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Empirical evaluation of drivers' start-up behavior at signalized intersection using driving simulator

Mustafa Almallah[a], Radwan Alfahel[a], Qinaat Hussain[b,c], Wael K. M. Alhajyaseen[c,*], Charitha Dias[c]

[a] *Qatar University – Department of Civil & Architectural Engineering, College of Engineering, P.O. Box 2713, Doha, Qatar*
[b] *Uhasselt, Transportation Research Institute (IMOB), Agoralaan, 3590 Diepenbeek, Belgium*
[c] *Qatar University – Qatar Transportation and Traffic Safety Center, College of Engineering, P.O. Box 2713, Doha, Qatar*

Abstract

Start-up behavior at signalized intersection mainly depends on perception reaction time of drivers to the green phase. This study investigated the start-up behavior at signalized intersections by considering reaction time, acceleration and jerk (the rate of change of acceleration) of drivers in the state of Qatar. Distributions for reaction time, acceleration and jerk were plotted and the mean and 50th percentile values were presented. Three demographic factors (i.e., gender, ethnicity and age) were analyzed using two-tailed/unpaired t-tests. The relationships between acceleration and reaction time, and jerk and reaction time were investigated by linear regression analyses. Descriptive analysis showed that drivers had a mean reaction time of 2.91 s. Furthermore, Arab drivers had significantly lower reaction time than non-Arab drivers. Regarding the jerk maneuvers, young drivers (below 30 years) displayed significantly higher jerk than drivers of 30 years or above. Results from linear regressions showed significant negative correlations in both models (i.e., reaction time on acceleration, reaction time on jerk). As this study targeted multi-cultural drivers' population, the results of reaction time and jerk distributions could be used as inputs in simulation models which are developed for evaluating driver behavior and safety at signalized intersections in regions with multi-cultural driving population.

Keywords: reaction time; acceleration profile; jerk; driving simulator; start-up behaviour; signalized intersection

* Corresponding author. Tel.: +974 44 03 66 79; Fax: +974 44 03 43 02
E-mail address: wyaseen@qu.edu.qa

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1. Introduction

Signalized intersections can be considered as one of the crucial locations in road networks in terms of traffic safety and management. To improve safety and efficiency of signalized intersections, it is important to understand drivers' start-up behavior at the onset of green interval as well as their stopping behavior at the onset of yellow and red intervals. The green interval is not effectively utilized because of the starting delay of drivers and that is called start-up lost time [1]. This is because drivers stopping at the beginning of the queue require some time to react, accelerate and move after the onset of the green phase [2, 3]. According to Setti et al. [4], the total reaction time taken by a person to respond to an event can be divided into three main components, i.e., the drivers' mental processing, the action to perform an event, and the vehicle capacity to respond to a certain input. These parameters could differ from person to person depending on the drivers' characteristics, such as age, gender, and ethnicity. Therefore, it is important to study drivers' start-up behavior by investigating such parameters for a heterogenous driving population with various cultural backgrounds, such as the state of Qatar [5, 6]. Previous studies explained that different parameters could affect start-up behavior of drivers at signalized intersections, e.g., reaction time, acceleration and jerk behavior [7, 8]. At the onset of the green interval, reaction time can be considered as the main factor that affects drivers' start-up behavior [9]. Li et al. [2] investigated the perception reaction time (PRT) at signalized intersections by utilizing digital image processing. The results showed that utilizing a countdown system in signalized intersections reduced driver's PRT from 2.12 s to 1.48 s.

The acceleration maneuvers and reaction time of each individual driver affect the separation of a queue at the onset of green interval. Therefore, the total time for a group of vehicles to pass through a signalized intersection can differ frequently depending on the aggressiveness and alertness of the individual drivers [10]. Aggressive drivers are considered having unsafe driving behavior [11]. Research shows that drivers who drive at high speeds with high variations in accelerations can be considered as aggressive drivers [11]. Lu and PernÍA [12] described that older drivers took more time to react to the green phase than the middle age and young drivers.

Feng et al. [13] studied the drivers' aggressiveness (i.e., jerk values and gas pedal inputs) for different factors such as gender and age. They found that younger drivers were more aggressive than older drivers. The relation between high jerk values and the stress levels has been studied by Othman et al. [14] using a driving simulator. The results showed a direct relationship between jerk and stress level, i.e., the higher the drivers' stress level the larger the jerk. Bagdadi & Várhelyi [15] used jerk values to detect safety critical events. The authors identified accident-prone drivers by comparing the number of critical jerk values they reached and their self-reported accident involvements. The visual analysis proposed a threshold value of approximately 1.0 g/s as an adequate value for detecting potentially critical events while a peak-to-peak jerk value of approximately 1.5 g/s for critical situations.

The main contribution of this study is to evaluate drivers' start-up behavior considering a heterogeneous population of the state of Qatar. The first objective is to investigate Qatari drivers' start-up behavior considering reaction time, acceleration, and jerk for different influencing factors, such as age, gender, and ethnicity. The second objective is to investigate if there is any relationship between drivers' reaction time and acceleration and jerk maneuvers. To the best of our knowledge, a study on drivers' start-up behavior considering such parameters and demographic factors has not been conducted particularly in any Arab country. The outcomes of this study could be useful for reevaluating design practices of traffic signals at intersections to making intersections more efficient and safer.

2. Methods

2.1. Driving simulator

The experiment was carried out at the Qatar Transportation and Traffic Safety Centre of Qatar University. The simulator has been validated objectively for actual speed and speed perception, and for subjective validity [16]. The driving simulator's primary elements are the driving unit and three large screens (5760 x 1080 pixels; 60 hertz refresh rate) that can project 135-degree field of view (as shown in Fig. 1). Force feedback steering wheel with indicators, speedometer, pedals and automatic gearbox identifying a real Range Rover Evoque was presented at the fixed based cockpit. STISIM Drive® 3 software and the CalPot32 are the programs that inter-connects the components. Sound processing and high-speed graphics are offered by the integrated system. A huge data including reaction time, speed,

longitudinal/lateral position, longitudinal/lateral acceleration, red-light tickets number, number of accidents, number of speeding tickets, pedal inputs, etc. can be collected by the simulator.

2.2. Participants

All participants possessed valid Qatari driving licenses of type B (allows to drive all types of passenger cars). A total of sixty-five participants were recruited and divided into two groups based on the transmission type (i.e. sixty-two participants for automatic and five for manual transmission). The participants were from Qatar University society (i.e., staff members, students, and faculty) and drivers from outside. Three participants were influenced by simulation queasiness and were finally eliminated from the data. Thus, the final sample consisted of sixty-two drivers (15 females and 47 males with ages ranging between 19 to 58 years). Thirty-two drivers were non-Arabic and 30 were Arabic from different 20 countries. The proportion of subjects' groups were 24.2%, 30.6% and 45.2% who drove less than 10,000 km, 10,000 – 20,000 km, and more than 20,000 km per annum, respectively.

2.3. Design of scenarios

The driving scenario was designed to replicate the real environment and road layout of the south approach of the Corniche road in the state of Qatar. To maximize the driving experience realism in the simulator [17, 18], the road environment was replicated as realistic as possible with the implication of exact roadside elements, cross-section furniture, and geometrical alignment. The total length of the driving scenario was approximately 16 km, and consisted 11 signalized intersections. Six out of the eleven intersections were designed as analysis intersections, while the other five were dummy intersections. For analysis intersections, the yellow interval was set according to the Qatar Traffic Control Manual as 4 s [19]. Furthermore, to force the drivers to stop at these analysis intersections, the signal was designed in a way that the signal phase was changing to yellow and then red on the drivers' approach. For dummy intersections, most of the intersections were designed with green intervals upon the approach to create variations in the study.

2.4. Experiment procedure

The participants were enrolled by posting up announcements on social web-portals with a link for registration (www.qatardrivingsimulator.com). Official emails were sent to the students and staff of Qatar University for additional recruitments. The length of a driving sessions was approximately one hour and was structured as follows. Firstly, once the participant arrived at the lab of simulation, a pre-experiment questionnaire focused on the driving experience and sociodemographic variables was filled by the participants. Each participant was given a trial run to get familiar with the driving simulator. They drove on an approximately 7 km long segment of Doha Expressway. Then, participants were instructed to drive normally as they usually do following traffic rules. Further, they were given

Fig. 1. Driving simulator: Qatar Transportation and Traffic Safety Centre (QTTSC), Qatar University.

freedom to quit the experiment at any time if they feel any difficulty. Each participant took two driving experiments with a short interval in between. Finally, the participants were asked to response a post-test questionnaire after completion of the test on thoughts/feedback on the driving simulator itself and on the driving experience.

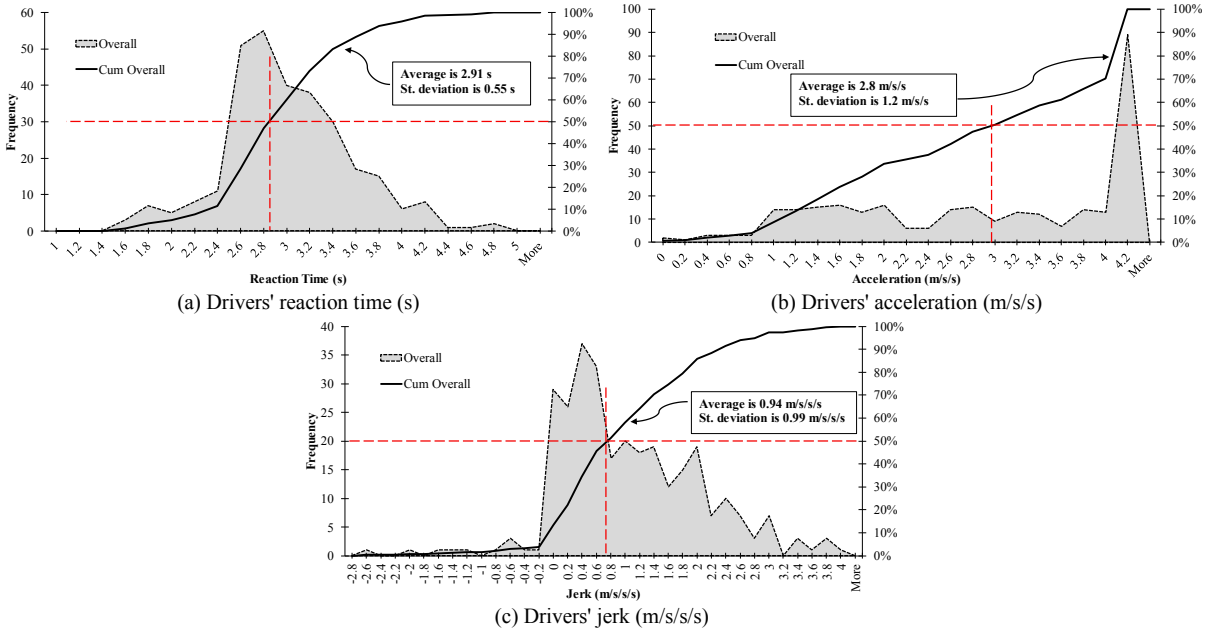
2.5. Data collection and analysis

STISIM Drive® Software was utilized to collect the data for different driving parameters. The parameters of the collected data were longitudinal distance, total longitudinal acceleration/deceleration, longitudinal speed, deceleration due to brake, elapsed time (the total time of the simulation from the point participant start driving), and red light/speed violations occurrence.

Acceleration, jerk and reaction time were considered in data analysis. Descriptive analysis and linear regression were used to analyze the data. Acceleration, jerk and reaction time were depended on gender (male and female), ethnicity (Arab, non-Arab) and age group (younger below 30 years old and drivers of 30 years old and more). The acceleration evaluated was taken after 1 s of driver start accelerating. While the jerk was between 0.5 s and 1.5 s and was calculated by dividing the difference between the acceleration at 1.5 s and 0.5 s to time difference equal to 1 s. The relation between (acceleration and reaction time) and (jerk and reaction time) was studied by linear regression.

3. Results

Fig. 2(a-c) shows the distributions for reaction time, acceleration and jerk respectively. The average reaction time for drivers was 2.91 (± 0.55 SD) s. It can be observed from the figure that almost 80% of drivers had a reaction time ranging between 2.4 s and 3.8 s, while half of drivers had a reaction time of 2.8 s and less. The distribution of drivers' accelerations is plotted in Fig. 2(b). Drivers' accelerations are distributed in the range between 0 m/s^2 to more than 4 m/s^2. The 50th percentile value was 2.95 m/s^2, however, around 20% of drivers had driven with higher acceleration of 4 m/s^2 and more. This percentage reflects drivers who generated higher gas pedal inputs. The average jerk was 0.94 m/s^3 with a standard deviation of 0.99 m/s^3. About 10% of drivers had a negative jerk which means that their acceleration at 1.5 s was lower than the acceleration at 0.5 s. In contrast, around 5% of drivers generated a high jerk of 3 m/s^3 and more.



(a) Drivers' reaction time (s)

(b) Drivers' acceleration (m/s/s)

(c) Drivers' jerk (m/s/s/s)

Fig. 2. Frequency and cumulative distributions

Table 1. Descriptive analyses and two-tailed/unpaired t-tests of different demographic factors

Variable	*Factor*	*Sub-group*	*Descriptive*			*t-test*		
			n	*Mean*	*SD*	*df*	*t stat*	*P-value*
Reaction Time	*Gender*	Male	229	2.92	0.559	120	0.769	0.443
		Female	69	2.86	0.515			
	Ethnicity	Arab	151	2.84	0.504	287	-2.07	**0.039**
		non-Arab	147	2.97	0.586			
	Age	< 30	207	2.92	0.514	146	0.327	0.744
		≥ 30	91	2.89	0.623			
Acceleration	*Gender*	Male	229	2.79	1.258	124	0.06	0.95
		Female	69	2.79	1.117			
	Ethnicity	Arab	151	2.69	1.21	296	-1.48	0.141
		non-Arab	147	2.9	1.23			
	Age	< 30	207	2.69	1.21	170	-2.25	**0.025**
		≥ 30	91	3.03	1.23			
Jerk	*Gender*	Male	229	0.896	0.983	109	-1.42	0.158
		Female	69	1.09	1.01			
	Ethnicity	Arab	151	0.883	0.97	293	-1.07	0.286
		non-Arab	146	1.01	1.02			
	Age	< 30	207	1.05	0.966	164	2.70	**0.007**
		≥ 30	91	0.705	1.01			

The impacts of demographic factors (i.e., gender, age, and ethnicity) were investigated for the different parameters, i.e., reaction time, acceleration, and jerk. Table 1 shows both the descriptive analysis and the independent two-tailed unpaired t-test for the two samples of each demographic factor. Results from the t-test explain that reaction time was significantly different for the factor 'Ethnicity' (p-value=0.039). Mean reaction times for Arab and non-Arab drivers were 2.84 s and 2.97 s, respectively. However, reaction time was not significant for the other factors (i.e., gender and age). Results also show that acceleration and jerk were significantly different between the two age groups. The mean acceleration and standard deviation were 2.69 m/s^2 and 1.21 m/s^2 respectively for drivers below 30 years, while the other age group drivers had a mean and standard deviation of 3.03 m/s^2 and 1.23 m/s^2, respectively. For jerk, drivers below 30 years had a higher mean jerk of 1.05 m/s^3, while drivers aged 30 years or above had a mean jerk of 0.705 m/s^3. Moreover, acceleration and jerk were not significant for the gender and ethnicity factors.

Results from linear regression are presented in Table 2. Results show a significant correlation between acceleration and reaction time (p-value=0.008) and between jerk and reaction time (p-value=0.04). For both models, the correlation is negative, which means that as the reaction time increases the acceleration/jerk decreases. A unit increase in reaction time (1 s) would reduce the acceleration and jerk values by 0.343 m/s^2 and 0.215 m/s^3, respectively.

For further investigation, regression models were plotted to show the relation between acceleration/jerk and reaction time as shown in Fig. 3. The horizontal axis shows the intervals of reaction time (s), while the acceleration (m/s^2) is shown on the left vertical axis and jerk (m/s^3) is presented on the right vertical axis. It can be visualized from the regression profiles that both the jerk and acceleration decrease as the reaction time increases. In addition to the

Table 2. Linear regressions of reaction time on acceleration and jerk

Variable	**Reaction time on acceleration**				**Reaction time on jerk**			
	β	*SE*	*t-value*	*Sig.*	*β*	*SE*	*t-value*	*Sig.*
Constant	3.789	.379	9.992		1.568	.308	5.084	
Acceleration/jerk	-.343	.128	-2.674	**.008**	-.215	.104	-2.066	**.04**

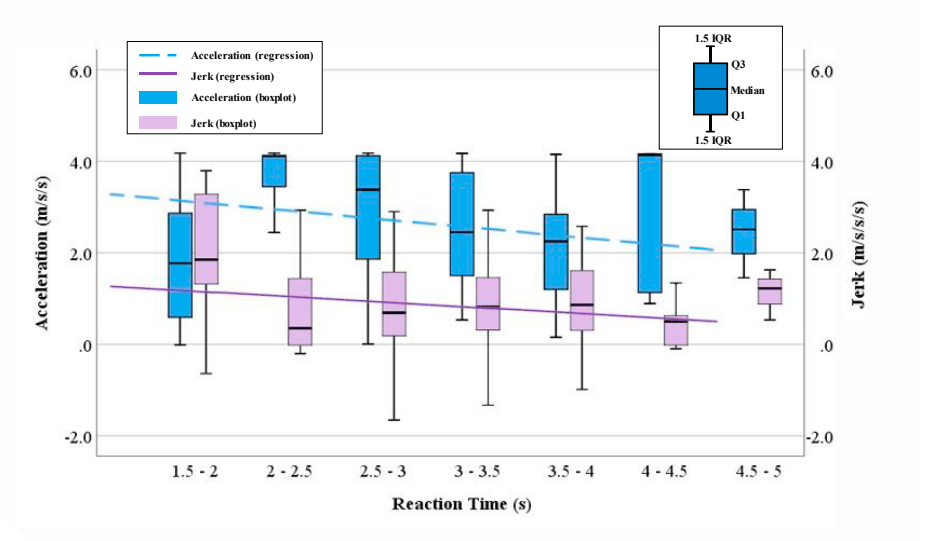


Fig. 3. Linear regression profiles and boxplots for reaction time on jerk/acceleration

regression, boxplot of acceleration and jerk for 0.5 s intervals of reaction time are presented in the figure. The boxplots show that for almost all the reaction time intervals, the highest acceleration of 4.2 m/s^2 was achieved. Moreover, the variation of acceleration for all reaction time intervals (except the [2, 2.5] s and [4.5, 5] s intervals) was higher ranging from the maximum to zero acceleration. For jerk, the [1.5, 2] s interval had significantly higher jerk compared to the other intervals (t-test: two-tailed/unpaired) [2-2.5: p-value<0.01; 2.5-3: p-value<0.01; 3-3.5: p-value<0.01; 3.5-4: p-value=0.011; 4-4.5: p-value<0.01]. The variation in jerk was higher for the first 5 intervals (i.e., from 1.5 s to 4 s) ranging from 3.75 m/s^3 to -1.75 m/s^3, However, the variation reduced after 2.5 s of reaction time.

4. Discussion

This study investigated the start-up behavior of drivers at signalized intersections in the state of Qatar with multi-cultural drivers' population. The start-up behavior was investigated by measuring drivers' reaction time to the green phase, acceleration and jerk maneuvers. In order to measure these maneuvers, drivers waiting as a first vehicle of the queue at the onset of green phase were considered. The effect of demographic features (i.e., gender, ethnicity and age) on reaction time, acceleration and jerk were investigated.

Descriptive analysis showed that the mean reaction time of drivers was 2.91 (± 0.55 SD) s. The value is, however, higher compared a previous study which reported a mean reaction time of 2.12 (± 1.08 SD) s [2]. The results of their study were based on digital image processing with comparably lower sample. The reaction time was measured from the onset of the green to the time the driver starts to move (i.e., when the driver release his foot from the brake pedal). The reaction time in this study was taken from the onset of the green phase until the driver release his foot from the brake pedal and starts to accelerate which is more realistic. The foot movement of driver from the brake pedal to the accelerator could explain the higher value of reaction time in our study. Some drivers released their foot from the brake and did not press the accelerator immediately. Furthermore, the results showed that Arab drivers reacted significantly quicker than the non-Arab drivers. Considering the results of our regression analysis, this finding indicates that Arab drivers could behave more aggressively compared to non-Arab drivers. This is somehow in line with a previous study from the state of Qatar showing that Arab drivers drive significantly faster than non-Arab drivers [20]. Regarding acceleration and jerk maneuvers, drivers aged 30 years or above had a higher mean acceleration and a lower mean jerk. A possible explanation could be that the acceleration was taken at 1 s after the drivers started to accelerate while jerk was calculated between 0.5 s to 1.5 s. Therefore, the jerk maneuvers could be considered as a good representation of drivers' initial start-up behavior. The acceleration is related to how much drivers press the gas pedal while jerk is related to how fast they press it [13]. The higher jerk for drivers below 30 years old means that their rate of change in acceleration was higher from 0.5 s to 1.5 s compared to the drivers aged above 30 years. This

higher rate of change in acceleration maneuvers of drivers aged below 30 years could be considered as aggressive behavior [11]. This is in line with previous studies which showed that young drivers (i.e., aged 30 and below) are more aggressive than the elderly drivers [13, 21].

There are certain limitations of this study that should be considered before generalizing the results. The study was conducted using a fixed base medium fidelity driving simulator, which might reduce the degree of realism. However, in the validation study, drivers travelled and estimated their speeds in a significant similar manner between both (real-world and simulation) environments [16]. In addition, the results from previous studies on subjective assessment confirmed that the settings of this driving simulator are comparable with the settings offered by a real car [16, 22]. Furthermore, due to the length of the scenario, the intersections were not designed with higher waiting time. The red interval for most intersections was set around 10 to 20 s. Thus, the effect of waiting time on the start-up behavior of drivers was not studied. Future research could investigate the effect of longer waiting time at intersection on drivers' reaction time, acceleration and jerk.

5. Conclusion

This study investigated the start-up behavior of drivers at signalized intersection in the state of Qatar considering multi-cultural drivers' populations. The effects of demographic factors on reaction time to the green phase, acceleration and jerk were investigated. Moreover, the relations between acceleration and reaction time, and jerk and reaction time were studied by analyzing linear regression models. The mean reaction time, acceleration and jerk were found to be 2.91 s (± 0.55 SD), 2.8 m/s^2 (± 1.2 SD) and 0.94 m/s^3 (± 0.99 SD), respectively. Arab drivers had significantly lower reaction time than non-Arab, while drivers below 30 years old had higher jerk than the other age group drivers. The relationship between acceleration and reaction time, and jerk and reaction time were both significant with negative correlations. This study results suggests that Arab drivers and drivers below 30 years are more aggressive than non-Arab drivers and drivers more than 30 years old, respectively. The results of this study, such as reaction time and jerk distributions, could be used in simulation models which are developed for evaluating driver behavior and safety at signalized intersections.

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