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## Analysis of the Trajectories of Left-turning Vehicles at Signalized Intersections

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### Abstract

Internationally, an annual number of more than a million fatalities are caused by road traffic crashes, with particularly signalized intersections being crash prone locations within the highway system. An accumulation of conflicts between drivers is caused by the different movements (through and turning) from different directions at the intersection; hence, studying the trajectories of turning vehicles is an important step towards improving traffic safety performance of these facilities. In view of that, the current paper aims at providing further insight into the behaviour of left-turning vehicles (right-hand traffic rule) at signalized intersections in the State of Qatar. At first, a total of 44 trajectories of free-flowing vehicles were manually extracted from a recorded video for a single approach of Lekhwair signalized intersection in Doha City, State of Qatar. After that, the extracted trajectories were statistically analysed in an attempt to explore the factors affecting the path of left-turning vehicles at signalized intersections. The results suggest that the characteristics of the extracted paths are significantly related to the vehicle's entry speed, minimum speed throughout its turning manoeuvre, and the lateral distance between the exit point and the curb (i.e., targeted exit lane). Provided that the speed parameters can be fairly an indication to the driving behaviour, it can be concluded that the driver's attitude plays an important role in drawing the manoeuvre of a turning vehicle as does the pre-selection of the exit lane. Finally, the effort presented in this paper can be regarded as a way forward towards understanding the behaviour of turning vehicles at signalised intersection in the State of Qatar.

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**Keywords:** Signalized intersections; Vehicle trajectories; Left turning vehicles, Traffic safety; Conflict analysis.

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## 1. Introduction

With a global estimate of 1.4 million fatalities and 73.25 million disabilities due to Road Traffic Crashes (RTCs) on an annual basis, traffic safety is a major issue worldwide (Gao et al., 2016). Up to 1.5% of the gross national product for middle income countries, which equals to approximately 518 billion dollars, is lost to finance the costs of deaths, injuries and disabilities caused by RTCs on an annual basis (Gao et al., 2016). Within the highway system intersections are found to be crash prone locations; for example, 50% of the total RTCs within the urban areas and 30% within the rural areas are crashes occurring at intersections (Zhang et al., 2016). The complexity of intersections is generated by a variety of traffic streams moving in different directions, leading to multiple points of conflict and thereby increasing the risk for traffic crashes (Zhang et al., 2016; Alhajyaseen, 2015). Turning traffic in specific plays a significant role in traffic safety reduction at intersections (Tan et al., 2012). Depending on the geometry of the intersection, the drivers' instinctive judgment and their targeted exit lane, turning traffic often have major variations in path and speed (Ma & Yang, 2008; Alhajyaseen et al., 2012). For instance, Lui et al. (2013) found that left-turning traffic (right-hand traffic rule) often change their driving routes randomly after they pass the stop line at intersections, that can lead to serious conflicts between drivers which has a negative impact on traffic safety. For that reason, it is required to examine the trajectories of left-turning vehicles in order to identify suitable countermeasures that improve the safety performance at signalized intersections. Several studies have been conducted in the past few decades to grasp, as possible, the turning behavior of vehicles at signalized intersections. In general, significant characteristics concerning the intersection layout and the turning vehicle were highlighted (Reed, 2008; Sando et al., 2009; Stover and Koepke, 2002; Stover, 2008). As an example, Alhajyaseen et al. (2013) underlined that the trajectory of the turning vehicle is strongly related to the intersection's geometric layout (e.g., intersection angle), the vehicle's type, and speed. However, it is well-agreed that the turning maneuver of vehicles is a further complex phenomenon whose variability extends to be related to highly-dynamic factors (Gu et al., 2017; Kaysi and Abbany, 2007). For instance, the turning behavior was observed to depend on the inter- and intra-subject factors concerning drivers such as perception of traffic environment, information processing, and the ability to react correctly and to cooperate with others (Moussa et al., 2012; Sun, 2005). Moreover, the driver behavior in built up areas is largely a function of the geometry and layout of the roads, their usage, their location - in other words, urban morphology (Alexander et al., 2002). Other factors such as the waiting time of the turning vehicles (Alexander et al., 2002), relative speed of the vehicles in conflict (Liu et al., 2014), and gaps (Pollatschek et al., 2002) were observed to impact on the decision behavior of turning vehicles.

In this paper, the trajectories of 44 left-turning free-flowing vehicles were extracted from a recorded video of a signalized intersection in the State of Qatar. Spline fitting was used to extract the parameters governing the shape of the turning trajectories. After that, the extracted parameters were statistically analyzed to understand and model the factors affecting the trajectories of left-turning vehicles.

This document is organized as follows: Section 2 discusses the data collection and trajectory extraction process. Section 3 explains the parameters extracted from the resulting trajectories. The statistical modeling of the extracted parameters is described in Section 4. Finally, Section 5 concludes the paper.

## 2. Data collection

The south approach of Lekhwair signalized intersection in Doha City, State of Qatar was video-monitored for a duration of two and hours. The video was recorded at a frame rate of 30 fps and a resolution of 3840×2160 pixel. A total of 44 trajectories of left-turning vehicles were extracted from the recorded video. These trajectories are



Fig. 1. The extracted trajectories in image coordinates.

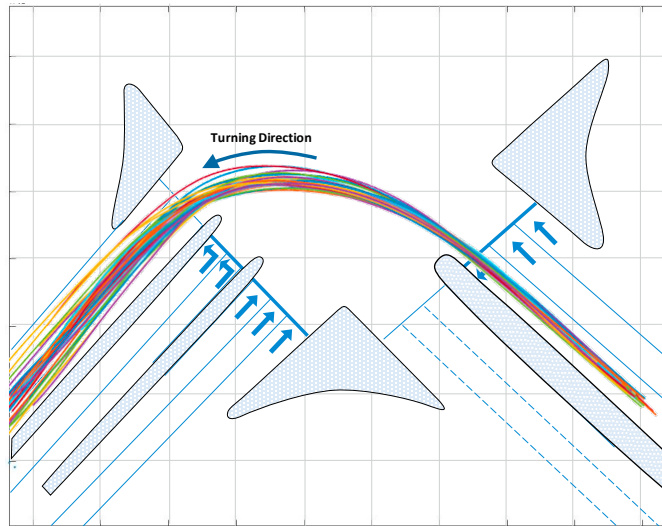


Fig. 2. The extracted trajectories in real-world coordinates.

shown in image coordinates in Fig. 1 and in real coordinates in Fig. 2. It is worth mentioning that, here, all extracted trajectories correspond to free-flowing vehicles unimpeded by traffic or pedestrians. In the following sections, these trajectories are analyzed to obtain the key parameters governing the trajectory characteristics. A stochastic model is then created to develop relationships among the extracted parameters.

### 3. Extraction of trajectory parameters

According to (Alhajyaseen et al., 2013), the trajectory of a left-turning vehicle at a signalized intersection can be represented by a spline consisting of five segments. The spline starts with a straight line followed by an Euler spiral having a curvature profile that varies almost linearly with a gradient of  $1/A_1^2$ . This spiral is followed by a circular segment with a curvature of  $1/R_{\min}$ . The end of the spline consists of another Euler spiral having a nearly linear curvature profile with a gradient of  $-1/A_2^2$  followed by a straight line. As shown in Fig. 3, there are four main locations that define the beginning and end of each Euler spiral and circular segments. These locations are basically the points of discontinuity along the curvature profile of the vehicle's path. Another important parameter can be identified, which is the lateral distance  $D_e$  between the exit point of the second Euler spiral and the left-hand side curb (Fig. 3). This distance reflects the exit lane of a left-turning vehicle.

A Matlab code was written to fit the aforementioned spline to each of the extracted paths in order to identify their governing parameters ( $R_{\min}$ ,  $A_1$ ,  $A_2$ ,  $D_e$ ). The code applies the nonlinear programming solver "fmincon" available in Matlab Optimization Toolbox to compute the optimal location of the four key points described in Fig. 3 so that the error between the tracked path and the fitted spline is minimized. Four constraints were imposed to enforce continuity of the fitted spline at the four points. Also, another four constraints were applied to ensure that no sudden jump exists at the key points of the curvature profile. The fitting of the two Euler spirals was conducted according to the approach proposed in Bertolazzi and Frego (2011).

Fig. 4 displays examples of four splines fitted to their actual extracted paths. Moreover, the figure shows the curvature profile of the fitted splines along with the speed profiles of the corresponding trajectories (obtained by applying finite central difference on the extracted trajectories). In addition to  $R_{\min}$ ,  $A_1$ ,  $A_2$ , and  $D_e$ , another two important parameters were extracted from the speed profiles, which are the entry speed  $V_{\text{ent}}$  (measured at the beginning of the first Euler spiral) and the minimum speed along the trajectory  $V_{\min}$ .

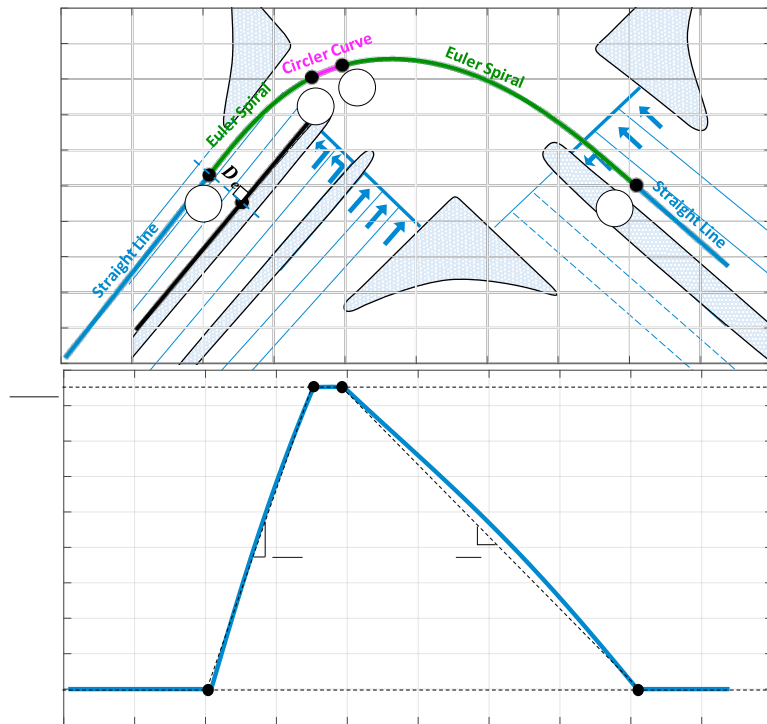


Fig. 3. Components of the spline used for trajectory curve fitting.

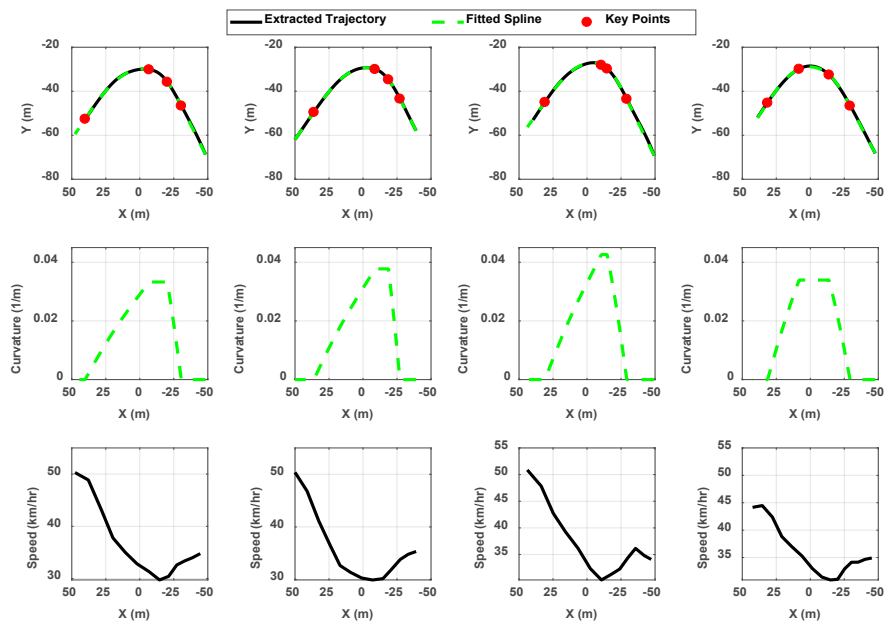


Fig. 4. Examples of the curve fitting process showing the fitted splines and their curvature profiles along with the speed profiles.

#### 4. Statistical analysis

The Matlab code explained in Section 3 was used to estimate the six parameters of the extracted trajectories. The probability distributions of these parameters are displayed in Fig. 5. As shown in the figure, a normal distribution was fitted for each parameter. One-sample Kolmogorov-Smirnov test (95% confidence level) showed that each of the six parameters follows a normal distribution, of which the mean and standard deviation are presented in Table 1.

The results given in Table 1 demonstrate the geometric variations of the extracted paths. As shown in Fig. 2, the monitored approach of the intersection has a single-entry lane and three exit lanes. Therefore, a considerable variation can be observed in the distribution of the exit points  $D_e$  since the drivers are allowed to exit the intersection from any of these three lanes. However, the distribution of  $D_e$  shows that around 70% of the drivers preferred the middle lane. Also, it can be noticed that the coefficient of variation increases along the trajectory from 8.82% at the first Euler spiral to 11.02% at the circular segment to 26.9% at the exit Euler spiral. In other words, the variation of the spline segments close to the exit point are much higher than that of segments near the entry point. This significant variation can be attributed to the large size of the intersection and the fact that the exit approach has three lanes, as opposed to the single left-turning lane at the entry approach.

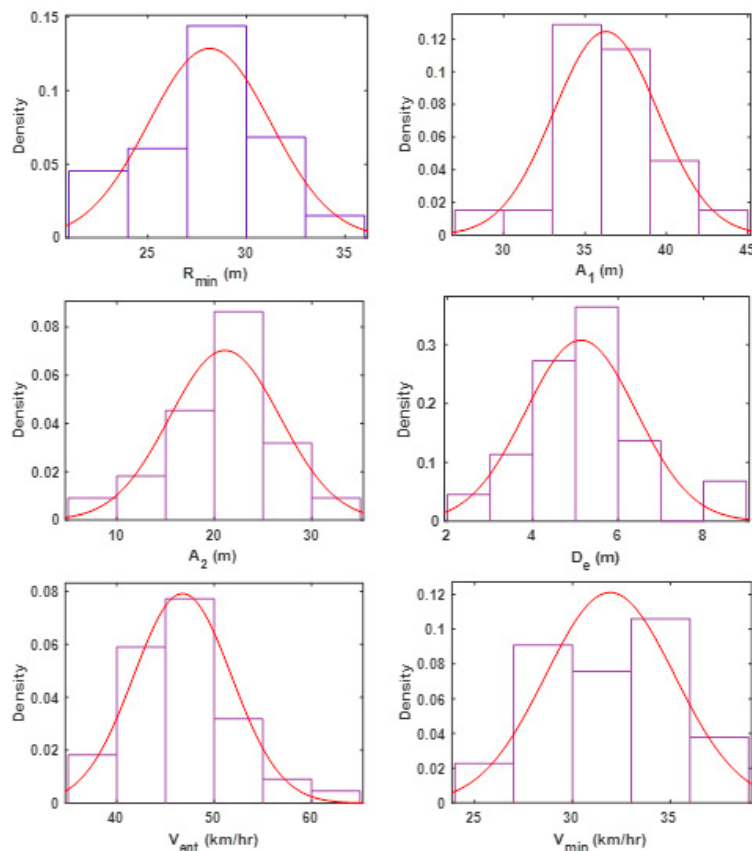


Fig. 5. Probability distribution of the six extracted parameters across the 44 trajectories.

Table 1. Mean, standard deviation, and coefficient of variation of the parameters' distribution.

Statistic	$R_{\min}$ (m)	$A_1$ (m)	$A_2$ (m)	$D_e$ (m)	$V_{\text{ent}}$ (km/hr)	$V_{\min}$ (km/hr)
$\mu$	28.14	36.28	21.08	5.13	46.75	31.92
$\sigma$	3.10	3.20	5.67	1.30	5.03	3.29
CoV (%)	11.02	8.82	26.9	25.34	10.76	10.31

#### 4.1. Modelling of the variations in paths

Based on the parameters computed from the extracted trajectories, three multiple regression models were created to identify the factors affecting the paths of left-turning vehicles at the monitored approach. The output variables of the model were the distributions of  $R_{\min}$ ,  $A_1$ , and  $A_2$ , while the explanatory variables were the entry speed  $V_{\text{ent}}$ , the minimum speed  $V_{\min}$ , and the distance from the exit point to the curb  $D_e$ . Assuming a normal distribution, the mean of the  $i^{\text{th}}$  output variable  $P_i$  can be written as:

$$\mu(P_i) = \beta_{0,i} + \beta_{1,i}D_e + \beta_{2,i}V_{\text{ent}} + \beta_{3,i}V_{\min} \quad (1)$$

where  $\mu$  is the mean of the normal distribution and  $\beta_{0,i}, \dots, \beta_{3,i}$  are the model coefficients obtained by the maximum likelihood method. IBM SPSS Statistics package (2008) was used to compute the parameters of the three models. The results are shown in Table 2.

Table 2. Coefficients of the three multiple regression models.

Explanatory variables	$R_{\min}$ (m)				$A_1$ (m)				$A_2$ (m)			
	$\beta$	Std. error	t-value	Sig.	$\beta$	Std. error	t-value	Sig.	$\beta$	Std. error	t-value	Sig.
Constant	15.111	3.494	4.325	0.000	32.445	5.336	6.080	0.000	-4.269	7.178	-0.595	0.555
$D_e$	1.128	0.258	4.366	0.000	0.680	0.395	1.723	0.093	2.571	0.531	4.842	0.000
$V_{\text{ent}}$	-0.212	0.073	-2.911	0.006	0.089	0.111	0.796	0.431	0.022	0.150	0.147	0.884
$V_{\min}$	0.537	0.116	4.644	0.000	-0.119	0.177	-0.673	0.505	0.349	0.238	1.468	0.150
Sample size	44				44				44			
Adjusted $R^2$	0.552				0.293				0.473			

The resulting models show that the geometric variations of the extracted paths, represented by the fitted spline parameters  $R_{\min}$ ,  $A_1$ , and  $A_2$ , are significantly dependent on the variables  $D_e$ ,  $V_{\text{ent}}$ , and  $V_{\min}$ . The computed t-values show that there is a significant correlation between the radius of the circular curve  $R_{\min}$  and all three output variables. Furthermore, it can be observed the variable  $A_2$ , associated with the second Euler curve, depends mostly on the variable  $D_e$  which reflects the exit lane. However, the output  $A_1$  (i.e. the parameter of the entry Euler spiral) relatively exhibited a lower correlation with the three explanatory variables. Provided a free-flowing trajectory, the speed parameters can somehow indicate the aggressiveness of the drivers and therefore, it can be said that the driver's behaviour and the selected exit lane influence on the trajectory of the turning vehicle.

#### 4.2. Comparison between simulated and observed tracks

Monte-Carlo simulation with 500 trials was conducted using the models explained in Table 2. In each trial, the three models were used to compute  $R_{\min}$ ,  $A_1$ , and  $A_2$  based on random values of  $D_e$ ,  $V_{\text{ent}}$ , and  $V_{\min}$  which were generated according to the normal distributions described in Fig. 5 and Table 1. The resulting spline parameters were then used to obtain the simulated trajectories shown in Fig. 6. As shown in the figure, three cross-sections were considered along the path of left-turning vehicle. The distribution of the simulated paths was computed along each cross-section. Similarly, the distribution of the observed trajectories was analysed along the same cross-sections. Both observed and simulated distributions are displayed in Fig. 7. After that, Kolmogorov–Smirnov test (with 95% confidence level) was conducted to compare between the observed and simulated distributions. It was found that the simulated distributions at the three cross-sections are not significantly different from the observed counterparts.



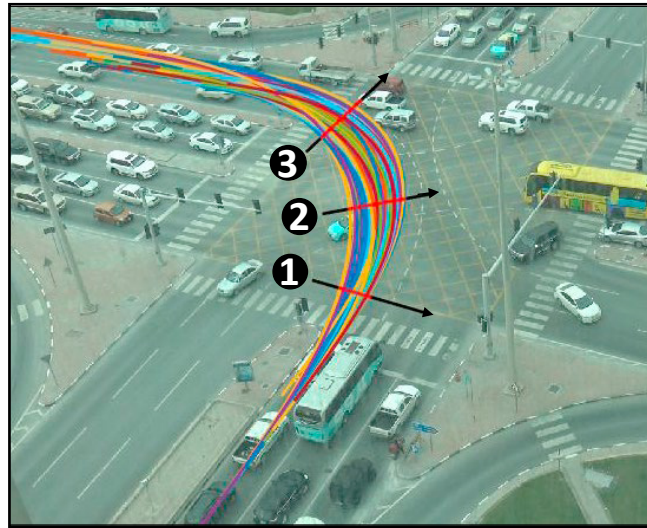


Fig. 6. Simulated paths of left-turning vehicles.

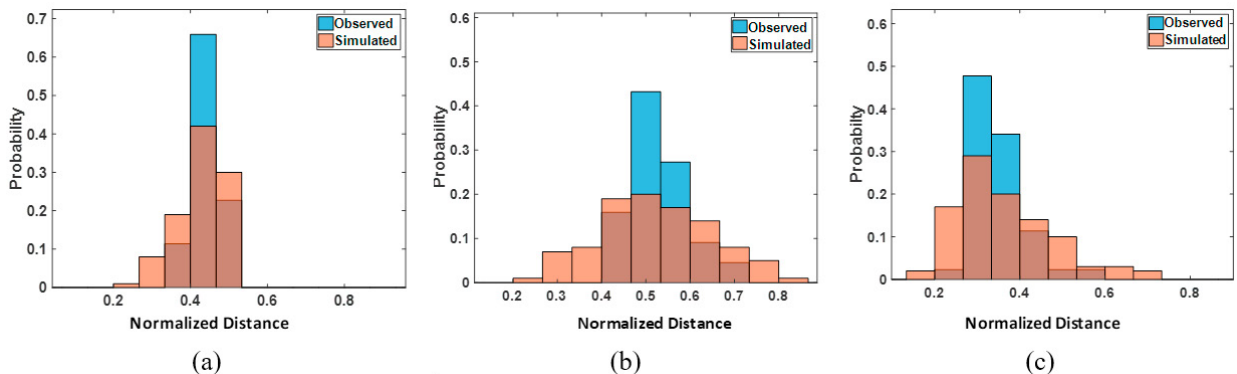


Fig. 7. Comparison between observed and simulated distributions at: (a) cross-section 1, (b) cross-section 2, and (c) cross-section 3.

## 5. Conclusion

In this paper, a total of 44 trajectories of left-turning vehicles were extracted from a recorded video of a signalized intersection located in Doha City, State of Qatar. The trajectories were then statistically analysed in order to identify the factors that impose the variation in paths of the left-turning vehicles at the monitored intersection. Wide variations in the paths of turning vehicles lead to larger conflict areas and thus more safety risks. The results showed that the geometry of the vehicle's path depends significantly on the entry speed, minimum speed throughout the manoeuvre, and the lateral distance between the exit point and the curb (i.e., choice of exit lane). The demonstration of the significance of the speed parameters suggests the likely effect of the driving attitude on the turning vehicle's path. Nonetheless, in order to provide deeper insight into the turning behaviour at signalized intersections in the state of Qatar, it is highly recommended to analyse a larger number of trajectories extracted from several intersections.

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