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Investigating the effects of left-turn distracted drivers on signalized intersections' traffic operations

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ABSTRACT

Distracted driving represents a serious obstacle to maintaining an efficient transportation system. The safety impacts of distracted driving had been thoroughly explored. However, the traffic operations impact has received less attention. Few studies addressed distracted driving behaviors in through lanes, but less focus has been provided on the left turners. The goal of this study is to fill this gap in the research and address the impact of distracted driving for left turners on traffic operations at signalized intersections. Field data were collected from six (6) intersections, with thousands of observations analyzed in Orange County, Florida, studying different land use, lane configurations, and peak periods. The results demonstrated that 87% of all drivers were distracted. 28% were distracted by cell phone usage and showed significant effect only during the AM peak. During the PM peak, talking to passengers and dashboard categories were significant. In all peak periods, the category of "not identified" distractions was dominant (48%), indicating drivers not paying attention and staring through the windshield. Drivers in the first row in the queue experienced more distractions in the PM peak than in the AM peak. Motorists in residential & school land use had lower headway than those in mixed land use. This can be attributed to motorists' cautious driving behavior due to the existence of school zones and pedestrian crossings. In contrast, motorists in mixed land use tend to be more distracted by the commercial and tourist areas. The statistical models demonstrated that the overall effect of distracted drivers in the left lanes on the discharge headway at signalized intersections is significant. The TOD analysis showed that the distractions increased the headway by 40%, 37%, and 43% during the AM, MD and PM peak hours, respectively. Conversely, the overall distractions model results showed that the base headway increased by 40% resulting in reducing the intersection's capacity by 30%.

1. Introduction

The advances in communications and technology that our society is now witnessing are rapidly changing our way of life. Consequently, smartphones have now evolved and have become an integral part of our daily activities. Americans spend, on average, around three hours daily on their smartphones and about 344 times per day checking them, according to a recent survey (Wheelwright, 2022). The survey also shows that 35% get distracted by checking their smartphones while driving. Driver distraction is considered one of the main reasons for roadway crashes. In addition, tasks such as texting and conversations cause an increase in the driver's cognitive workload, which pose a limitation on attention and focus spans.

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Fig. 1. Recording camera.

Fig. 2. Solar powered tower trailer (SPTT-3000).

Table 1
Study intersections and their characteristics.

No	Location	Land-Usef	Approach Configuration	Studied Movement	No. of Hours Collected
1	Lake Underhill Road & Woodbury Road	Residential & School	↰↰⮥	↰↰ SBL	30
2	SR 482 (Sand Lake Rd) & OBT	Commercial	↰↰↑↑↑↱	↰↰ SBL	33
3	International Dr & Jamaican Ct.	Tourist	↰↑↑↱	↰ SBL	50
4	SR 436 & Wilshire Dr	Residential/Commercial	↰↑↑↑↱	↰ NBL	10
5	Narcoossee Rd & Lee Vista Blvd	Commercial	↰↑↑	↰ NBL	27
6	SR 536 & SR 535	Tourist	↰↰↑↑	↰↰ WBL	28
Total Hours					**178**

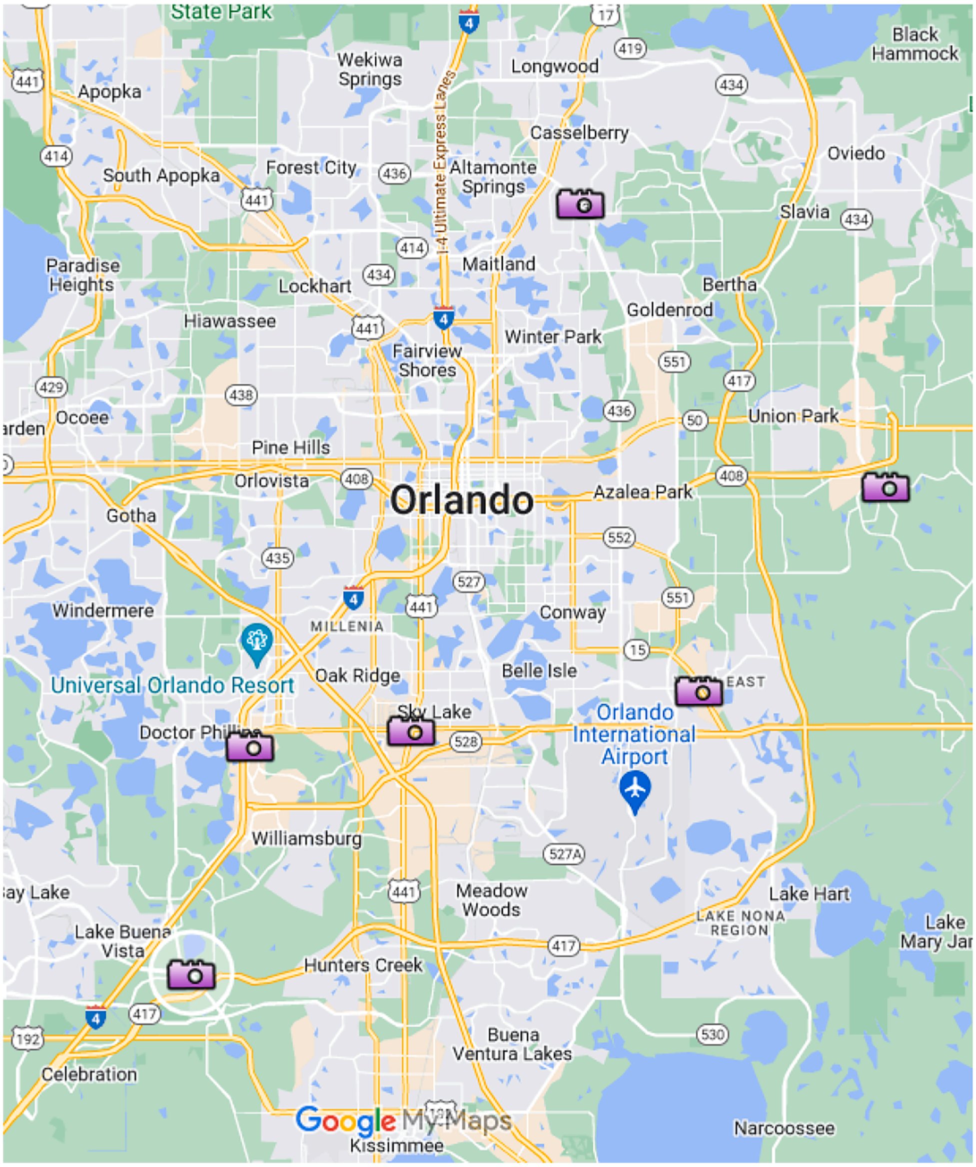


Fig. 3. Site locations.

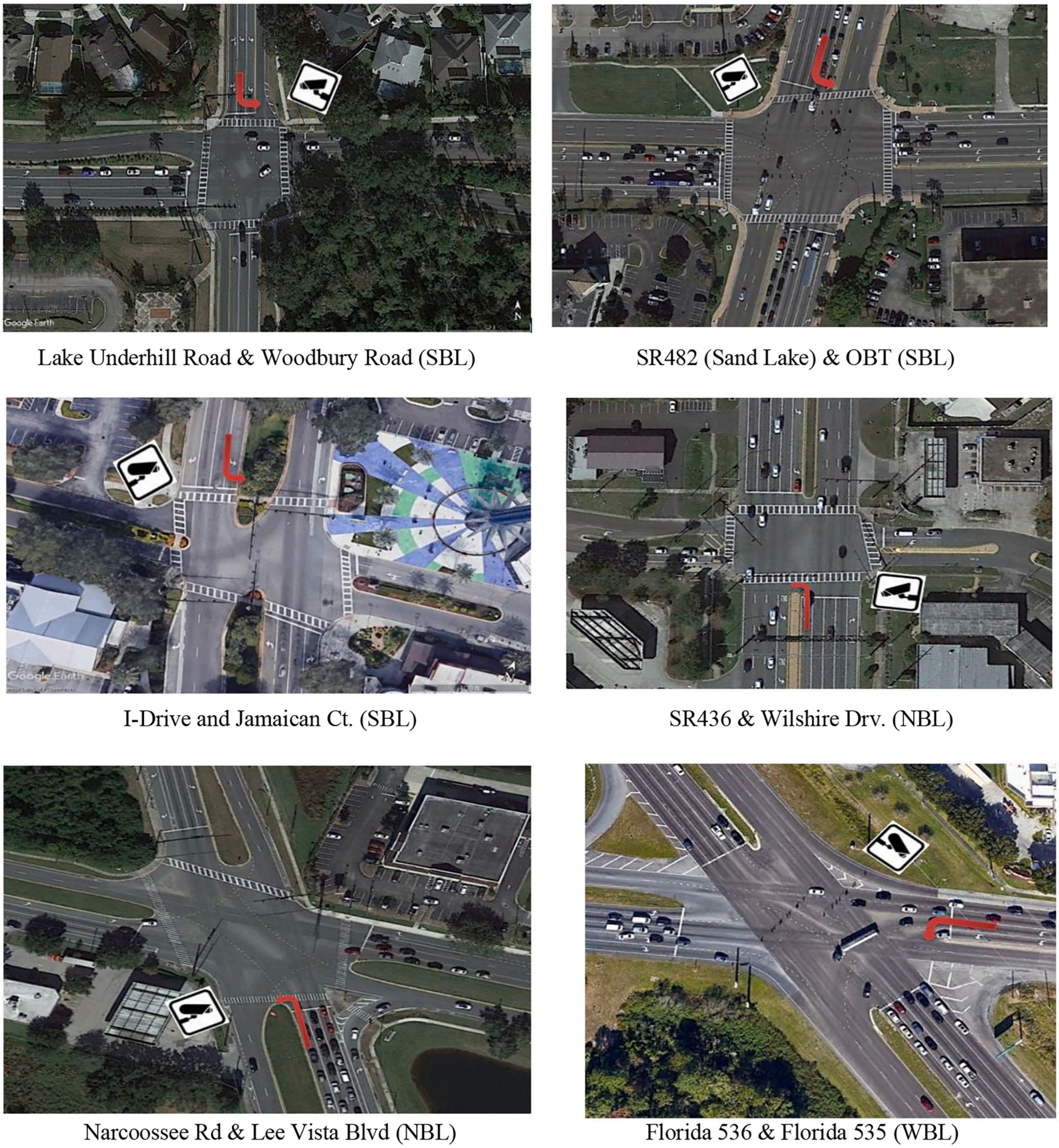


Fig. 4. Intersections and camera locations.

Distracted driving is a topic that has been studied extensively for many years, with findings as early as 1998 (N. T, 1998). With advances in distracting technology, advances have also been made in the study methodologies. The methods of monitoring and researching distracted driving have changed over time too. As mentioned, newer studies have implemented smart cameras and sensors deployed inside cars that measure the driver's exposure to distractions (Dingus et al., 2006; Stutts et al., 2003; Klauer et al., 2006). Survey methods have also seen notable changes over the years. While earlier studies did not specifically focus on the details regarding cell-phone use, newer study methodologies have been more suited to investigating smartphone usage. For example, a national survey conducted by the USDOT, NHTSA in 2018 focused on smartphone usage while driving and asked more questions regarding the types of mobile applications drivers used when operating their vehicles (Schroeder et al., 2008). This study concluded that around 13% of the people surveyed used their mobile phones to send or read text messages while driving, with a majority being in the 21 to 24 age group. These results represent an alarming general increase in phone-related distractions. It is evident that the issue of distracted driving activities is evolving and requires constant attention in response to the rapid innovation in distraction sources.

Table 2
Excerpts from data collection.

Collection Date	Weather.	Int. No.	Distraction Cause	Green Time	Crossing Time	Headway (sec)	Group.	Cycle No.	Lane No.	Row No.
12/23/2021	Sunny	I08	Not Identified Dist.	16:59:42.094	16:59:46.394	4.300	17	16	1	1
12/23/2021	Sunny	I08		16:59:42.094	16:59:49.028	2.634	17	16	1	2
12/23/2021	Sunny	I08	Not Identified Dist.	16:59:42.094	16:59:52.194	3.166	17	16	1	3
12/23/2021	Sunny	I08		16:59:42.094	16:59:53.728	1.534	17	16	1	4
12/23/2021	Sunny	I08		16:59:42.094	16:59:55.561	1.833	17	16	1	5
12/23/2021	Sunny	I08		16:59:42.094	16:59:58.194	2.633	17	16	1	6
12/23/2021	Sunny	I08		16:59:42.094	16:59:59.694	1.500	17	16	1	7
12/23/2021	Sunny	I08		16:59:42.094	17:00:01.528	1.834	17	16	1	8
12/23/2021	Sunny	I08	Not Identified Dist.	17:03:31.528	17:03:37.528	6.000	18	17	1	1
12/23/2021	Sunny	I08		17:03:31.528	17:03:39.694	2.166	18	17	1	2
12/23/2021	Sunny	I08	Not Identified Dist.	17:03:31.528	17:03:43.028	3.334	18	17	1	3
12/23/2021	Sunny	I08	Cell phone	17:07:22.161	17:07:26.994	4.833	19	18	1	1
12/23/2021	Sunny	I08		17:07:22.161	17:07:29.994	3.000	19	18	1	2
12/23/2021	Sunny	I08		17:07:22.161	17:07:32.661	2.667	19	18	1	3
12/23/2021	Sunny	I08		17:07:22.161	17:07:35.328	2.667	19	18	1	4
12/23/2021	Sunny	I08		17:07:22.161	17:07:37.794	2.466	19	18	1	5
12/23/2021	Sunny	I08		17:07:22.161	17:07:40.528	2.734	19	18	1	6
12/23/2021	Sunny	I08	Passengers	17:11:10.761	17:11:15.428	4.667	20	19	1	1
12/23/2021	Sunny	I08		17:11:10.761	17:11:17.761	2.333	20	19	1	2
12/23/2021	Sunny	I08		17:11:10.761	17:11:20.761	3.000	20	19	1	3
12/23/2021	Sunny	I08		17:11:10.761	17:11:22.928	2.167	20	19	1	4
12/23/2021	Sunny	I08		17:11:10.761	17:11:36.261	3.333	20	19	1	5

Table 3
Parameters and Effects.

Parameters	Effects
Weather	Sunny
	Rainy
	Cloudy
Distraction Cause	No Distraction
	Cell phone
	Dashboard
	Eating/Drinking
	Not Identified Distraction
	Passengers
	Smoking
	Other
Green start	The timestamp when the drivers' signal turned green
Cross time	The timestamp when the driver crossed the stop line
Green End	The timestamp when the green signal ended

Policymaking plays a significant role in changing drivers' behaviors and can have a vital role in eliminating negative behaviors, such as distracted driving. On July 1st, 2019, The Wireless Communications While Driving Law, section 316.305, Florida statutes (FLHSMV, 2020) became effective and required all drivers to put down their phones while driving the vehicle. The law allows law enforcement to stop any motor vehicles and issue citations to drivers who are texting while driving. However, the law ignored motorists in a stationary vehicle and did not consider it an operated vehicle. This weakness in the policy could allow motorists at stop signs and stoplights to be exempted from the law, which may lead to a possible increase in startup lost time due to distractions. This may represent an issue, especially for the traffic operations aspect at signalized intersections, as will be further discussed in the following sections.

The impact of distracted driving on safety has been thoroughly investigated in the literature review. However, fewer studies focused on the impact of distracted driving on traffic operations, especially on the left turners. The statistics have shown that tasks such as conversations and texting have a negative impact on the driver's performance that is equal to or greater than driving under the influence (DUI) (Strayer et al., 2006; Sumie et al., 2012). Distracted drivers tend to commit traffic violations such as failing to stop at traffic controls, increased lane-changing, and speeding (Beede and Kass, 2006). According to current statistics from the National Highway Traffic Safety Administration (NHTSA), 3,142 lives were lost in crashes that involved distracted drivers in 2020 only. From 2012 to 2020, distracted driving fatalities amounted to more than 29,000. Eight percent (8%) of fatal crashes in 2020 involved distracted drivers (N. H. T. S. A. (NHTSA), 2020).

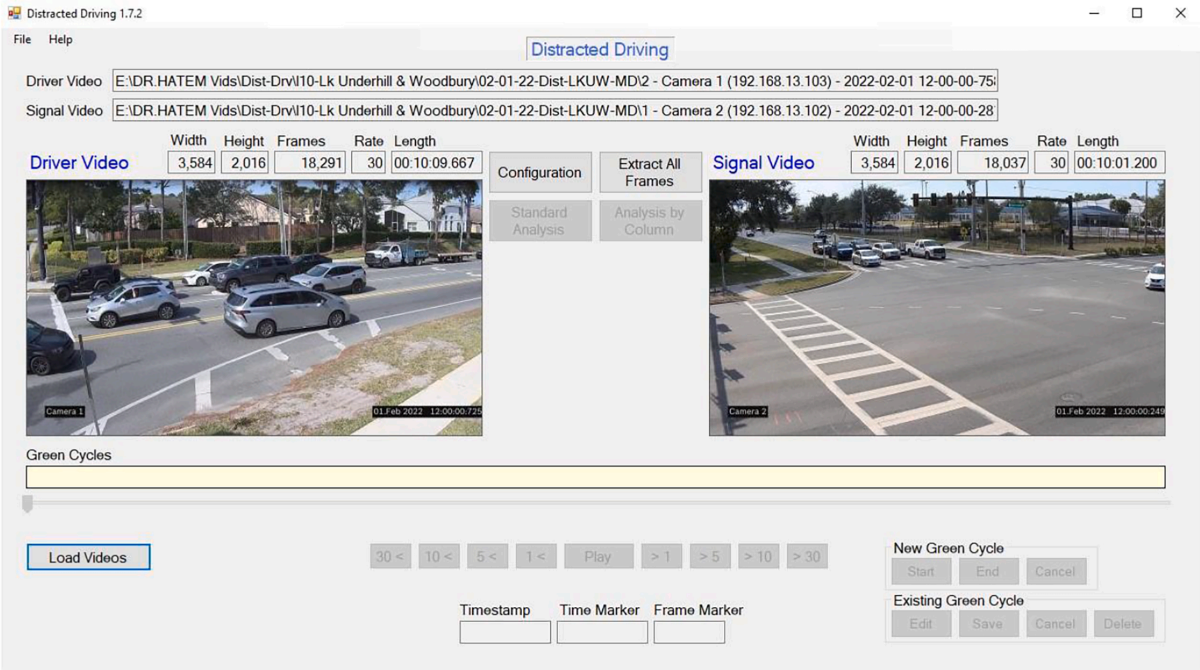


Fig. 5. Distracted driving left user interface.

Table 4
Parameters and variables.

Parameter	Variables
Weather	Sunny
	RainyCloudy
Distraction Types	No Distraction
	Cell phone
	Dashboard
	Eating/Drinking
	Passengers
	Smoking
	Not Identified DistractionOther
Land-use	Commercial
	Residential & School
	Mixed UseTourist
Vehicle Queue Position	1, 2, 3, 4
Time Of Day (TOD)	AM, MD, PM
Distraction Status	Distracted or Not Distracted
Movement Type	Through, Left
Number of Lanes	1, 2, 3

In a study called “The 100-car study”, NHTSA has revealed that distraction is frequent with young drivers ages 18–20 years old, as they have a 68% higher chance of engaging in a phone call. Additionally, young drivers scored the highest involvement rate in crashes or near-crash phone-related incidents, according to the 100-car study (Dingus et al., 2006). The study observed 100 vehicles over 13 months. It demonstrated that almost 80% of all crashes (previously estimated in the range of 25%) and 65% of all near crashes are related to taking eyes off the road just a few seconds before the conflict. In addition, eyes-off-the-road incidences represented 93% of rear-end-striking crashes. The 100-car study also showed that younger age groups (i.e., 18–20 years old) were more involved than older age groups in aggressive driving activities, such as judgment error and driving while impaired.

Regarding the traffic operations effects, studies have shown that reaction times suffer significantly from distracted driving, as texting drivers showed an increase in brake onset time (Drews et al., 2009). In a study conducted on a highway setting, distracted driving has caused lower traffic speeds and increased lane change occurrence (Cooper et al., 2009). The study has also revealed that though distracted drivers had smaller headways, their travel time increased. Another study showed that mobile phone usage, in all traffic circumstances, has always been significantly correlated with lower traffic speeds, especially for the young age-group drivers. Therefore, drivers who used their phones had higher vehicle headway; however, the study could not statistically validate this result due to the strong correlation between speed and headway (Yannis et al., 2010). Charlton et al. observed older drivers’ distracted

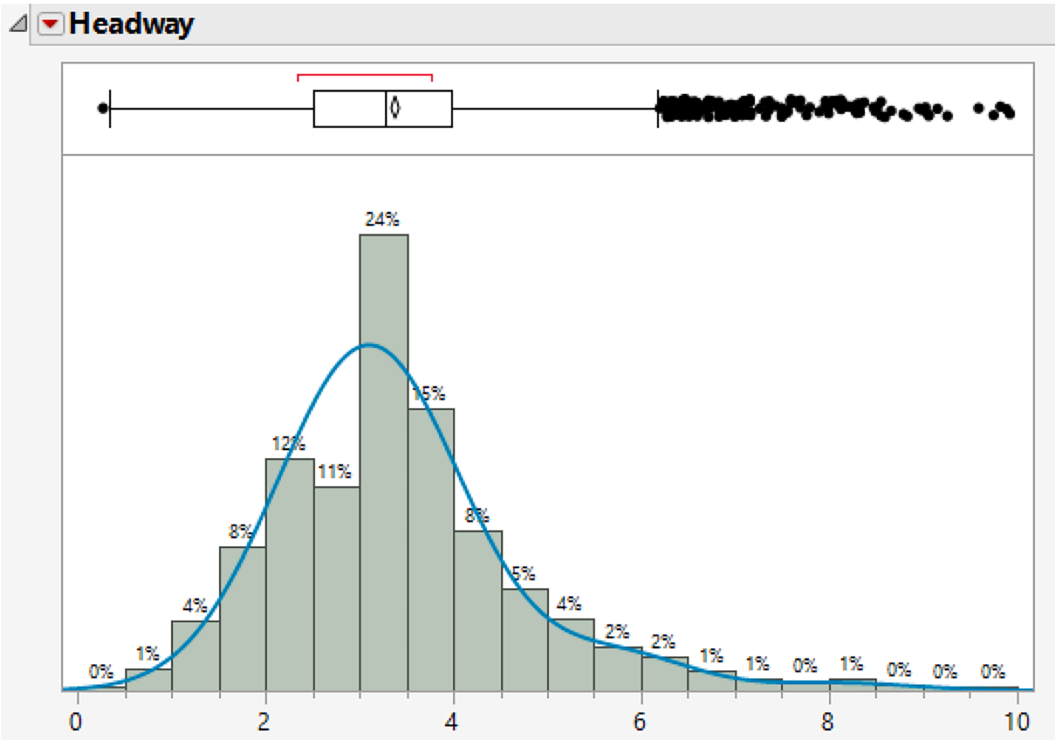
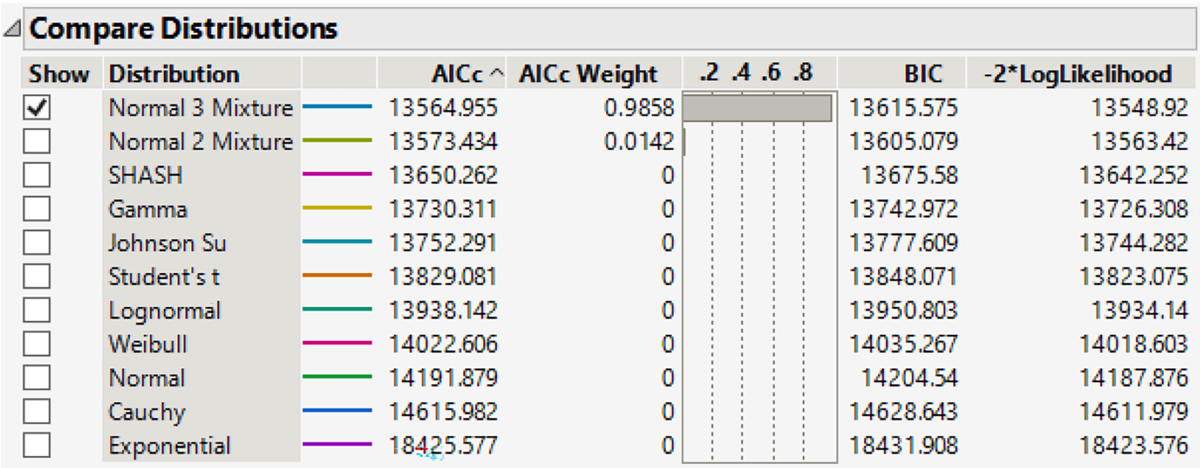


Fig. 6. Headway histogram.



Compare Distributions

Show	Distribution	AICc ^	AICc Weight	BIC	-2*LogLikelihood
✓	Normal 3 Mixture	13564.955	0.9858	13615.575	13548.92
	Normal 2 Mixture	13573.434	0.0142	13605.079	13563.42
	SHASH	13650.262	0	13675.58	13642.252
	Gamma	13730.311	0	13742.972	13726.308
	Johnson Su	13752.291	0	13777.609	13744.282
	Student's t	13829.081	0	13848.071	13823.075
	Lognormal	13938.142	0	13950.803	13934.14
	Weibull	14022.606	0	14035.267	14018.603
	Normal	14191.879	0	14204.54	14187.876
	Cauchy	14615.982	0	14628.643	14611.979
	Exponential	18425.577	0	18431.908	18423.576

Fig. 7. Headway distribution.

behavior at intersections to determine any behavioral changes in response to increased cognitive demand for maneuvers (e.g., taking a permissive left-turn and the need to find a gap in the opposing traffic). Several distraction types showed that older drivers self-regulate by reducing engagement in distracting activities with more demanding maneuvers. However, this study did not consider quantitative effects on intersection performance factors such as queue discharge rate and startup lost times (Charlton et al., 2013). Sherif et al., quantified how distracted driving affects vehicle discharge headways at signalized intersections for through movements. The results demonstrated that approximately 25% of all drivers were distracted reducing the intersections' capacity by 46% with the effect of cell phone use having a share of 17% (Sherif et al., 2023). Only one study by Hurwitz et al. investigated traffic operations for left turn movement in three states (Hurwitz et al., 2013). The study demonstrated that distracted drivers significantly experienced higher startup lost times. The startup lost times in Kansas, Oregon, and Utah were 3.36–4.06 s, 2.97–4.41 s. and 2.25–5.14, respectively.

The literature review has demonstrated that distracted driving significantly impacts driver's safety as well as traffic operation. However, safety impacts have been studied extensively, while less attention has been given to the traffic operations aspect. The

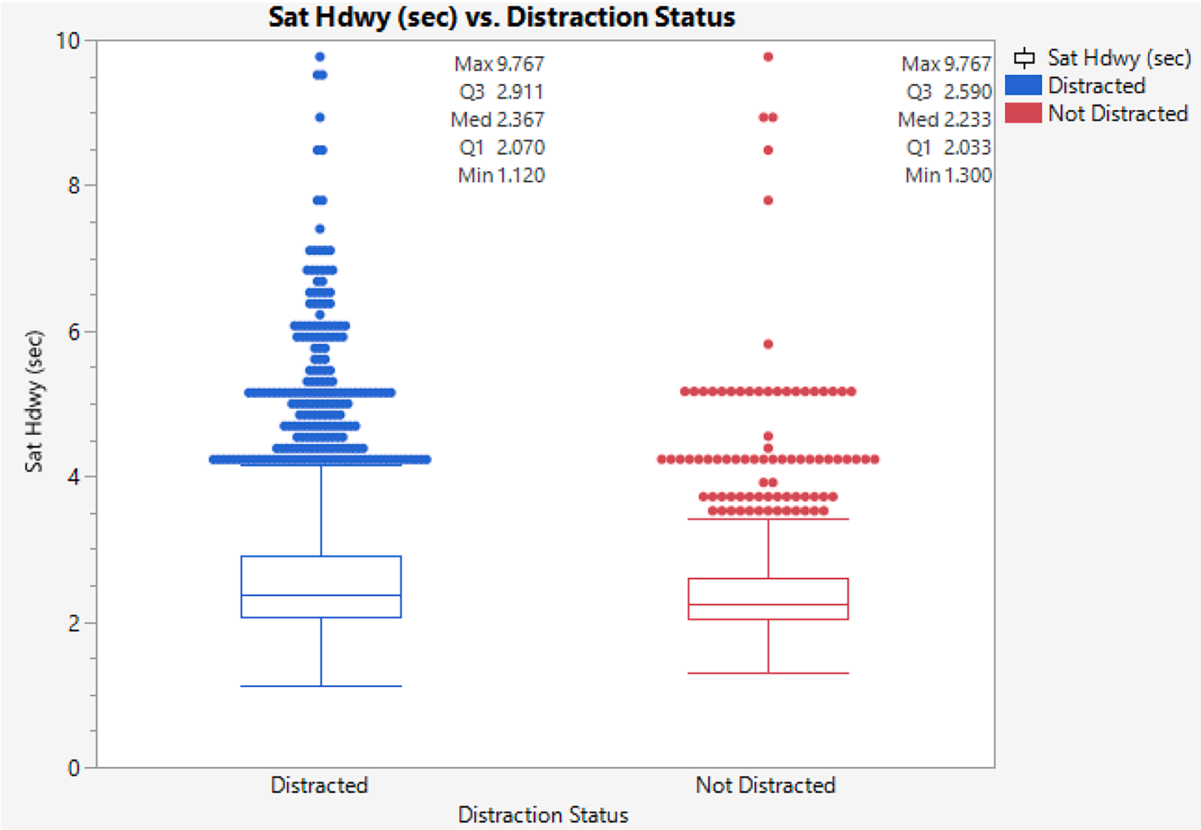


Fig. 8. Saturation headway vs. distraction status.

previous studies showed that distracted driving caused lower traffic speeds, higher travel times, and startup lost times but could not capture driver's behavior at signalized intersections approaches especially at the onset of the green signal. This paper aims to fill this gap.

2. Methodology

2.1. Background

This study aims to quantify the impact of distracted driving, for left turners, on the intersection's headway by measuring the startup lost time at the beginning of the green phase and the average intersection's saturation headway. The saturation headway and the startup lost time are the primary tools in traffic operations to evaluate the capacity and the saturation flow rates at signalized intersections. For the first vehicle in the queue, the headway is the time between the green signal start and the time the vehicle crosses the stop line. For the following vehicles, the headway, as defined by the Highway Capacity Manual (HCM) 2010, is "the time between successive vehicles as they pass a point on a lane or roadway, also measured from the same point on each vehicle." (Transportation Research Board (TRB), 2010).

Typically, when the signal turns green, the first few vehicles in the queue has larger headway than the following ones. The headway then tends to decrease until it levels out with the fourth or fifth vehicle, and this is known as the saturation headway (h). As per the Federal Highway Administration (FHWA), the startup lost time is defined as "the additional time, in seconds, consumed by the first few vehicles in a queue at a signalized intersection above and beyond the saturation headway due to the need to react to the initiation of the green phase and to accelerate to a steady flow condition." The traffic signal timing manual considers the startup lost time to be around two (2) seconds, known as the Perception and Reaction time (PRT).

2.2. Hardware setup

The goal was to monitor distracted drivers' behaviors from the vehicles' windows and windshield through several lanes without alerting the drivers. Therefore, two high-quality/resolution cameras (Bosch IP8000i) were obtained to record 4k (UHD, 3840 × 2160p) video footages. Fig. 1 shows the camera type. The camera has a 3.3x optical zoom, which allows the researchers to monitor the distractions from a far distance. Each camera had a motorized pan range of 0-361°, tilt range −3 to 90°, roll range ± 95°, varifocal lens

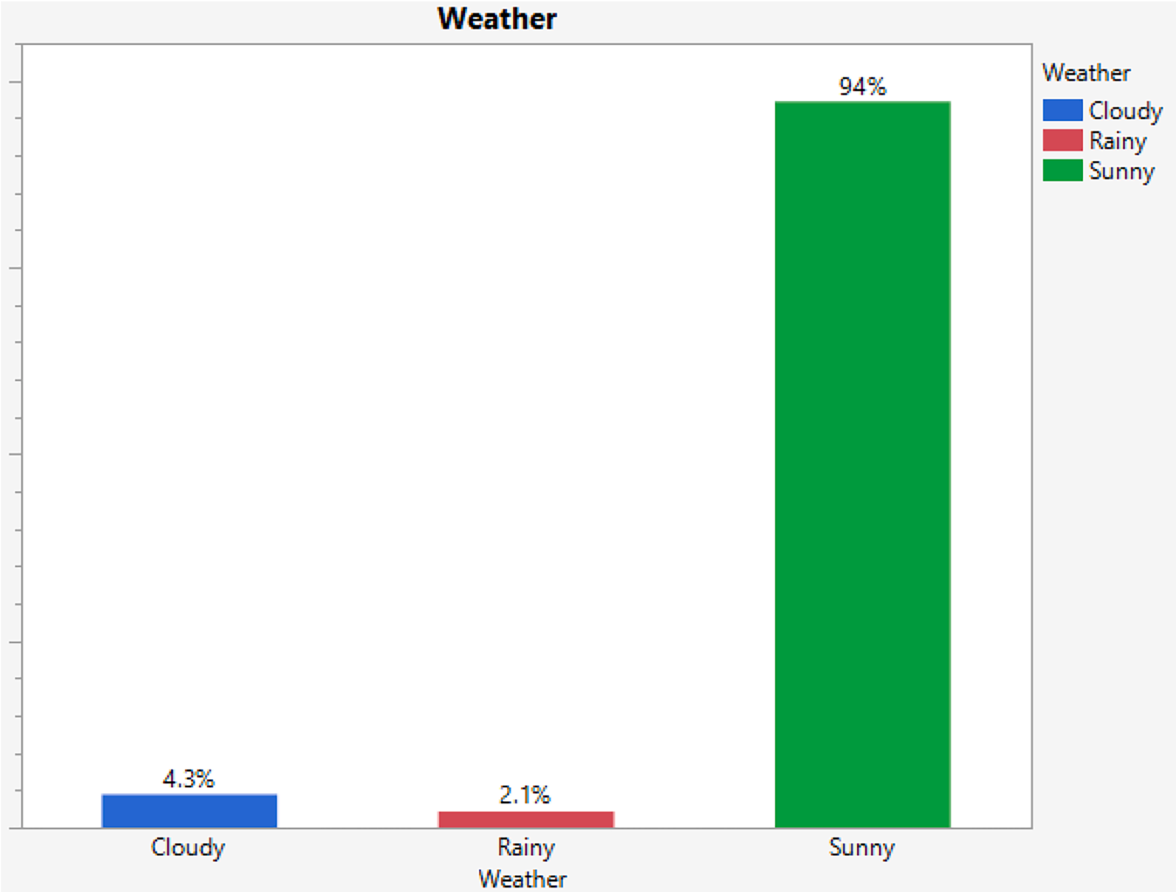


Fig. 9. Weather histogram.

(12–40 mm) that provided a horizontal field of view of 36.2 to 19.9°, CMOS sensor (1/1.8″) that captures videos with 30 frames per second and a resolution of 3840 × 2160. The 4k high-quality recordings allowed the researchers to clearly identify the distraction types even through the windows/windshield and over multiple lanes. Additionally, the camera had a high dynamic range, which provided clear recordings even in low light situations.

Both cameras were mounted on an SPTT-3000 trailer (solar powered tower trailer). The trailer has a 30 feet high tower and can support several cameras, lights, sensors, and batteries. The height was set to around 15 feet to guarantee that the drivers would not detect the cameras. Fig. 2 demonstrates a picture of the trailer taken from the field. The two cameras are set to record the driver's and the traffic signal view. Both cameras need to be synchronized to show the same timestamp before recording. This is an essential step to guarantee the accuracy of the data extraction process later.

2.3. Data collection

The study was conducted at six (6) intersection approaches in District 5, Florida, and the City of Orlando to meet several criteria. They covered a wide range of different land use types, such as commercial, tourist, offices, residential, and college/school. The approaches were composed of one or two left lanes. It should also be noted that data were collected at approaches with protected only phasing due to the difficulty in identifying longer headways due to distractions versus yielding to oncoming traffic during the permissive phase. The data were collected on weekdays (Monday to Friday) during peak hours (7–9 AM; 12–2 MD; 4–8 PM) to be able to calculate saturation flow rates and headways. The total recording hours were 178, exported from the cameras in more than 100 h. Table 1 shows the study locations, land use, lane configuration, study movement, and the number of recorded hours. Fig. 3 and Fig. 4 show the map locations, while Table 2 shows an excerpt from the data collection.

2.4. Data extraction

The data extraction process was conducted using professional editing software that allowed the researchers to identify the distraction types accurately. The data included the following parameters and effects. Weather (sunny, rainy, cloudy); Distraction cause

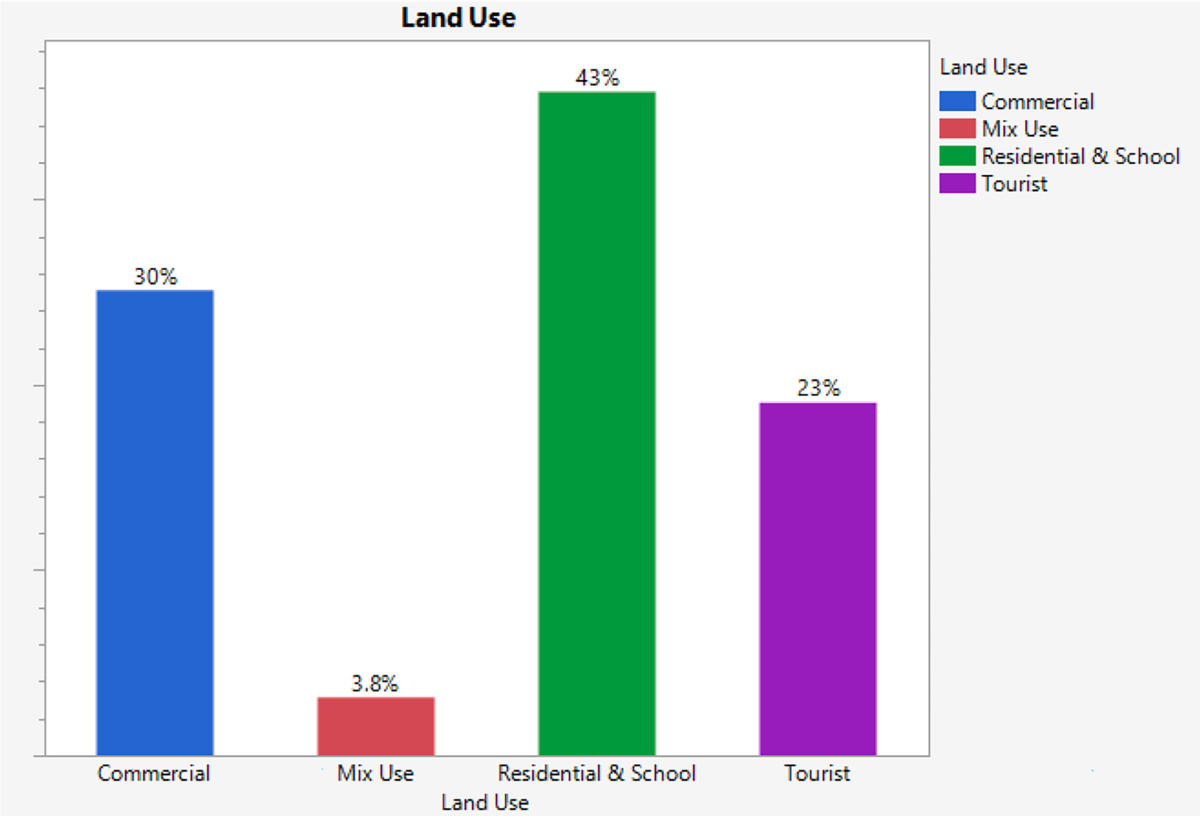


Fig. 10. Land use histogram.

(No distraction, Cell phone, Dashboard, Eating/Drinking, No Identified Distraction, Passengers, Smoking, Other). Passenger distraction is identified when the driver is distracted by looking or talking with the other passengers in the car. The Dashboard distraction is identified when the driver is distracted by his vehicle's dashboard. Three timestamps were collected with an accuracy of up to two decimal places: green start, crossing time, and green end. The green start indicates when the signal turned green. The crossing time indicates when the vehicle crossed the stop line. The green end indicates when the signal turned red. Table 3 summarizes the parameters and effects used in the data extraction process.

As a quality control measure, a professional software "Distracted Driving Software" was developed to assist the researchers in accurately measuring and recording the distraction types. One of the cameras was positioned to record the driver's view, while the other camera was set to record the traffic signal light changes. The software synchronizes both videos and provides the researchers with a simple user interface. In addition, the software has specific buttons to record each distraction and record the timestamp of green start, cross time, and green end. Fig. 5 shows the user interface.

3. Sample calculation

This section provides an example to illustrate how the calculations have been applied. As shown in Table 2 previously, the first row shows the data collected for the first vehicle in the queue, in group number 17. First, the headway (in seconds) is calculated by subtracting the crossing time from the green time: 16:59:46.394−16:59:42.094 = 4.3 s. Next, the headway is calculated for the following vehicles in the queue by subtracting the crossing time between successive vehicles. So, in this case, the headway of the second vehicle in the queue: 16:59:52.194−16:59:49.028 = 3.166 s.

4. Results and discussion

The analysis of the left turn movement was considered for single and dual lefts operating in a protected-only mode due to the fact that permissive mode will have a confounding effect with increased headway yielding to oncoming traffic. The response variable for the left movement was the headway. Table 4 shows the parameters and variables used in the statistical analysis. The headway distribution for the left movement is shown in Fig. 6 and follows a normal distribution (Normal 3 Mixture) though it is slightly skewed to the left. The headway AIC was 13,564 (Fig. 7). Fig. 8 compares the overall saturation headway for distracted and non-distracted drivers. The overall saturation headway for non-distracted drivers was 2.2 s, which is slightly less than the distracted drivers' case (2.3 s).

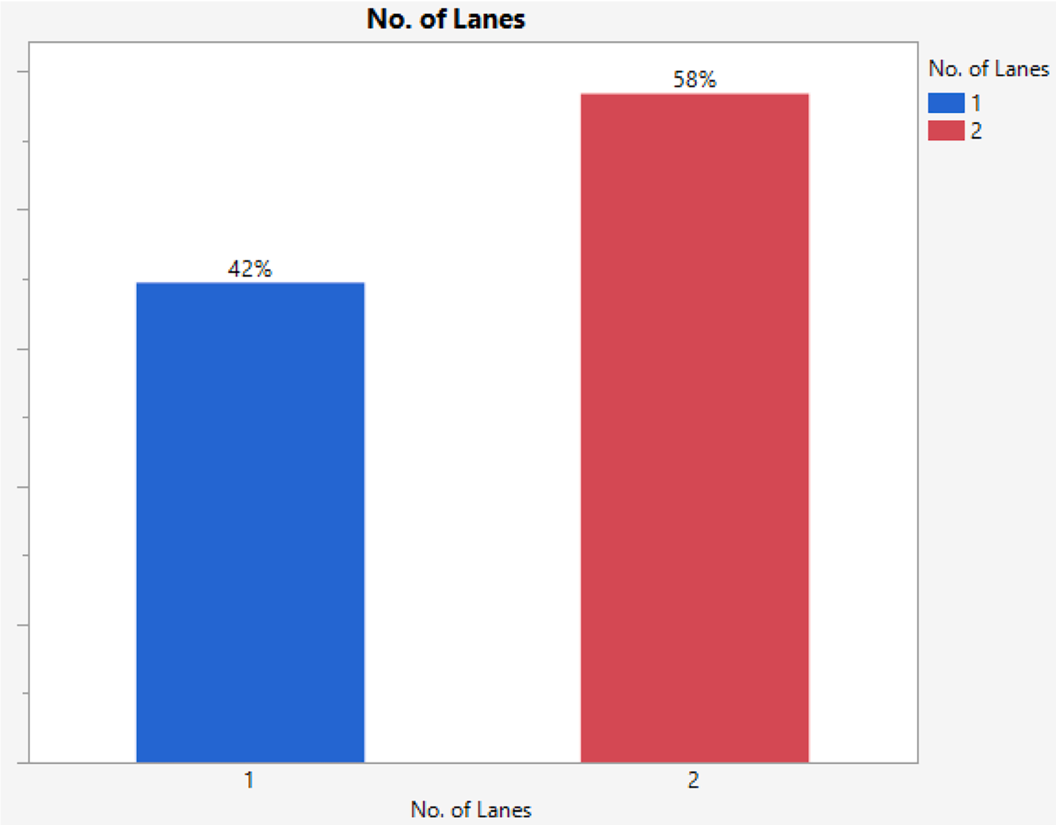


Fig. 11. Number of lanes.

4.1. Weather

The weather parameter contained three levels: Cloudy, Rainy, and Sunny. Most records were collected in sunny weather (94%). Cloudy and rainy weather percentages were negligible, 4% and 2%, respectively, as shown in Fig. 9.

4.2. Land use

Land use data were categorized into four levels: Commercial, Residential with School, Mixed-Use, and Tourist. Most records were collected from Residential & School areas (43%). Commercial and Tourist land uses represented 30% and 23%, respectively (Fig. 10). Mixed land use represented around 4%.

4.3. Number of lanes

The number of lanes denotes the total number of lanes analyzed for each movement. The left movement is composed of either one or two lanes. 58% of records were collected from two-lane approaches, while 42% were from one-lane approach intersections, as shown in Fig. 11.

4.4. Distraction cause

The percentage of distracted and non-distracted drivers was 87% and 13%, respectively, as shown in Fig. 12. The majority of the left turn drivers, more than two-thirds, were distracted. Distractions were studied by types (Fig. 13). Almost half (48%) of the distractions were not identified. The predominant distraction was cell phone usage by almost a third (28%), followed by 13% for not distracted drivers, and around 8% for passenger distractions. The remaining types had negligible proportions.

4.5. Vehicle queue position

The vehicle queue position percentages for the left-turn movement are shown in Fig. 14. Almost half of the records (47%) were from position one (first row). Positions two and three in the queue represented 31% and 21%. The remaining positions were not significant

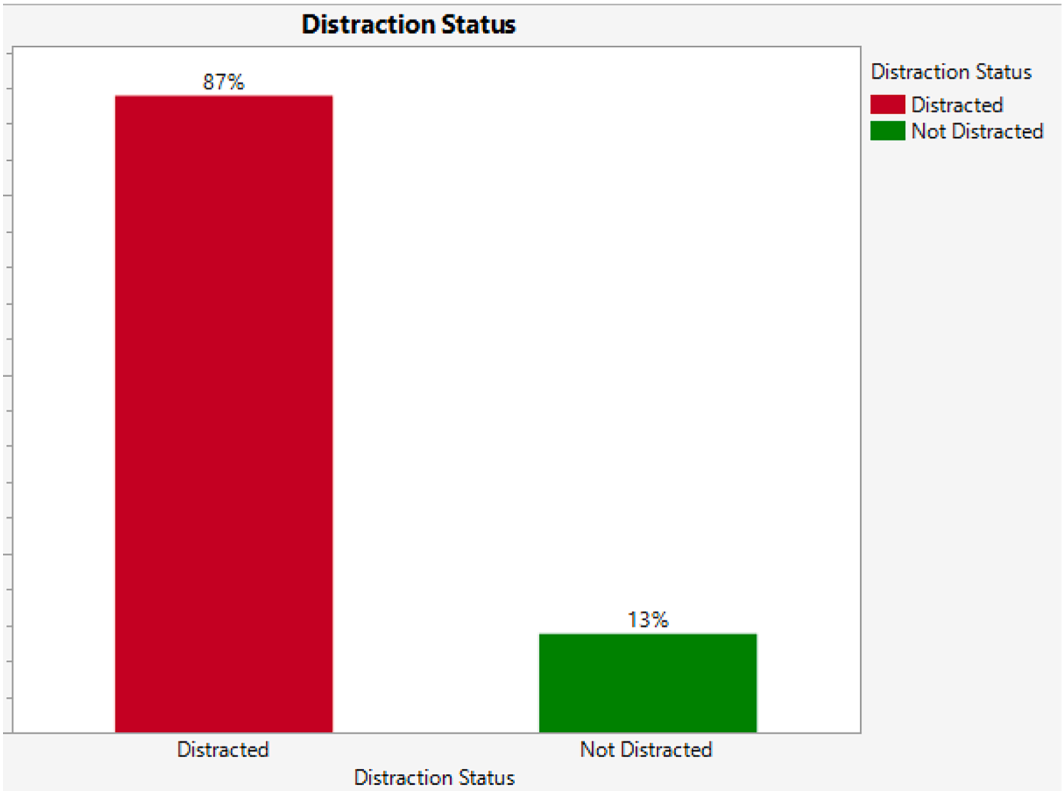


Fig. 12. Distraction status.

(around 1%).

4.6. Statistical comparison – generalized linear regression analysis

4.6.1. AM peak

A Generalized Linear Model was formulated by time of day (TOD), with a Poisson distribution and Identity link. The estimation method is Maximum Likelihood. The whole model test was significant (P <.0001) and provided a low overdispersion (0.39), as shown in Fig. 15.

The model parameters were Weather, Land Use, Distraction Cause, and Veh. Queue Position. All parameters were significant (Fig. 16). The base headway was at 4.28 s. Cloudy weather increased the headway by 0.3 s when compared to the sunny conditions. Also, residential areas with school land-use showed a lower effect on headway than mixed land use. For distraction causes, cell phone usage and not identified categories increased the headway by 0.4 s. Also, the first three vehicle positions in the queue were significant. A headway reduction of 0.45 s compared to the fourth vehicle, which showed that front row drivers were more alert than the vehicles in the back of the queue.

4.6.2. MD peak

The MD peak whole model test was significant and provided a small acceptable overdispersion of 0.27. The model AIC was 8,783 (Fig. 17). All model parameters were significant, except for the weather (Fig. 18). The intercept (base headway) was significant (3.29 s). Commercial land use had an increasing effect on the headway by 0.25 s, while residential & school zones had a decreasing effect by 0.44 s when compared to the base category of Mixed-Land use. In the distraction causes parameter, not identified distractions were significant and increased the headway by 0.4 s. The drivers that were “Not distracted” had a decreasing effect on the headway by 1.35 s. Fig. 19 demonstrates the parameter estimates.

4.6.3. PM peak

The PM peak whole model was significant and presented a low overdispersion (0.29). The model AIC was 32,501. Fig. 20 shows the whole model test. All model parameters, shown in Fig. 21, were significant (P <.0001). The base intercept was significant (3.97 s). Cloudy weather increased the headway by 0.25 s. Mixed land use increased the response by 0.75 s, while drivers were more attentive in residential and school land uses. Dashboard, not identified, and passengers’ categories increased the headway by 0.52, 0.17, and 0.18 s, respectively. The drivers that were “Not distracted” significantly reduced the headway by 1.28 s. Only the first queue position was significant and increased the headway by 0.09 s (Fig. 22).

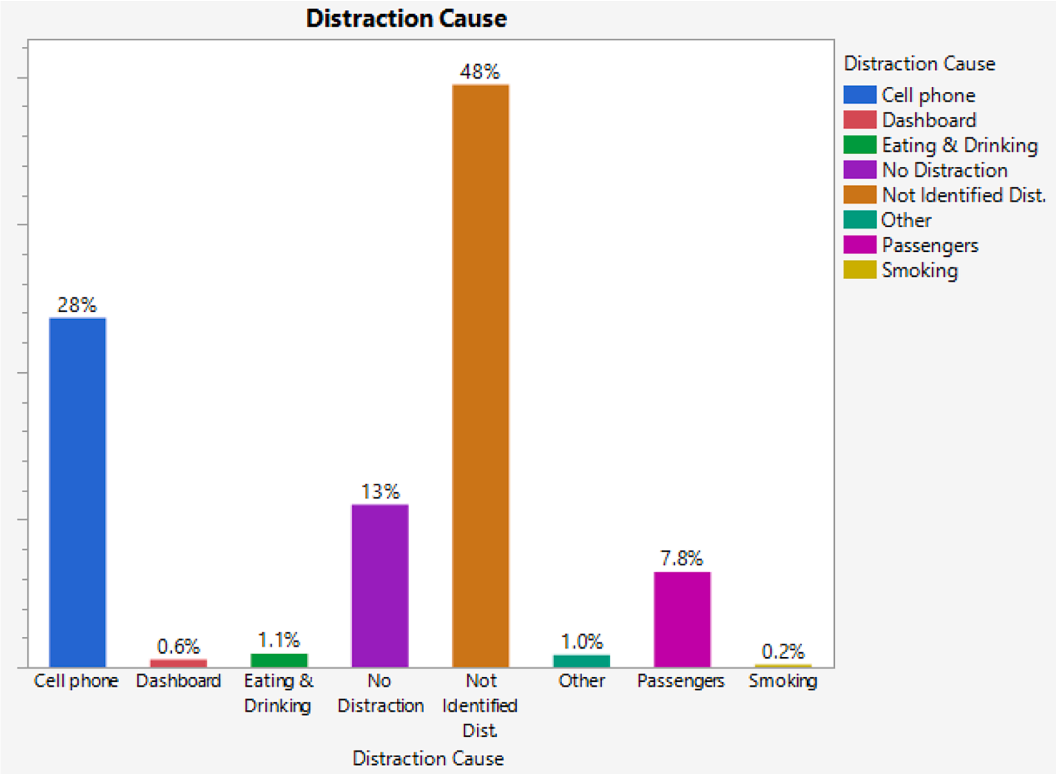


Fig. 13. Distraction types.

5. Discussion

The AM peak model showed that cloudy weather, cell phone, and not identified categories positively affected the headway. Drivers were more attentive near residential areas with school land uses. The first three vehicle positions in the queue did not affect the headway. On the other hand, the MD peak model showed that the commercial land use and not identified categories increased the headway. Similarly, drivers were more attentive near residential and school land uses. The PM peak model showed that cloudy weather and mixed land use increased the headway. Again, drivers are more careful in residential and school land use. The distraction causes; Dashboard, not identified, and passengers' categories as well as the first vehicle in the queue significantly increased the headway.

The base headway (Intercept) for the AM, MD, and PM peaks were 4.28, 3.29, and 3.97 s, respectively. The cloudy weather increased the headway during the AM and PM peaks and showed no effect during the MD peak. Residential and school land uses reduced the headway as explained earlier due to drivers being more attentive near these areas. However, commercial, and mixed land uses increased the headway which showed that motorists waiting during the red light at intersections surrounded by commercial land uses are more observant of the surrounding activities and more entertained by the commercial zones. Cell phone distractions had an increasing effect on the headway but was only detected during the AM peak. However, dashboard usage and talking to passengers increased the headway more during the PM peak period. Drivers who were not distracted significantly decreased the headway in the three peaks while "not identified" category positively affected the headway in all peaks. Distracted drivers in the first row increased the headway in the PM peak compared to the AM peak due to the fact that drivers were more attentive in the morning going to work while less attentive due to fatigue and distractions when returning home.

This model demonstrated that driving during cloudy weather in mixed land use would increase the headway in the PM peak. Drivers in residential and school land use drive slower due to the presence of students or residents crossing. Left turn motorists tend to be distracted by their phones during the AM peak and the dashboard during the PM peak. As expected, motorists who were not distracted significantly decreased the headway. Not identified distractions increased the response in all peaks. Most of those unidentified distractions are probably related to drivers not paying attention and staring through the windshield. The results showed that left turners seem more distracted during the PM than in the AM peak.

5.1. Effect of distracted lefts on headway by time of day (TOD)

The above analysis showed that different distraction types have significant effect on the intersection headway with different effect on each peak period which is based on three (3) separate models. Such formulations did not provide clear statistical inference whether overall distracted driving has really increased the headway since the control variables of the three models included mutually exclusive

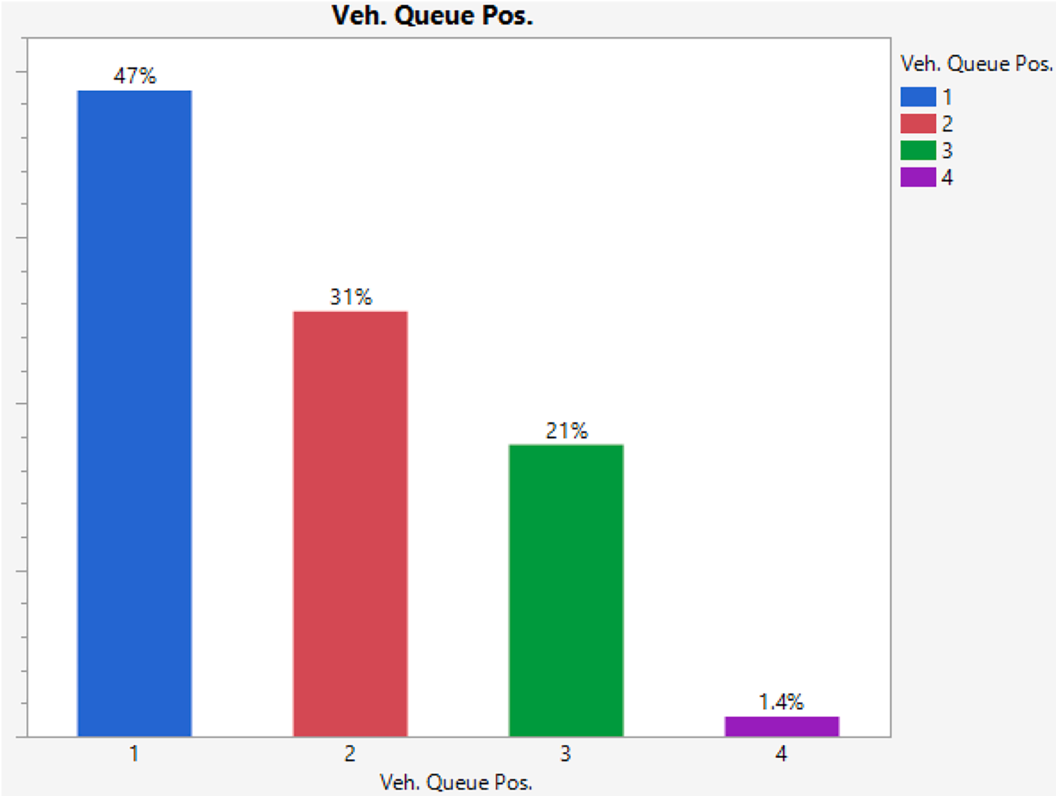


Fig. 14. Vehicle queue position histogram.

Whole Model Test

Model	-LogLikelihood	L-R ChiSquare	DF	Prob>ChiSq
Difference	163.294631	326.5893	13	<.0001*
Full	2386.45935			
Reduced	2549.75398			

Goodness Of Fit Statistic	ChiSquare	DF	Prob>ChiSq	Overdispersion
Pearson	206.0176	527	1.0000	0.3909
Deviance	187.9339	527	1.0000	

AICc
4803.8330

Fig. 15. GLM whole model test.

samples and use different coefficients. Therefore, it was crucial to develop a single model with all the control variables to investigate the overall distraction status which would be coded as a binary indicator (dummy variable). Therefore, another two (2) mixed models were developed which included the main control variables; weather, land use and vehicle queue position, time of day and excluded the lost time and different distraction types since they are positively correlated with the headway (h) and might create biased inferences as shown in Fig. 23 (a-d) and 24 (a-d). Fig. 23 is for the time-of-day (TOD) analysis while Fig. 24 is for the overall distraction effects. For example, the TOD analysis showed that the AM peak hour distractions increased from **2.14 s** to **2.99 s (40% increase)**, MD peak hour from **2.30 s** to **3.15 s (37% increase)** and the PM peak hour distractions increased the headway from **1.97 s** to **2.82 s (43% increase)** as shown in Fig. 23. On the other hand, the overall distraction model results in Fig. 24 show that the effect of distraction is significant with an increasing effect of **0.84 s** on the headway. The base headway center points for sunny weather, school land use and first vehicle

Effect Tests

Source	DF	L-R ChiSquare	Prob>ChiSq
Weather	2	25.640521	<.0001*
Land Use	2	31.317109	<.0001*
Distraction Cause	6	137.14446	<.0001*
Veh. Queue Pos.	3	15.052822	0.0018*

Parameter Estimates

Term	Estimate	Std Error	L-R ChiSquare	Prob>ChiSq	Lower CL	Upper CL
Intercept	4.2841435	0.2611217	269.17966	<.0001*	3.7711786	4.7971084
Weather[Cloudy]	0.335338	0.1259067	7.093622	0.0077*	0.0879985	0.5826776
Weather[Rainy]	0.1022554	0.1636835	0.3902674	0.5322	-0.219296	0.4238062
Land Use[Commercial]	0.0129601	0.1592053	0.0066267	0.9351	-0.299794	0.3257137
Land Use[Residential & School]	-0.627571	0.1633501	14.76004	0.0001*	-0.948467	-0.306675
Distraction Cause[Cell phone]	0.4066515	0.1412155	8.2924014	0.0040*	0.1292384	0.6840647
Distraction Cause[Dashboard]	-0.325559	0.5022929	0.4200921	0.5169	-1.312297	0.6611792
Distraction Cause[Eating & Drinking]	0.1350733	0.2932056	0.212224	0.6450	-0.440919	0.711066
Distraction Cause[No Distraction]	-1.443624	0.1595307	81.887849	<.0001*	-1.757017	-1.130231
Distraction Cause[Not Identified Dist.]	0.4356542	0.1349598	10.420171	0.0012*	0.1705301	0.7007784
Distraction Cause[Other]	0.2676482	0.3194511	0.7019724	0.4021	-0.359903	0.8951993
Veh. Queue Pos.[1]	-0.419516	0.1571564	7.1257769	0.0076*	-0.728244	-0.110787
Veh. Queue Pos.[2]	-0.538436	0.1652095	10.621799	0.0011*	-0.862985	-0.213887
Veh. Queue Pos.[3]	-0.494494	0.1691884	8.5424341	0.0035*	-0.82686	-0.162129

The confidence intervals and tests are Wald-based because the data has more than 1,000 rows.

Fig. 16. GLM parameter estimates.

Whole Model Test

Model	-LogLikelihood	L-R ChiSquare	DF	Prob>ChiSq
Difference	285.644493	571.2890	12	<.0001*
Full	4377.30275			
Reduced	4662.94724			

Goodness Of Fit Statistic	ChiSquare	DF	Prob>ChiSq	Overdispersion
Pearson	203.5699	729	1.0000	0.2792
Deviance	180.7599	729	1.0000	

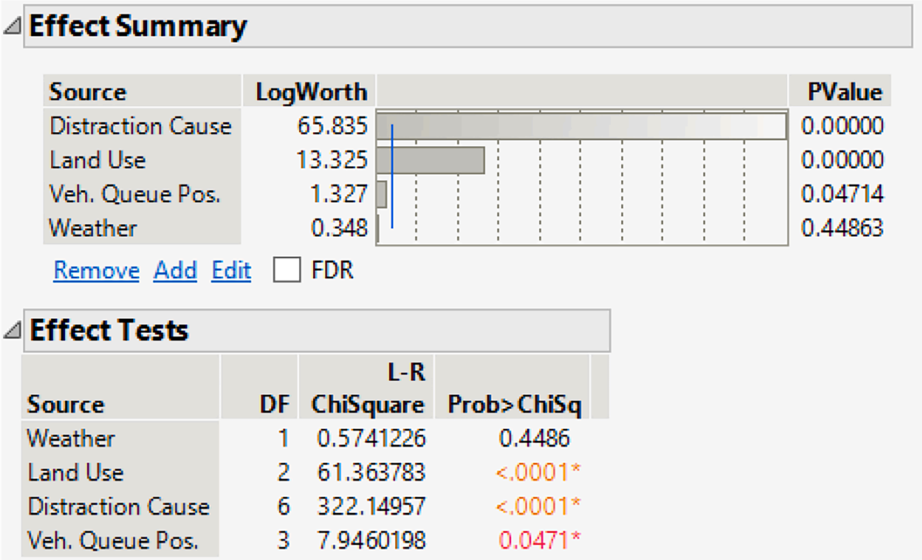
AICc
8783.1832

Fig. 17. Final model-whole model test-MD peak.

in the queue increased from **2.09 s** (Not Distracted) to **2.93 s** (Distracted).

5.2. Effect of distracted driving on intersection capacity

At signalized intersections, capacity for a particular movement is defined by two elements: the maximum rate at which vehicles can



Effect Summary

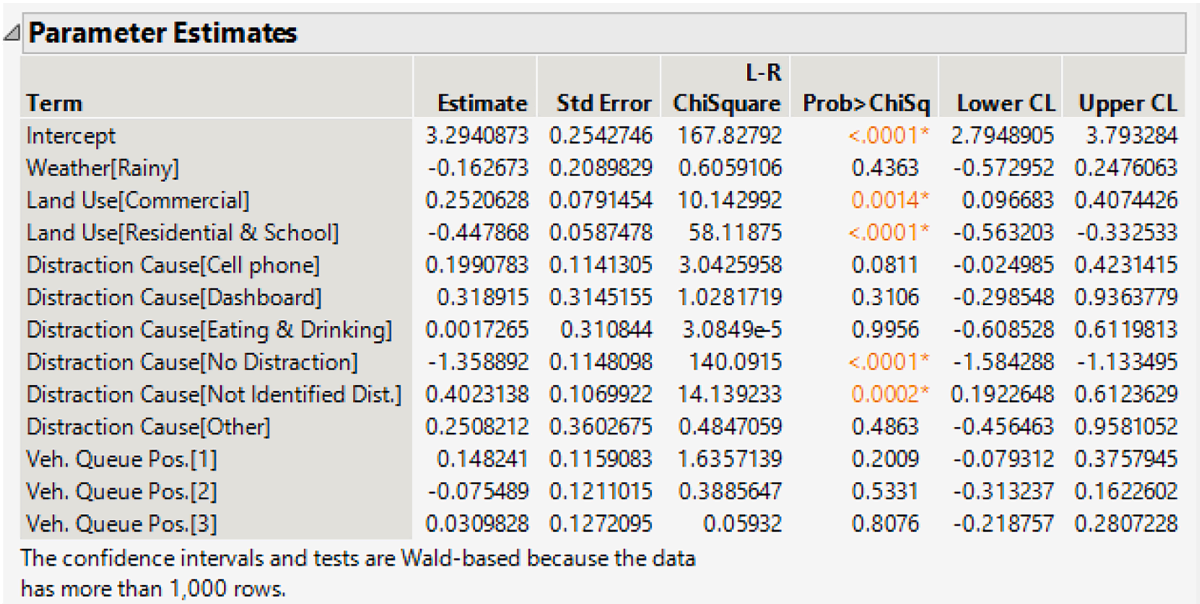
Source	LogWorth	PValue
Distraction Cause	65.835	0.00000
Land Use	13.325	0.00000
Veh. Queue Pos.	1.327	0.04714
Weather	0.348	0.44863

Remove Add Edit FDR

Effect Tests

Source	DF	L-R ChiSquare	Prob>ChiSq
Weather	1	0.5741226	0.4486
Land Use	2	61.363783	<.0001*
Distraction Cause	6	322.14957	<.0001*
Veh. Queue Pos.	3	7.9460198	0.0471*

Fig. 18. Final model-effects summary -MD peak.



Parameter Estimates

Term	Estimate	Std Error	L-R ChiSquare	Prob>ChiSq	Lower CL	Upper CL
Intercept	3.2940873	0.2542746	167.82792	<.0001*	2.7948905	3.793284
Weather[Rainy]	-0.162673	0.2089829	0.6059106	0.4363	-0.572952	0.2476063
Land Use[Commercial]	0.2520628	0.0791454	10.142992	0.0014*	0.096683	0.4074426
Land Use[Residential & School]	-0.447868	0.0587478	58.11875	<.0001*	-0.563203	-0.332533
Distraction Cause[Cell phone]	0.1990783	0.1141305	3.0425958	0.0811	-0.024985	0.4231415
Distraction Cause[Dashboard]	0.318915	0.3145155	1.0281719	0.3106	-0.298548	0.9363779
Distraction Cause[Eating & Drinking]	0.0017265	0.310844	3.0849e-5	0.9956	-0.608528	0.6119813
Distraction Cause[No Distraction]	-1.358892	0.1148098	140.0915	<.0001*	-1.584288	-1.133495
Distraction Cause[Not Identified Dist.]	0.4023138	0.1069922	14.139233	0.0002*	0.1922648	0.6123629
Distraction Cause[Other]	0.2508212	0.3602675	0.4847059	0.4863	-0.456463	0.9581052
Veh. Queue Pos.[1]	0.148241	0.1159083	1.6357139	0.2009	-0.079312	0.3757945
Veh. Queue Pos.[2]	-0.075489	0.1211015	0.3885647	0.5331	-0.313237	0.1622602
Veh. Queue Pos.[3]	0.0309828	0.1272095	0.05932	0.8076	-0.218757	0.2807228

The confidence intervals and tests are Wald-based because the data has more than 1,000 rows.

Fig. 19. Model parameter estimates -MD peak.

pass through a given point in an hour under prevailing conditions (known as saturation flow rate), and the ratio of green time during which vehicles may enter the intersection as shown in equations (2) and (3) (Transportation Research Board (TRB), 2010). Saturation flow rate is simply the headway in seconds between vehicles moving from a queued condition, divided into 3,600 s per hour.

$$c_i = s_i \frac{g_i}{C} \tag{2}$$

$$s_i = \frac{3600}{h} \tag{3}$$

Where, i is the intersection approach lane group,
c is the capacity of the intersection in vehicles per hour per lane (vphpl),
s is the saturation flow rate in vehicles per hour of green per lane (vphgpl),
g is the effective green time interval for the movement in seconds (sec),

Whole Model Test

Model	-LogLikelihood	L-R ChiSquare	DF	Prob>ChiSq
Difference	1169.30024	2338.600	15	<.0001*
Full	16233.5324			
Reduced	17402.8326			

Goodness Of Fit Statistic	ChiSquare	DF	Prob>ChiSq	Overdispersion
Pearson	828.3003	2855	1.0000	0.2901
Deviance	757.9241	2855	1.0000	

AICc
32501.279

Fig. 20. Whole model test-PM peak.

Effect Summary

Source	LogWorth	PValue
Distraction Cause	170.795	0.00000
Land Use	118.194	0.00000
Weather	6.419	0.00000
Veh. Queue Pos.	2.490	0.00324

Remove Add Edit FDR

Effect Tests

Source	DF	L-R ChiSquare	Prob>ChiSq
Weather	2	29.560956	<.0001*
Land Use	3	550.1638	<.0001*
Distraction Cause	7	814.19543	<.0001*
Veh. Queue Pos.	3	13.768516	0.0032*

Fig. 21. Effect summary & tests-PM peak.

C is the intersection cycle length in seconds (sec),

h is the average discharge headway in seconds per vehicle (sec/veh).

To determine the effect of distractions during one of the peak periods (PM Peak) Fig. 23 (c) and (d) show the profile of the marginal model parameters for the distract versus the non-distracted status at the same center points which included sunny weather, residential/school land use, first vehicle in the queue in addition to the distraction status. The average intersection's headway in the non-distracted model was 1.97 s while in the distraction-types model was 2.82 s. Comparing the headway between the two models show that the effect of distractions during the PM peak hour resulted in an increase in headway of approximately 0.85 s or 43% increase. Therefore, translating these values into the intersection's capacity using the above equations, it is concluded that the intersection capacity is reduced during the PM peak hour from 1,827 vphgpl to 1,277 vphgpl (30.1%) which can then be multiplied by the proportion of green time of the cycle length for this specific movement to determine the capacity per cycle.

$s_{\text{non-distracted}} = 3600/1.97 = 1{,}827$ vphgpl.

$s_{\text{cellphone-distraction}} = 3600/2.82 = 1{,}277$ vphgpl.

Reduction in capacity = (1827–1277)/1827*100 = 30.1%.

On the other hand, Fig. 24 (c) shows the parameter estimates for the distraction status model as "non-distracted" with the standard discharge headway of 2.09 s, while Fig. 24 (d) shows the status as "distracted" with discharge headway of 2.93 sec, a 40% increase. Using the above equations, it is concluded that distracted left turning drivers at signalized intersections reduces the intersection

Parameter Estimates

Term	Estimate	Std Error	L-R ChiSquare	Prob>ChiSq	Lower CL	Upper CL
Intercept	3.9710457	0.1033684	1475.8232	<.0001*	3.7683615	4.1737299
Weather[Cloudy]	0.2580356	0.0953127	7.3292247	0.0068*	0.071147	0.4449242
Weather[Rainy]	0.0727137	0.1113284	0.4266004	0.5137	-0.145578	0.2910058
Distraction Cause[Cell phone]	-0.010706	0.0725971	0.0217486	0.8828	-0.153054	0.1316418
Distraction Cause[Dashboard]	0.5231877	0.2449019	4.5638422	0.0327*	0.0429852	1.0033902
Distraction Cause[Eating & Drinking]	-0.29285	0.1757064	2.7778882	0.0956	-0.637374	0.0516744
Distraction Cause[No Distraction]	-1.287768	0.0732534	309.0435	<.0001*	-1.431403	-1.144133
Distraction Cause[Not Identified Dist.]	0.1783125	0.0696134	6.5611176	0.0104*	0.0418149	0.3148101
Distraction Cause[Other]	0.1008644	0.1803519	0.3127768	0.5760	-0.252769	0.4544974
Distraction Cause[Passengers]	0.1823222	0.0834373	4.7748385	0.0289*	0.0187188	0.3459257
Veh. Queue Pos.[1]	0.0918736	0.0454988	4.0773796	0.0435*	0.0026597	0.1810874
Veh. Queue Pos.[2]	-0.016941	0.0472924	0.1283189	0.7202	-0.109672	0.0757898
Veh. Queue Pos.[3]	-0.066625	0.0485991	1.8793724	0.1704	-0.161918	0.0286683
Land Use[Commercial]	-0.012873	0.0401569	0.102757	0.7485	-0.091612	0.0658669
Land Use[Mix Use]	0.7541891	0.0721473	109.2748	<.0001*	0.612723	0.8956553
Land Use[Residential & School]	-0.832016	0.0366352	515.78244	<.0001*	-0.90385	-0.760182

Fig. 22. Parameter estimates-PM peak.

capacity from 1,722 vphgpl to 1,229 vphgpl which is approximately 28.6%.

$s_{\text{non-distracted}} = 3600/2.09 = 1{,}722$ vphgpl.

$s_{\text{cellphone-distraction}} = 3600/2.93 = 1{,}229$ vphgpl.

Reduction in capacity = (1722–1229)/1722*100 = 28.6%.

6. Conclusions

Distracted driving has become an obstacle in achieving an efficient transportation system. Its impacts have been extensively studied in research from the safety point of view. However, the impact on the traffic network efficiency and operations has received less attention. The literature showed that few studies have addressed distracted driving effects for the through movement, but less focus has been given to the left lane movement. This paper addressed this gap by studying distracted left turners at six (6) intersections for more than 47,000 drivers and analyzing 178 recorded hours. The research was conducted using a professional video-editing software that provided high-quality control for the data extraction process. The selected intersections covered different land uses, lane configurations, and periods of high demand. The analysis showed that 87% of the left turners were distracted. Cell phone distractions represented 28% of all distractions. Dashboard usage and talking to passengers' distractions were dominant during the PM peak. Not identified distractions were dominant in all peak periods (48%). Motorists in the first row in the queue were more distracted in the PM peak than in the AM peak. Residential & School land use did not increase the headway, as drivers were more cautious when driving near school zones. In contrast, mixed land use increased the headway, especially in commercial areas. Motorists are usually distracted by the various stores around and searching for their destination, especially in tourist areas.

The statistical models demonstrated that the overall effect of distracted left tuners on the discharge headway at signalized intersections is significant. The TOD analysis showed that the AM peak hour distractions increased from **2.14 s** to **2.99 s (40% increase)**, MD peak hour from **2.30 s** to **3.15 s (37% increase)** and the PM peak hour distractions increased the headway from **1.97 s** to **2.82 s (43% increase).** On the other hand, the overall distraction model results showed that the effect of distraction is significant with an increasing effect of **0.84 s** on the headway. The base headway center points for sunny weather, school land use and first vehicle in the queue increased from **2.09 s** (Not Distracted) to **2.93 s** (Distracted). Thus, distracted drivers in the left turning lanes proved to have a detrimental effect on the headway at signalized intersections and consequently decreased the intersection capacity by up to **30%**.

7. Recommendations

Based on the results of this study, several recommendations can be implemented. As mentioned earlier, the current laws in Florida prohibit the driver from using his/her cell phone while operating the vehicle but allows the use if the vehicle is stationary, such as at stop signs or stoplights. As demonstrated from this research, distractions significantly increased the startup lost time and reduced the intersection capacity. Thus, it is recommended to update the laws to prohibit drivers from using their cell phones while the vehicle is stationary especially at traffic lights. Also, it is recommended to update traffic simulation models at signalized intersections by adding a new parameter that considers additional lost time due to distracted driving. Moreover, it is recommended to increase the standard

Effect Tests			
Source	DF	L-R ChiSquare	Prob>ChiSq
Weather	2	89.377552	<.0001*
Land Use	3	1295.0563	<.0001*
Veh. Queue Pos.	3	9.0213486	0.0290*
TOD	2	59.669875	<.0001*
Distraction Status	1	570.17408	<.0001*

(a) Model Parameters

Parameter Estimates						
Term	Estimate	Std Error	L-R ChiSquare	Prob>ChiSq	Lower CL	Upper CL
Intercept	4.1756692	0.0743193	3156.8103	<.0001*	4.0299629	4.3213754
Weather[Cloudy]	0.3788546	0.0781775	23.484513	<.0001*	0.2255842	0.532125
Weather[Rainy]	0.0967546	0.0930903	1.080275	0.2986	-0.085753	0.2792622
Land Use[Commercial]	0.0738151	0.0403436	3.3476579	0.0673	-0.00528	0.1529104
Land Use[Residential & School]	-1.079384	0.0344926	979.2665	<.0001*	-1.147008	-1.01176
Land Use[Residential/Commercial]	0.8043625	0.0789862	103.70525	<.0001*	0.6495066	0.9592184
Veh. Queue Pos.[1]	-0.055146	0.0447104	1.5212965	0.2174	-0.142803	0.0325104
Veh. Queue Pos.[2]	-0.0403	0.0465086	0.7508195	0.3862	-0.131482	0.0508825
Veh. Queue Pos.[3]	-0.138969	0.0483462	8.2625046	0.0040*	-0.233754	-0.044184
TOD[AM]	0.001765	0.0385261	0.002099	0.9635	-0.073767	0.0772972
TOD[MD]	0.1646087	0.0333605	24.346747	<.0001*	0.0992041	0.2300134
Distraction Status[Distracted]	0.4257513	0.0172501	609.15875	<.0001*	0.3919318	0.4595708

The confidence intervals and tests are Wald-based because the data has more than 1,000 rows.

(b) Parameter Estimates

Fig. 23. Mixed model for the distraction effects by time of day.

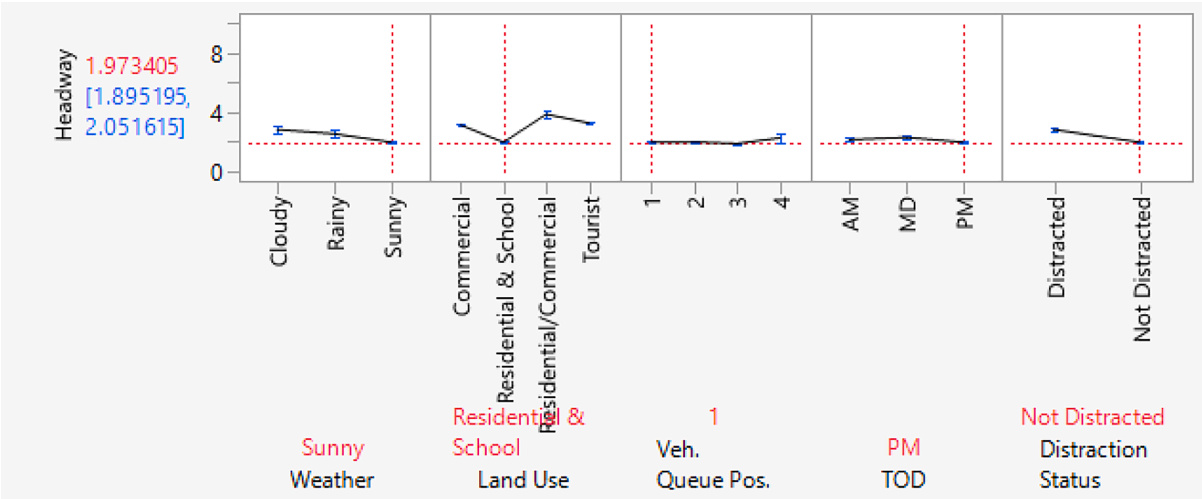
startup lost time from 2 to 2.8 s to consider the effect of distracted left turning drivers on traffic operations in signal timing design.

8. Limitations and opportunities for future research

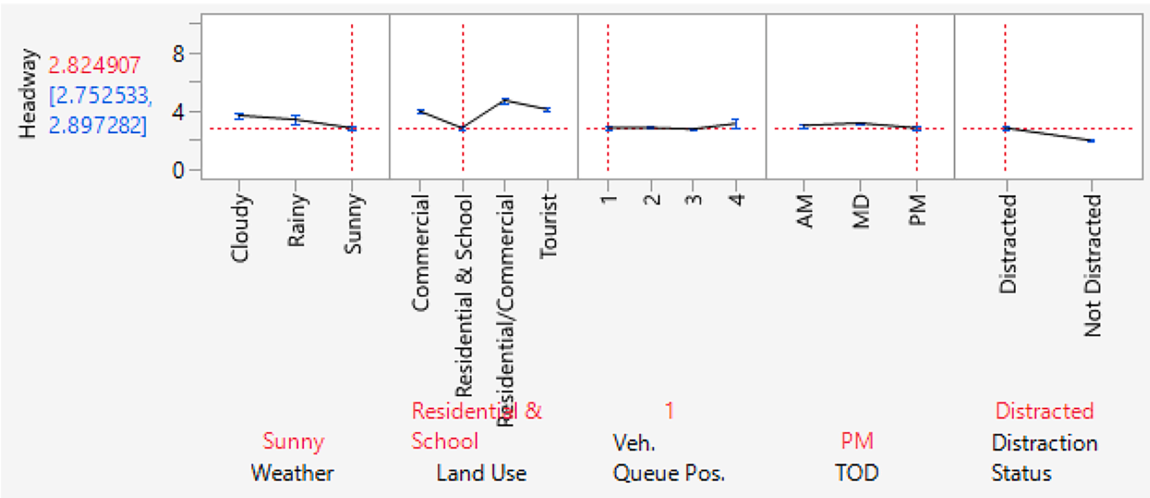
As the intent of the study was to quantify the effect of distracted drivers in the left lanes on the intersection capacity, the variables and data extraction process were prioritized with explicit focus on calculating the saturation headway and start up lost times. Other than the environmental factors such as weather, time of day and surrounding land use, delay factors that affect queueing and level of service (LOS) conditions were not extracted. In particular, the impact of distracted drivers on the intersections' delay and LOS is equally important, however this can be explored in future research. Another limitation of this research is the effect of distracted drivers at signals with permissive left turn phases. The analysis of the left turn movement was considered for single and dual lefts operating in a protected-only mode due to the fact that permissive mode will have a confounding effect with increased headways related to yielding to oncoming traffic and not mere distractions which can be further explored in future research.

Author Statement

This manuscript has not been published and is not under consideration for publication elsewhere. We have no conflicts of interest to disclose.



(c) Distraction Status – Not Distracted (PM Peak Hour)



(d) Distraction Status – Distracted (PM Peak Hour)

Fig. 23. (*continued*).

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Hatem Abou-Senna, Essam Radwan; data collection: Bassel Sherif; analysis and interpretation of results: Hatem Abou-Senna, Bassel Sherif; draft manuscript preparation: Bassel Sherif, Hatem Abou-Senna. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Competing 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.

Data availability

Data will be made available on request.

Effect Tests

Source	DF	L-R ChiSquare	Prob>ChiSq
Weather	2	90.437968	<.0001*
Land Use	3	1235.7516	<.0001*
Veh. Queue Pos.	3	12.642912	0.0055*
Distraction Status	1	550.69279	<.0001*

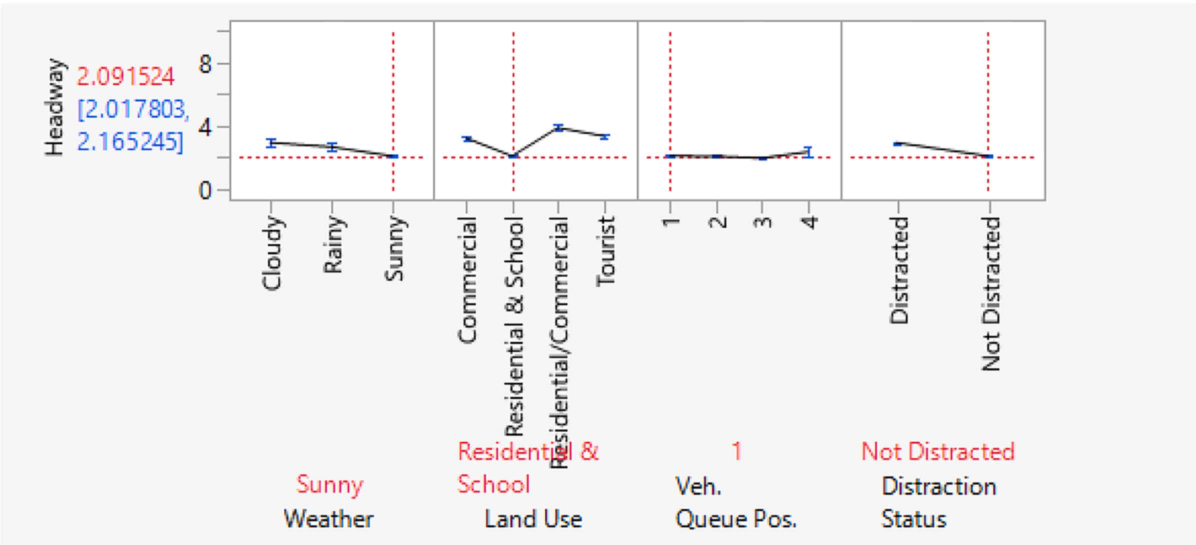
(a) Model Parameters

Parameter Estimates

Term	Estimate	Std Error	L-R ChiSquare	Prob>ChiSq	Lower CL	Upper CL
Intercept	4.0651445	0.0734108	3066.4265	<.0001*	3.9212196	4.2090695
Weather[Cloudy]	0.3785715	0.0786977	23.140436	<.0001*	0.2242813	0.5328618
Weather[Rainy]	0.0994753	0.0938543	1.1233688	0.2892	-0.08453	0.2834806
Land Use[Commercial]	0.0904152	0.039452	5.2522476	0.0219*	0.0130679	0.1677626
Land Use[Residential & School]	-1.04433	0.0344852	917.08553	<.0001*	-1.111939	-0.97672
Land Use[Residential/Commercial]	0.7369332	0.0791662	86.651629	<.0001*	0.5817245	0.892142
Veh. Queue Pos.[1]	-0.02929	0.0449891	0.4238499	0.5150	-0.117493	0.0589134
Veh. Queue Pos.[2]	-0.042847	0.04692	0.8339259	0.3611	-0.134836	0.0491416
Veh. Queue Pos.[3]	-0.157271	0.0487117	10.423877	0.0012*	-0.252772	-0.061769
Distraction Status[Distracted]	0.4219545	0.0174078	587.54899	<.0001*	0.3878258	0.4560832

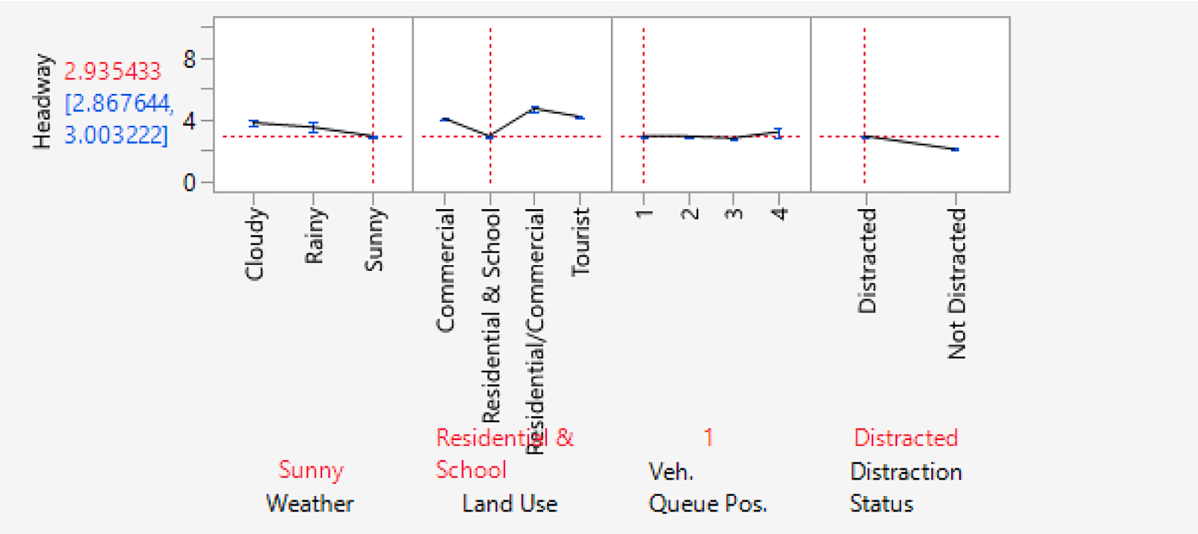
The confidence intervals and tests are Wald-based because the data has more than 1,000 rows.

(b) Parameter Estimates



(c) Distraction Status – Not Distracted

Fig. 24. Mixed model for the overall distraction effects.



(d) Distraction Status - Distracted

Fig. 24. (*continued*).

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