes are related to the drivers' behavior. Speeding can be attributed to a driver's reckless behavior, often stemming from overconfidence, a poor assessment of risks, and a disregard for traffic safety rules. This includes ignoring traffic regulations, disregarding road conditions, and exceeding the posted speed limit [3]. Higher traffic speeds increase the number and severity of traffic collisions [4]. Wang et al. [5] found that the crash frequency increased by 0.7% with a 1% increase in mean speed and by 0.74% with a 1% increase in speed variation. Based on that, the traffic speed enforcement, whether traditional (police) speed enforcement or speed camera enforcement (mobile speed cameras and fixed speed cameras), must be applied to reduce the number and severity of traffic crashes. Speed cameras have several advantages over traditional speed enforcement: (1) they are more effective in reducing the speed of drivers because they know the risk of being detected, (2) they increase enforcement fairness, (3) they are more practical

[1] Jordan University of Science and Technology, Department of Civil Engineering; Irbid 22110, Jordan; e-mail: mobaidat@just.edu.jo; orcid.org/0000-0001-5314-0232
[2] Jordan University of Science and Technology, Department of Civil Engineering; Irbid 22110, Jordan; e-mail: bwmistarehi@just.edu.jo; orcid.org/0000-0001-8440-0690
[3] Jordan University of Science and Technology, Department of Civil Engineering; Irbid 22110, Jordan; e-mail: anabuyamin15@eng.just.edu.jo; orcid.org/0000-0001-63202-0790
* Corresponding author. e-mail: mobaidat@just.edu.jo

in the ticketing process because they cover all lanes of the roadway, and (4) they are safer than police enforcement [6]. The Automated Enforcement Program (AEP), which involves fixed speed cameras and red-light cameras, is considered an effective technique to improve traffic safety, and it evolved gradually in Amman city. The first stage was implemented in 2004, and five cameras were installed. In 2007, 19 cameras were added, and 21 more cameras were added in 2014. The AEP that was installed in 2014 enhanced road safety on urban arterial roads and signalized intersections [7].

In May 2017 and March 2018, the Greater Amman Municipality (GAM), in collaboration with the Central Traffic Department, expanded the Automated Speed Enforcement Cameras Program (ASECP) on urban roads within the boundaries of Amman city. According to the Jordan Traffic Institute [8], 98% of traffic crashes in Jordan are attributed to driver behavior, with speeding being a major factor. Studies show that traffic speed has a direct negative impact on both the frequency and severity of crashes; for example, a 1-km/h increase in mean speed leads to a 0.7% increase in crash frequency and a 0.74% increase in speed variation [9]. A recent study using continuous GPS speed data found that drivers reduce their speeds by about 208 m upstream of fixed speed cameras and recover their speeds about 221 m downstream. This indicates that speed cameras influence driver behavior but may also create abrupt deceleration and acceleration zones. Naghawi et al. [9] considered the safety effect of seven excessive speed cameras installed in 2014 on Amman's urban roads. Their before-and-after study showed a significant reduction in both the number and severity of crashes after the installation of these cameras [10,11].

Every fixed speed camera has an area of influence that is divided into an acceleration distance and a deceleration distance. When drivers become aware of speed cameras, they are forced to comply with traffic rules and temporarily reduce their speed to avoid a violation. After passing the cameras, they return to their original speed. This behavior reflects a lack of awareness of driving [12-14]. The effectiveness of a speed camera increases as the distance from the camera decreases [15, 16]. Past studies have shown that the ASECP is a successful technique for reducing drivers' mean speed, the standard deviation of speed, and the proportion of vehicles traveling over the speed limit at speed cameras. In an article by Pauw et al. [13] on the impact of speed cameras implemented in a Belgian city, the researchers compared driver speed and adherence to traffic rules before and after their implementation, and a linear regression model with a normal distribution and correlation function showed that the average speed was lowered by 6.4 km/h. In addition, a logistic regression model with binomial distribution and logit link function showed that the odds of drivers exceeding the speed limit decreased by 80% while the odds of drivers exceeding the speed limit by more than 10% decreased by 86%. Oliveira et al. [17] considered the effectiveness of fixed speed cameras installed on urban roadways of Belo Horizonte in Southeast Brazil. They found that 40.0% of vehicles exceeded the speed limit 200 m downstream of fixed speed cameras and that 33.6% exceeded the speed limit on roadways without speed cameras. In addition, they found that at speed cameras, the drivers had the lowest mean speed and that the greatest number of drivers adhered to the speed limit. The ASECP that was implemented based on specific factors, such as the number of fatal and serious crashes, was successful in improving traffic safety [18-20].

Speed cameras improve road safety owing to their effect on drivers' speeds. Pérez et al. [21] evaluated the impact of fixed speed cameras applied on Barcelona's urban beltway with an 80-km/h speed limit in a time-series study with a comparison group. They found that the number of road crashes and injuries was reduced by 27%, and the number of vehicles involved in crashes was reduced by 26%. Shin et al. [20] evaluated the impact of the ASECP applied on urban freeways in Scottsdale, Arizona, with a 65-mph speed limit. The safety effect of the program was evaluated by three methods: a before-and-after method with a comparison group, a before-and-after method with traffic flow correction, and an empirical Bayes method with time-variation safety. These methods showed that the number of traffic crashes decreased by 44-54%, the number of property-damage-only crashes decreased by 45-56%, and the number of crashes resulting in an injury decreased by 28-48%. Tay [22] found that the installation of fixed speed cameras and mobile speed cameras applied in urban areas of Christchurch, New Zealand, significantly reduced the number of serious crashes as well as the total number of crashes. Continuous speed data rather than spot speed data is collected continuously along the road segment using the probe vehicle data (PVD) method or so-called floating car data (FCD), which involves a vehicle equipped with a global positioning system (GPS) or mobile phone triangulation to register the time and the position of the vehicles with a high frequency sampling (1HZ) [23].

Recently, cellular phones have been used to accurately collect and analyze transportation data. Obaidat [24] used cellular phone cameras for the first time in transportation engineering. It was found that cellular phones with high-resolution cameras are promising for traffic parameter mapping and vehicle classification and that an increase in resolution increases the results' accuracy. Fitzpatrick et al. [25] compared continuous speed data collected using a smartphone application (Ubipix) installed on volunteers' vehicles, with spot speed data collected by a LiDAR gun and pneumatic tubes with automated traffic records (ATRs) at eight sites along the same rural segment, to improve the safety of the roadway by integrating them. All data were collected at the same time of day, at the same time of the year, and under the same weather conditions in free-flow conditions. The continuous speed data was consistent with spot speeds collected by LiDAR and ATRs.

Studies on the effectiveness of automated speed enforcement cameras in the UK, Italy, and France (mainly by UK College of Policing) [26] found that speed cameras led to a 7% reduction in average speed, a 52% reduction in the number of vehicles exceeding the speed limit, a 19% reduction in collisions, an 18% reduction in injury collisions, and a 21% reduction in severe or fatal collisions. Another study by the London School of Economics [27] showed that speed cameras reduced accidents by 17-39% and fatalities by 58–68% within 500 m of cameras. Tang [27] analyzed 2,500 sites across England, Scotland, and Wales, reporting substantial reductions in collisions and serious injuries after camera installation. In Italy, Montella et al. [28] conducted a meta-analysis showing that fixed speed cameras reduced the total number of crashes by about 20%, with a stronger effect on fatal crashes (a reduction of 51%). La Torre et al. [29] evaluated an automated section speed control (ASSC) system on Italian motorways, reporting a significant overall reduction in crashes after its implementation. Moreover, in France, Blais and Carnis [30-32] analyzed the French speed camera program, which resulted in a 42% reduction in the mortality rate per 100,000 vehicles from 2003 to 2010, preventing about 15,000 fatal and 62,000 other accidents. Ultra GPS Logger is considered an accurate method for capturing speed data. Fitzpatrick et al. [25] found that continuous speed data collected using a smartphone application were consistent with spot speed data collected by a LiDAR and pneumatic tubes with automated traffic records. Furthermore, the GPS speeds of the Ultra GPS Logger application match the speeds of vehicle speedometers. The spatial accuracy of the Ultra GPS Logger is 5 m.

In this study, a new tracking technique using a mobile phone application was applied to collect continuous speed data and construct operating speed profiles of the speed camera`s segments for the first time in urban areas. In addition, four new statistical models were developed to correlate operating speeds with the most influential factors. No previous research has constructed statistical models to estimate the minimum speed at speed cameras, deceleration distance, acceleration distance, or the maximum speed downstream of speed cameras.

2. AIM OF THE STUDY

The main objectives of this study are:

1. To collect continuous speed data along speed cameras' segments using a new tracking technique that utilizes a mobile phone application.
2. To construct the operating speed profiles of the speed camera segments in the urban areas to understand how the drivers react to speed cameras.
3. To develop four new statistical models to correlate the minimum speed at the speed camera, deceleration distance, acceleration distance, and the maximum speed downstream of the speed camera with the most influential factors in the urban areas.
4. To evaluate the safety impacts of the ASECP.

3. METHODOLOGY

3.1. Data collection

3.1.1. Fixed speed cameras' properties and locations

Two types of fixed speed cameras are installed in the mid-blocks of urban roads. The first type is installed on the right side of the road, where the speed camera and radar are set on two columns with a distance of 4–5 m between them; this type of camera captures receding vehicles. The second type is installed on the median and serves two road directions, where the speed camera and radar are set on one column; this type of camera captures receding and approaching vehicles. The resolution of speed cameras is 16 Megapixels. The radar uses 3D tracking to detect vehicles that exceed the speed limit by more than 10 km/h. It can cover four lanes for 50 m in front of the speed camera and can record the speeds of multiple objects at the same time. In addition, it measures the distance between the offending vehicle and the radar to identify the offending vehicle. The speed camera registers the time, speed, date, type, and location of the offending vehicle, and it saves a photo of the vehicle on the road with a yellow gate on it. Automatic number plate recognition (ANPR) is used to supply automated access to number plate contents and extract their numbers and letters within a fraction of a second, which are then converted into a computer-readable format [33].

3.1.2. Selected Speed Cameras' Locations and Characteristics

Based on the success of speed traffic enforcement, the number of police stations doubled in 2008, and the Automated Speed Enforcement Program was implemented in 2014 in Amman city. GAM, in collaboration with the Central Traffic Department, installed new speed cameras on arterials, collectors, and local urban roads with speed limits between 50 and 100 km/h within the boundaries of Amman city for traffic law enforcement. The speed cameras' positions were taken from Traffic Tech Middle East Company. Eighteen of 30 speed cameras were chosen to study drivers' behavior around the speed cameras. Twelve speed cameras installed on congested urban roads were excluded because it is hard to obtain off-peak periods to collect free-flow speeds.

Eighteen cameras were installed on urban collector roads within commercial, residential, and industrial areas with speed limits of 50-70 km/h. Fifteen speed cameras were installed on the right side of the road, and three were installed on the median. The speeds of vehicles at the speed camera are influenced by the environmental, geometrical, and traffic characteristics of the speed camera segment. Thus, these characteristics were collected for all 18 speed camera segments so we could construct operating speed models and consider the traffic safety results of the analyzed speed cameras.

- Environmental Data

The following environmental data were used in this research: land use (residential, commercial, or industrial areas), the distance between the warning sign and the speed camera, pavement conditions (excellent, good, or poor), and speed camera age.

- Geometrical Data

The following geometrical data were used in this research work: posted speed limit, lane marking existence, pedestrian sidewalk existence, the existence of vehicles parked on the shoulder, the existence of traffic calming measures before the speed camera, the existence of traffic calming measures after the speed camera, the type of intersection nearest to the speed camera upstream, the distance between the speed camera and the nearest upstream intersection, the distance between the speed camera and the nearest access upstream of the speed camera, the distance between the speed camera and the nearest U-turn upstream of the speed camera, the distance between the speed camera and the nearest curve upstream of the speed camera, the access-point density of the road segment upstream of the speed camera (access points/km), the type of intersection nearest to the speed camera downstream, the distance between the speed camera and the nearest intersection downstream of the speed camera, the distance between the speed camera and the nearest access downstream of the speed camera, the distance between the speed camera and the nearest U-turn downstream of the speed camera, the distance between the speed camera and the nearest curve downstream of the speed camera, access-point density of the road segment downstream of the speed camera (access points/km), longitudinal slope (measured using Google Earth), number of lanes, lane width, shoulder type, shoulder width, median type, median width, the existence of a pedestrian bridge or tunnel along the speed camera segment, the existence of pedestrian crosswalks along speed camera segment, segment type, the existence of a bus stop upstream of the speed camera, speed camera position, the change in the radius of the curve upstream of the speed camera, the change in the radius of the curve downstream of the speed camera, the difference in slope upstream of the speed camera, and the difference in slope downstream of the speed camera.

3.1.3. Speed data collection

In order to conduct free-flow speeds, we collected continuous speed in specific conditions such as dry pavement, no police on the road segment, off-peak hours, and workdays. A GPS tracking technique was used to collect continuous speed data. A vehicle equipped with a mobile phone application (Ultra GPS Logger) followed a random vehicle that came from the upstream intersection of the road segment containing the fixed speed camera. A constant distance between the vehicles was maintained until they reached the downstream intersection, as shown in Fig. 1. At each fixed speed camera, the vehicle equipped with the mobile application followed 30 random vehicles to capture 30 speed profiles. Every second, the Ultra GPS Logger captured the speed, coordinates, and time for the vehicle traveling along the fixed speed camera segment. The data was prepared and reduced using Excel and ArcMap GIS to obtain the operating speed profiles along the speed camera segment.

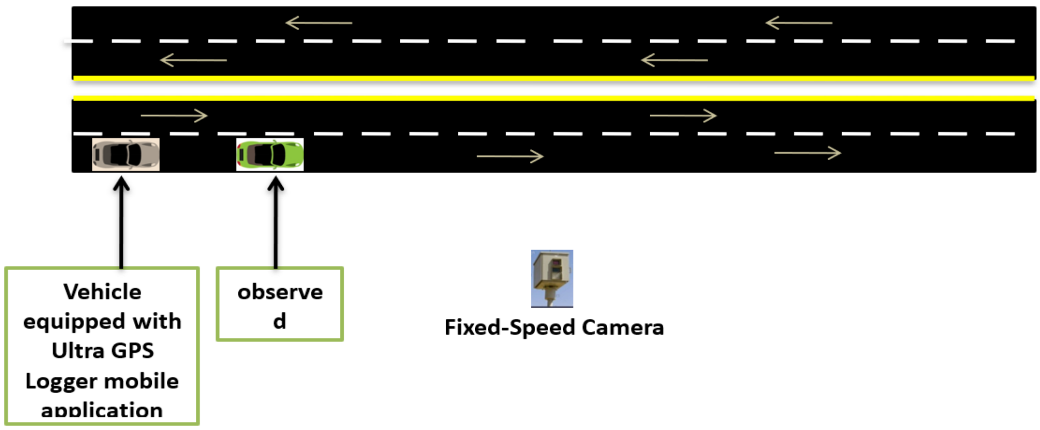

Fig. 1. GPS tracking for a vehicle

The data exported to the Excel file comprised approximately 7000 points, along with their latitudes, longitudes, speeds, and times. Table 1 shows an example of the data exported from the Ultra GPS Logger mobile application. These speed data points were added to ArcMap GIS, as shown in Fig. 2, to remove invalid data.

Table 1

An example of Ultra GPS Logger mobile application data

ID	Lat	Long	TimeWithTZ	Speed(m/s)	Speed(km/h)
0	31.8963	35.90492	16:55:30 EEST	8.4	30.24
1	31.89632	35.90483	16:55:31 EEST	7.83	28.188
2	31.89633	35.90475	16:55:32 EEST	7.07	25.452
3	31.89634	35.90467	16:55:33 EEST	6.08	21.888
4	31.89636	35.9046	16:55:34 EEST	5.45	19.62
5	31.89637	35.90454	16:55:35 EEST	4.78	17.208
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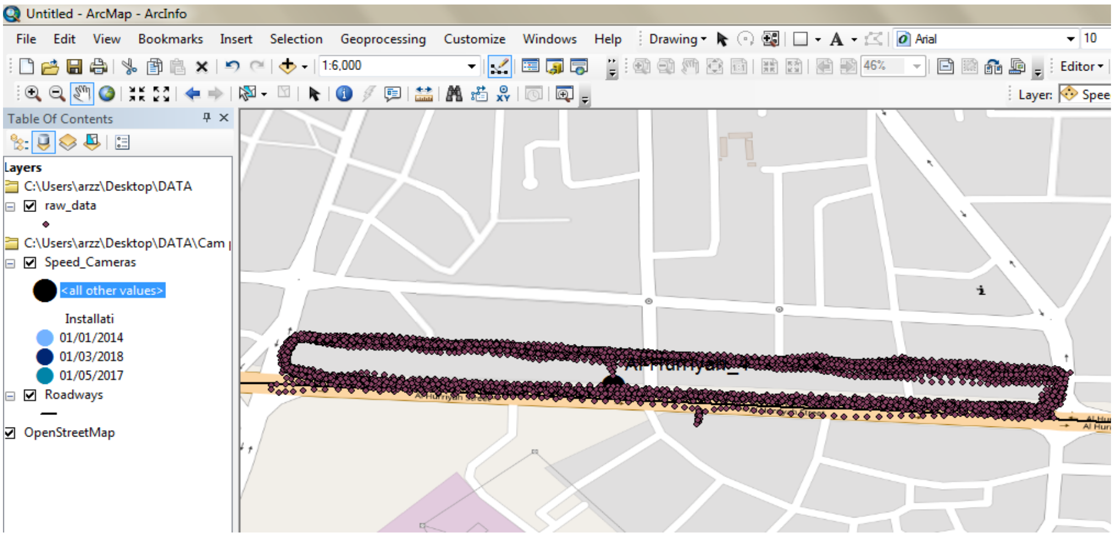

Fig. 2. Speed data points on ArcMap GIS (example)

3.1.4. Traffic crash data

Traffic crash data was obtained for 10 speed cameras from the Central Traffic Department (Table 2). The data includes the number and severity of traffic crashes in the 10 months before and the 10 months after speed camera installation. The traffic crashes included in this study were determined spatially using ArcMap GIS within a circle with a 100-m radius around the speed camera. This range was chosen to avoid overlapping by excluding crashes that were not influenced by the speed camera, such as crashes at the nearest intersection or on other roads.

Table 2

Traffic crash data

Camera No.	Crash frequency		No. of fatalities/ injuries		Property damage crashes	
	Before camera installation	After camera installation	Before camera installation	After camera installation	Before camera installation	After camera installation
1	2	0	0	0	2	0
2	3	3	0	0	3	3
3	2	2	0	0	2	2
4	1	3	0	0	1	3
5	3	1	0	0	3	1
6	0	1	0	0	0	1
7	0	2	0	0	0	2
8	2	0	0	0	2	0
9	0	4	0	2	0	3
10	3	1	4	0	2	0
Sum	16	17	4	2	15	15

3.2. Data analysis

This section contains the analysis of the operating speed profile along the fixed speed camera segments and the regression models developed to predict the minimum speed, deceleration distance, acceleration distance, and maximum speed downstream of the speed camera along segments containing fixed speed cameras. It also describes the safety evaluation of the installation of speed cameras.

3.2.1. Speed profile analysis

For every fixed speed camera, 30 individual speed profiles were conducted along the camera segment using a GPS tracking technique by following 30 random vehicles. The operating speed profile represented by the 85th percentile speed profile was used to study drivers' behavior around the speed camera. Nineteen speed profiles for 18 speed cameras were constructed (one of the speed cameras installed in the median had two speed profiles for both directions). The differences in the geometrical and environmental properties of the speed camera segments caused differences in the behavior of drivers along the speed camera segments. Fig. 3 shows that the operating speed profiles are V-profiles, as drivers decelerated quite abruptly before speed cameras and then accelerated quite abruptly after the speed camera. The zone of influence ranges from 260–660 m, the minimum speed at the speed camera ranges from 43–57 km/h, the maximum speed before the speed camera ranges from 63-93 km/h, and the maximum speed downstream of the speed camera ranges from 68–109 km/h. Table 3 shows the data exported from the 85th percentile speed profiles.

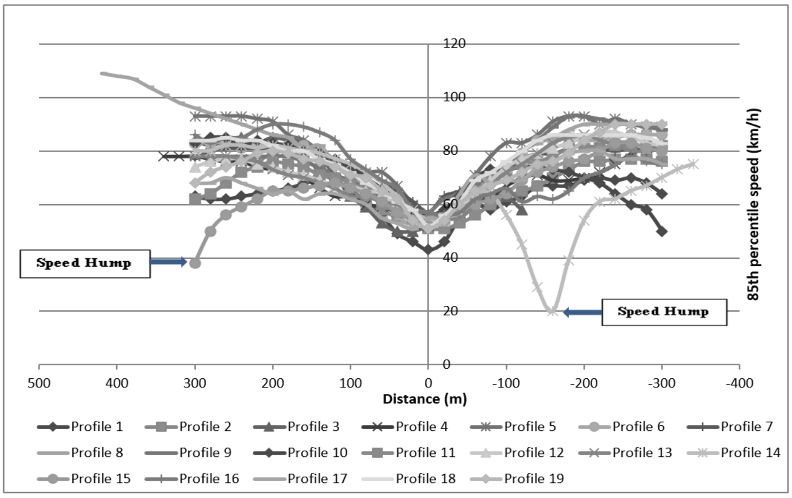

Fig. 3. Operating speed profiles (2D speed profiles of 85th percentile speed)

Table 3

Minimum speed, maximum speed, and zone of influence

Segment No.	Maximum speed upstream of the speed camera (km/h)	Deceleration distance (m)	Minimum speed at the speed camera (km/h)	Maximum speed downstream of the speed camera (km/h)	Acceleration distance (m)
Mean	81.90	208.42	53.53	81.47	221.05
Maximum	93	340	57	109	420
Minimum	63	80	43	68	120

3.2.2. Regression Analysis Models

Regression analysis was used to estimate the 85th minimum speed at the speed camera, 85th deceleration distance, 85th acceleration distance, and 85th maximum speed after the speed camera as a function of geometrical and environmental properties of the road segments that contain the speed cameras. SPSS software was used to estimate the relationship between the dependent variables (DVs) and the independent variables (IVs) by constructing regression models. The correlations between the DVs and the IVs were investigated by the Pearson's correlation coefficient to determine which IVs are highly correlated with the DV and whether they should be used in the model. Then, a stepwise method was used to choose the highest Pearson's correlation between the IVs and the DVs and put them into the regression analysis until it found the IVs with weak Pearson's correlations, at which point it stopped. Table 4 contains the DVs and IVs included in the following regression models, along with their codes.

Different transformations were applied to the DVs, the IVs, or both; these included square transformation, square root transformation, cubic transformation, inverse transformation, and logarithmic transformation. DV transformation was applied to change the distribution of the residual term in the model. While IV transformation may increase the correlation between the DVs and the IVs, it does not change the distribution of residual terms.

The correlation matrix shows only simple correlations between two variables, and it is not sufficient to examine the multicollinearity between the IVs; thus, variance inflation factor (VIF), tolerance, and condition index values were used to check multicollinearity.

Table 4

DV and IV coding

Variable No.	Variable type	Variable description	Variable Code
1	DV	85^{th} minimum speed at the speed camera (km/h)	$V_{c,85}{}^{th}$
2		85^{th} maximum speed after the speed camera (km/h)	$V_{a,85}{}^{th}$
3		85^{th} deceleration distance (km)	$D_{d,85}{}^{th}$
4		85^{th} acceleration distance (km)	$A_{d,85}{}^{th}$
5	IV	Speed limit (km/h)	SL
6		Existence of traffic calming measures (speed humps) upstream of speed cameras	TC_b
7		Existence of traffic calming measures (speed humps) downstream of speed cameras	TC_a
8		Distance between the speed camera and the nearest intersection upstream of the speed camera (km)	D_{ciu}
9		Longitudinal slope at the speed camera	S_{at}
10		Longitudinal slope downstream of the speed camera	S_a
11		Change in the radius of the curvature upstream of the speed camera	I_u=increased D_u=decreased N_u=not changed
12		Difference in slope downstream of the speed camera	ΔS_d

When the IVs included in the model have a VIF value less than 10, the condition index value is less than 30, and the tolerance is higher than 0.1. Thus, we can say there is no multicollinearity (interassociation) among the independent variables. The Durbin-Watson test examines the autocorrelation in the errors; the value is between 0 and 4. The autocorrelation is positive if the values approach 0, is negative if the values approach 4, in absent if the value is 2. Autocorrelation values of 1.5–2.5 are acceptable. The residuals in the regression standardized residual chart must be normally distributed, and the residual values must be plotted in a straight line in the normal probability plot chart to conclude that the errors are normally distributed. In the regression standardized residual scatterplot, the range of the width of the predicted values must be the same to confirm that the variance of the errors is equal. With respect to the ANOVA table, the F-value was compared to the critical F-value to ensure that the null hypothesis (that there is no relationship between the DVs and IVs) is rejected and confirm that there is a relationship between the DVs and IVs. In addition, at a 95% confidence level, there was a statistically significant for the regression models and their regression parameters.

The four models chosen to estimate the minimum speed at the speed camera, deceleration distance, acceleration distance, and maximum speed after the speed camera are shown in Table 5. Their associated statistical characteristics are shown in Table 6.

Table 5

Regression models

Model no.	Regression model	R^2	Adj.R^2
1	$(V_{c,85}{}^{th})^2 = 2302.467 + 0.198SL^2 + 34.54S_{at} - 266.58I_u$	0.607	0.528
2	$D_{d,85}{}^{th} = 0.251 - 0.029D_{ciu}{}^{-1} + 0.129TC_b$	0.681	0.642
3	$(A_{d,85}{}^{th})^{-1} = 4.512 + 2.83\Delta S_d + 2.404TC_a$	0.706	0.667
4	$(V_{a,85}{}^{th})^2 = 5437.25 + 68880.407(A_{d,85}{}^{th})^3 - 155.98S_a$	0.718	0.683

Table 6

Statistical characteristics of the regression models

Model no.	DV	R^2	Adj.R^2	ANOVA		IVs	Unstandardized Coefficients		t-test	
				F-value	Sig.		B	Std. error	t-statistics	Sig.
1	$(V_{c,85^{th}})^2$	0.607	0.528	7.714	0.002	Constant	2302.467	356.702	6.455	0.000
						SL^2	0.198	0.089	2.241	0.041
						S_{at}	34.54	13.308	2.596	0.02
						I_u	-266.58	115.967	-2.299	0.036
2	$D_{d,85^{th}}$	0.681	0.642	17.112	0.000	Constant	0.251	0.014	17.930	0.000
						TC_b	0.129	0.036	3.585	0.000
						D_{ciu}^{-1}	-0.029	0.007	-4.381	0.002
3	$(A_{d,85^{th}})^{-1}$	0.706	0.667	19.221	0.000	Constant	4.512	0.185	24.417	0.000
						ΔS_d	2.83	0.069	4.100	0.001
						TC_a	2.404	0.846	2.843	0.012
4	$(V_{a,85^{th}})^2$	0.718	0.683	20.391	0.000	Constant	5437.25	289.203	18.801	0.000
						$(A_{d,85^{th}})^3$	68880.407	13582.41	5.071	0.000
						S_a	-155.98	50.482	-3.090	0.007

3.2.3. Analysis of the safety impacts of speed cameras

A before-and-after study using a paired t-test statistical comparison method was applied with a 95% confidence level to consider the effect of the ASECP on the number and severity of traffic crashes. A paired samples t-test showed that, at a 5% level of significance, the average number of crashes after the installation of speed cameras is between 1.625 crashes more and 1.425 crashes less than the average number of crashes before the installation of speed cameras. In addition, the hypothesis testing showed that there is no difference in the number of crashes before and after the speed cameras' installation, or an increase with no statistical significance. Also, a paired samples t-test showed that, at 5% level of significance, the mean traffic crash severity after the installation of speed cameras is between 0.856 more and 1.256 (fatalities and injuries) less than the mean traffic crash severity before the installation of speed cameras. In addition, the hypothesis testing showed no difference in the severity of crashes before and after the speed camera installation, or a decrease with no statistical significance. Based on the minimum speed at the speed camera model, there is some difference between the adjusted coefficient of determination and the coefficient of determination because there are too many coefficients with a small sample size. For this model, the coefficient of determination is 0.607, and the adjusted coefficient of determination is 0.528, indicating a moderate regression model. The coefficient of determination represents the variability in the dependent variable demonstrated by the model, while the adjusted coefficient of determination relates to the standard error of the regression model rather than the standard deviation of the errors. In addition, it is better to use the adjusted coefficient of determination rather than the coefficient of determination because it is not increased by too many independent variables that add nothing to the model. The coefficient of determination and the adjusted one are calculated based on the following equations [34]:

$$R^2 = 1 - \left(\frac{SSE}{SST}\right), \tag{1}$$

$$AdjR^2 = 1 - \left({SSE}/_{n-k-1}\right) / \left({SST}/_{(n-1)}\right), \tag{2}$$

where:
$AdjR^2$: the adjusted coefficient of determination, R^2: the coefficient of determination, SSE: sum of squares of errors about the regression line, SST: total sum of squares, n: sample size, and k: the number of the independent variables in the regression equation.

Their associated relationship could be found using this equation:

$$AdjR^2 = {1 - (1 - R^2) * ((n-1)/)}/_{(n - (k+1)))} \tag{3}$$

The adjusted coefficient of determination is less than the coefficient of determination, and they are close to each other unless there are too many coefficients with a small sample size, as happened with the minimum speed at the speed camera model. Fig. 4 shows that the first month after the installation of speed cameras has the most traffic crashes (five), while the other months' crashes range between zero and three.

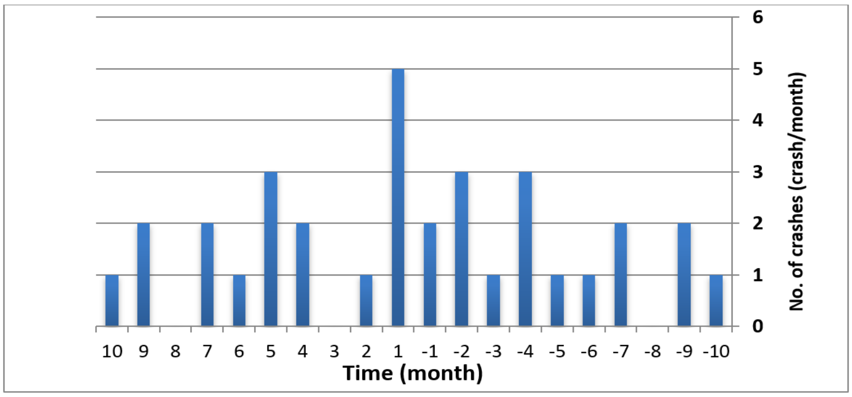

Fig. 4. Traffic crash distribution across months

4. RESULTS AND DISCUSSION

4.1. Operating Speed Profile Analysis

Nineteen speed profiles for 18 speed cameras were used as a sample to study drivers' behavior. The speed cameras were installed on urban collector roads within commercial, residential, and industrial areas with speed limits of 50-70 km/h. Fifteen speed cameras were installed on the right side of the road, and three were installed on the median. Four of them were installed in 2014, three were installed in May 2017, and 11 were installed in March 2018. For each speed camera, 30 random and representative cycles were registered by following 30 passenger cars that moved along the speed camera segment to construct a speed profile. For each cycle data point, the linear interpolation was applied to calculate the spot speed every 20 m; then, the 85th percentile speed profile was found.

4.1.1. 85th Percentile Speed Profiles

The operating speed profiles are V-profiles, as the drivers decelerate quite abruptly before the speed camera, then accelerate quite abruptly after the speed camera, as shown by [12]. With respect to the operating speed profiles, the drivers reduced their speeds about 208 m before the speed camera and then recovered their speeds about 221 m after the speed camera.

4.1.2. Zone of Influence and Kangaroo Effect

Liu et al. [12] found that the area of influence was about 1 km around speed cameras on rural roads with speed limits between 60 and 80 km/h in China. The drivers reduced their speeds 300 to 400 m upstream of the speed cameras, then recovered their speeds 300 to 400 m downstream of the cameras. Speed profiles show that drivers slow down before the speed camera until they reach their minimum speed at the speed camera; then, they regain their speed when they pass the speed camera. This is called the kangaroo effect of the speed camera. The speed camera influences drivers' speed along the zone of influence (ZI). The ZI is divided into deceleration distance (DD) and acceleration distance (AD). DD is the distance from the maximum speed upstream of the speed camera to the minimum speed at the speed camera, while the AD is the distance from the minimum speed at the speed camera to the maximum speed downstream of the speed camera (Fig. 5).

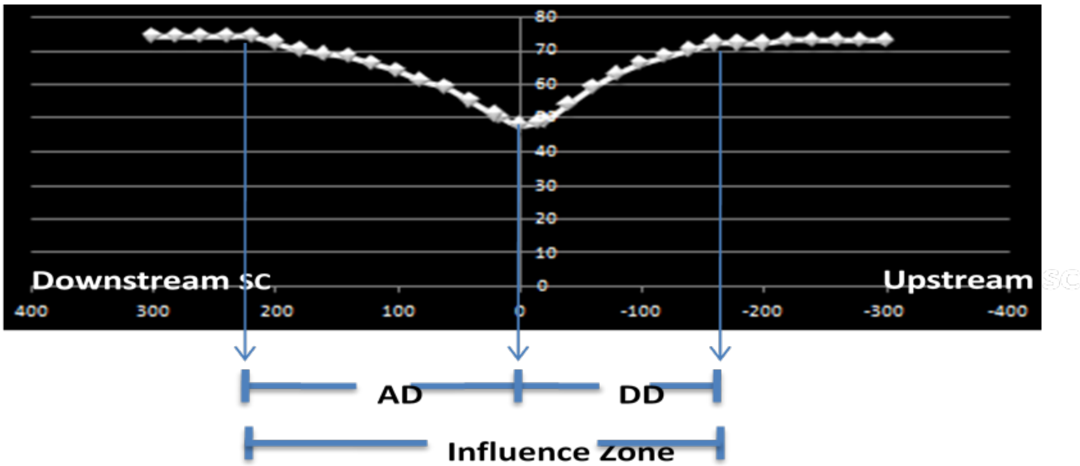

Fig. 5. Zone of influence

4.1.3. Data Exported from the 85th Speed Profiles

The speed profiles showed that the zone of influence ranges between 260 m and 660 m, the minimum speed at the speed camera ranges between 43 km/h and 57 km/h, the maximum speed before the speed camera ranges between 63 km/h and 93 km/h, and the maximum speed downstream of the speed camera ranges between 68 km/h and 109 km/h. Drivers' behavioral differences are due to geometrical and environmental properties.

4.1.4. Minimum Speed at the Speed Camera

Drivers slowed down before the speed camera until they arrived at the minimum speed at the camera before regaining their speed once they had passed the speed camera. When the speed limit was compared with the minimum operating speed (85th spot speed) at the speed camera along 19 speed profiles, the 85th spot speed at the speed camera is less than the speed limit by 6.03-10.08 km/h at a 95% confidence level. This reduction depends on the geometrical and environmental properties of the road segment and is explained by the regression models later.

4.2. Regression Analysis Models

Regression analysis was used to estimate the 85th minimum speed, deceleration distance, acceleration distance, and maximum speed downstream of the speed camera as a function of geometrical and environmental properties of the road segments. Four new models were developed to explain how the geometrical and environmental properties of the road segment influence the four estimated values.
The first model was constructed to estimate the 85th minimum speed:

$$(V_{c,85th})^2 = 2302.467 + 0.198SL^2 + 34.54S_{at} - 266.58I_u \ (R^2 = 0.607). \qquad \text{Model 1}$$

The square of the 85th minimum speed at the speed camera is positively related to the square of the speed limit (SL^2) and the street longitudinal slope at the speed camera (S_{at}); it is negatively related to the increase in the radius of the curvature upstream of the speed camera (L_u). An increase in the street slope decreases drivers' speeds, but at the speed camera, when the street is steeper, the drivers were more careful, and they reduced their speeds to avoid a speed violation fine [23].

The second model was constructed to estimate the 85th deceleration distance:

$$D_{d,85^{th}} = 0.251 - 0.029D_{ciu^{-1}} + 0.129TC_b \ \ (R^2 = 0.681). \qquad \text{Model 2}$$

The 85th deceleration distance is positively related to the existence of a traffic calming measure upstream of the speed camera and negatively related to the inverse of the distance between the speed camera and the nearest intersection upstream of the speed camera. If there is a traffic calming measure upstream of the speed camera, the deceleration distance increases, and it creates a longer area of influence before the speed camera because the drivers reduce their speed before the traffic calming measure and do not have a chance to increase their speed just before the camera.

The third model was constructed to estimate the 85th acceleration distance:

$$(A_{d,85^{th}})^{-1} = 4.512 + 2.83\Delta S_d + 2.404TC_a \ (R^2 = 0.706). \qquad \text{Model 3}$$

The inverse of the 85th acceleration distance is positively related to the existence of a traffic calming measure downstream of the speed camera and the increase in the difference in slope downstream of the speed camera. If there is a traffic calming measure downstream of the speed camera, the acceleration distance decreases. Drivers reached their minimum speed at the speed camera, then started accelerating after the speed camera. However, because of the traffic calming measure after the speed camera, the drivers stopped accelerating a short distance after the camera, which reduced the maximum speed after the camera.

The fourth model was constructed to estimate the 85th maximum speed:

$$(V_{a,85^{th}})^2 = 5437.25 + 6888.407(A_{d,85^{th}})^3 - 155.98S_a \ (R^2 = 0.718). \qquad \text{Model 4}$$

The square of the 85th maximum speed downstream of the speed camera is positively related to the cubic of the 85th acceleration distance and negatively related to the longitudinal slope downstream of the speed camera. If the acceleration distance decreases because of the existence of traffic calming measures downstream of the speed camera or the increased street slope downstream of the speed camera, the maximum speed downstream of the speed camera also decreases.

4.3. Safety Effect of the Speed Camera

Pérez et al. [21] found that the number of road crashes and injuries was reduced by 27%, while the number of vehicles involved in crashes was reduced by 26%. Shin et al. [20] found that the number of traffic crashes decreased by 44-54%. Li et al. [15] found that the number of crashes of all types reduced at the speed cameras; fatal, serious, and personal injury crashes were reduced the most when the distance from the speed camera was less than 200 m. Naghawi et al. [7] studied the safety effect of seven speed cameras in 2014 on urban roads in Amman. Crash data were collected for three years before and three years after the cameras' installation. A before-and-after study based on a paired t-test with a 95% confidence level showed that the number of crashes and their severity were reduced significantly after the installation of speed cameras. The safety effect of 10 fixed speed cameras installed in 2017 and 2018 on urban roads in Amman was evaluated using the same analysis method used by [7]. The results showed that the average number of crashes after the installation of speed cameras is between 1.625 crashes more than and 1.425 crashes less than the average number of crashes before the installation of speed cameras, and there is no difference in the number of crashes before and after the speed cameras' installation. A paired samples t-test showed that, at the 5% level of significance, the mean crash severity after the installation of speed cameras was between 0.856 more than and 1.256 less than the mean traffic crash severity before their installation, and there was no difference in the severity of crashes before and after the cameras' installation. The failure of new fixed speed cameras in traffic safety improvement could be because cameras are installed at inappropriate positions [15], there is low awareness about the speed cameras [7], there is only a one-directional effectiveness of speed cameras, or rear-end crashes increase due to traffic congestion.

5. CONCLUSIONS

Based on the outcomes of this article, the following conclusions can be drawn:

1. The 85th speed profiles are V-profiles showing that drivers reduce their speed about 208 m upstream of the speed camera, then regain their speed 221 m downstream of the speed camera.
2. The minimum speed at the speed camera reduces as the speed limit decreases, the longitudinal street slope (the street is steeper) decreases, and the radius of curvature upstream of the speed camera increases. In other words, when we transition from a curve (before the speed camera) to a tangent (at the speed camera), the minimum speed at the speed camera is reduced.

3. The deceleration distance increases as the distance between the speed camera and the nearest intersection upstream of the speed camera increases. The acceleration distance increases if the street is steeper downstream of the speed camera than at the speed camera. The maximum speed downstream of the speed camera increases as the longitudinal street slope decreases (i.e., if the street is steeper).
4. Traffic calming measures increase the efficiency of the ASECP. The presence of a speed hump upstream of the speed camera increases the deceleration distance, and the presence of a speed hump downstream of the speed camera decreases the maximum speed downstream of the speed camera.
5. The most traffic crashes occurred in the first month after the installation of speed cameras, and the traffic safety efficiency of fixed speed cameras improves with time.
6. GPS tracking systems using a mobile phone application for speed measures should be adopted as a reliable system for traffic data collection.

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