



# Characterizing Technology's Influence on Distractive Behavior at Signalized Intersections

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**ABSTRACT:** Distracted driving existed since the invention of the automobile; however, the emergence of the cell phone and electronic devices created another source of distraction that affected drivers visually, physically, cognitively, and audibly. Many studies investigated factors that influenced saturation flow and startup lost time at a signalized intersection, but the impact of new distractions, such as electronic devices and in-vehicle entertainment systems, remained less investigated. This study aimed to characterize technology's influence on driver behavior at intersections and the impact of distractions on startup lost time through a field test conducted at three intersections in Texas. This study used observational analysis and hypothesis testing to understand distraction behaviors and their impacts on individual and aggregated startup lost time. On average, 15% of drivers experienced distraction during a red indication, and a cell phone distracted

more than 60% of these drivers. However, in vehicles located behind a heavy vehicle at an intersection, 20% of drivers were distracted, and 80% used a cell phone. Statistical analysis showed that distraction caused significantly higher headways and total lost times than non-distraction conditions. More importantly, technology-induced distraction, which created significant intersection delay, was more uncertain and varied from event to event more than non-technology-induced delay. This study showed that technology-induced distractions from the prevalent use of cell phones created an impact on startup lost time and saturation flow, which remained critical to properly determine the phase and cycle lengths.

**KEYWORDS:** Distraction; Intersection; Saturation Flow; Start Up Lost Time; Technology

## 1. INTRODUCTION

State and local agencies placed traffic control devices at intersections to address roadway operations and safety (FHWA, 2013). Properly installed and operated traffic signals played an essential role in achieving optimal performance at an intersection by assigning vehicular and pedestrian rights of way. In urban transportation, the performance of signalized intersections required attention because they represented the primary source of delay for urban roads.

Turning movement counts, saturation flow rate, lost time, and queue length represented essential parameters for planning, designing, and controlling a signalized intersection. These factors and other operating parameters, traffic conditions, roadway parameters, and environmental conditions might influence a signalized intersection's optimal timing and performance (Hadiuzzaman et al., 2008). The Highway Capacity Manual 2016, Australian-based SIDRA software analysis package, the Canadian capacity guide, and the Swedish capacity guide provided methods for estimating intersection performance measures (HCM, 2016; Zhao et al., 2015). According to the Highway Capacity Manual 2010 (HCM, 2010), capacity represented a planning level estimate that incorporated the effect of lost time and typical saturation flow rates. Saturation flow provided the foundation for evaluating intersection performance and determining traffic signal timing. Factors that impacted the saturation flow of a given lane or approach generally included the urban environment, local driver behavior, lane width, turning radius, gradient, pedestrian interference, parking or transit interference, interaction with priority, opposing or adjacent flows, and limited queuing or discharge space (Teply & Jones, 1991). While demand modeling and simulation might provide reasonable

estimates of turning movements and queue length at intersections, factors impacting the saturation flow rate and lost time appeared more uncertain.

While the saturation flow rate characterized the initial capacity of an approach, even a highly congested approach could not achieve this flow rate throughout a green indication. At the initiation of the green phase, the first driver in the queue observed and reacted to the signal change and accelerated through the intersection from a stand-still, which created a relatively long first headway. This process continued until a certain period when the startup reaction and acceleration no longer influenced the headways. Hence, the startup lost time represented the additional time in seconds that the first few vehicles in a queue at a signalized intersection used beyond the saturation headway (Roughail et al., 2001). The factors that affected the startup lost time included vehicle type and road gradient, pedestrians in the intersection, perception-reaction time, which varied from driver to driver, and psychological factors. Under ideal conditions, physiological conditions caused most startup lost time variance; however, any distraction might also significantly impact a driver's perception reaction and response time, which influenced both saturation flow and startup lost time (Çalışkanelli et al., 2017).

Distracted driving emerged at the invention of the automobile. The emergence of the cell phone and especially electronic devices created another source of distraction that could affect a driver visually, physically, cognitively, and audibly (Rahman et al., 2018). Studies found that using a cell phone while driving appeared riskier than any other distracting activity for drivers (Drews et al., 2009). In 2013, the Centers for Disease Control and Prevention reported that about 69% of the United States drivers talked on their cell phone, and 31% emailed or used text messages while driving (CDC, 2013). In 2014, the National Highway Traffic Safety Administration (NHTSA) published a report that focused on the behavioral

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factors of crashes across the nation. This report showed that distracted driving caused 32,999 highway fatalities and 3.9 million injuries and resulted in economic losses of \$46 billion (or  $46 \times 10^9$  dollars) (Blincoe et al., 2014).

Many factors impacted the saturation flow rate and startup lost time at a signalized intersection. Many researchers already investigated the relationships between saturation flow and intersection geometry, such as lane type, peak hour, queue length, and green time (Alembo, 2014; Bivina et al., 2016; Shawky & Al-ghafli, 2016). However, the impact of new distractions, such as electronic devices and in-vehicle entertainment systems, on distracted driving and the startup lost time at intersections remained less investigated. In addition, the Highway Capacity Manual (2016) identified an average control delay of 10 to 15 seconds for a Level of Service B (HCM, 2016). These values derived from historical data without the large variety of electronic distractions available to drivers currently. The emergence of new technology (i.e., smartphones and in-vehicle entertainment systems) might increase driver distraction and delay at traffic signals.

This study aimed to characterize technology's influence on driver behavior at intersections and the impact of distractions on startup lost time. This research conducted a comprehensive literature review to gather state-of-art investigations on driver distraction and startup lost time. Based on the initial findings from the literature, the researchers designed a field test, developed a startup lost time data analysis framework, and performed the field test at three intersections in Arlington and Grand Prairie, Texas. This study also used descriptive analysis and hypothesis testing to understand distraction behaviors and their impacts on individual and aggregated startup lost time at locations with different land use and drivers.

## 2. LITERATURE REVIEW

### 2.1 Saturation Flow Rate and Driver's Response Time

Common measures to evaluate intersection performance included delay, queue length, and cycle failure (Zheng et al., 2013). Saturation flow represented an essential input for optimal signal timing; therefore, a slight variation in saturation flow could significantly change the optimal cycle and phase lengths, which affected the efficiency and operation of an urban street system. As a macro performance measure of intersection operations, saturation flow indicated the potential capacity under ideal operating conditions assuming no heavy vehicles or pedestrians/cyclists and a single movement type (i.e., only straight movement or only turning movement) (HCM, 2016). The HCM (2010) prescribed an ideal saturation flow rate of 1,900 passenger cars per hour per lane, which equated to a saturation headway of about 1.9 seconds per vehicle (HCM, 2010). Startup lost time represented another important parameter in signalized intersection performance. It measured the additional time the first few vehicles consumed in a queue at a signalized intersection above and beyond the saturation headway (FHWA, 2013). The HCM 2010 indicated that the first four vehicles in a queue generally lose two seconds of green time combined to accelerate to their desired speed. However, vehicle type and gradient, pedestrians in the intersection, perception/reaction time (which varies from driver to driver), and psychological factors also affected startup lost time.

### 2.2. Historical drivers' distraction at the intersections

Distracted driving occurred when the presence of an event, activity, object, or person within or outside the car deviated a driver's attention away from the driving task. Driver distraction represented a primary concern for traffic engineers and planners before the availability of technology in per-

sonal vehicles (Stutts et al., 2001). A study in 1965 confirmed that listening to the radio caused driver inattention and distraction, which resulted in prolonged responses during complex maneuvers on the road (Brown, 1965). A study by the National Highway Traffic Safety Administration (NHTSA) in 1997 estimated that 35-50 percent of police-reported crashes at an intersection involved some form of driver's inattention. The inattentions resulted from fatigue, "lost in thoughts", eating or drinking, watching outside objects, talking inside the car with an occupant, and other forms of distraction (Goodman et al., 1999). A study in 2000 suggested that watching an outside object, person, or event (30%), moving any object inside the car or adjusting the radio (15%), and talking to a person in the vehicle (11%) represented the most common driver distractions (Stutts et al., 2001). Choudhury and Velaga (2020) designed a simulated environment to understand the impact of the most common distracted activities - eating and drinking - on drivers' stop and cross decisions at the onset of yellow indication. They used a scenario consisting of six urban signalized intersections and showed up to 12% increase in crossing time and 7% reduction in stopping time compared to non-distracted driving (Choudhary & Velaga, 2020). The proliferation of cellular telephones, vehicle navigation systems, wireless internet capabilities, wireless messaging, and other in-vehicle technology greatly concerned the NHTSA; they expressed concern for traffic safety and performance (Stutts & Hunter, 2003). The impact of communication technologies on distracted driving required further investigation to identify the consequences for traffic operation and safety.

### 2.3. Technology involved distractions and their impact

According to the NHTSA, 3,142 people died in 2019 due to distracted driving, and cell/smart phones caused most of these distractions (NHTSA, 2021). In 2017, around 5.3 percent of drivers used cell phones (either handheld or hands-free) during typical daylight driving times (NHTSA, 2019). A cell phone visually, physically, cognitively, and audibly distracts a driver with or without the hands-free feature. Many researchers reported that call receiving and dialing and texting could increase the chances of decision impairment. Rachel et al. (2019) provided a comprehensive review on distracted driving due to mobile phones, in-built vehicle infotainment systems, and wearable devices, and found that handheld electronic devices distracted drivers more easily than devices that only require voice interactions. The introduction of different social apps increased the use of smartphones during driving maneuvers. Hashash et al. (2019) showed that using or browsing a social media app had the same negative impact as texting on a driver's performance.

Several studies focused on driver performance at intersections when they were engaged with their cell phone in a simulated or controlled environment. Several researchers discovered that drivers using a cell phone had a delayed response to stop at traffic signals (Beede & Kass, 2006; Irwin et al., 2015; Papantoniou et al., 2016; Strayer & Johnston, 2001). A study comparing drunk drivers and drivers using their cell phone (Strayer et al., 2006) found that drivers using their cell phone had slower reaction time and were more likely involved in crashes. Consiglio et al. (2003) found that drivers increased their reaction time by 72 milliseconds when using a cell phone. Haque and Washington (2014) also confirmed that reaction time at an intersection rises by 40% when a driver used a cell phone.

Only a few previous research studies investigated the impact of technology-induced distracted driving using a field investigation that could more accurately capture the impacts on technology-induced distraction in real-life environment. Brumfield and Pulugurtha (2011) conducted a field inves-

tigation at four intersections in Charlotte, North Carolina, and found 54% higher startup loss times when drivers text. A recent study by Alshabibi (2021) investigated the impact of cell phones at 24 signalized intersections in Saudi Arabia and confirmed a significant increase of startup loss time of 0.7 seconds. Moreover, Huth et al. (2015) showed that most distractions were initiated at a red indication, and half of the drivers used their phones even before completely stopping at the intersection.

Driver distraction represented a significant concern for most transportation authorities and represented a focus of US state governments since 2007 when Washington banned texting (GHSA, 2020). Technology's role in causing distracted behaviors might become more important with the advancements in technology within vehicles due to their uncertain but substantial impacts. .

### 3. DATA COLLECTION AND DATA PROCESSING

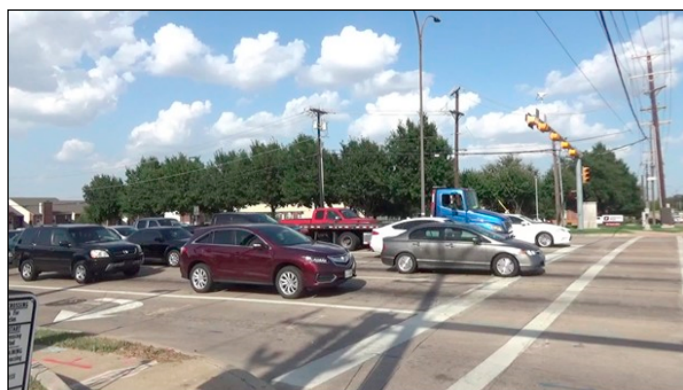
This study selected three data collection sites in Arlington and Grand Prairie, Texas as shown in Table 1. The first and second sites represented a mixed land-use area (commercial and residential) with high intensity and high traffic volumes (i.e., long traffic queue and volume/capacity ratio). The third site, South Belt Line Road, represented an industrial area and observed a high truck or heavy vehicle volume of about 11.4%. Heavy vehicles were defined as FHWA (Federal Highway Administration) Truck Class 8 and above in the US, weighing over 4.5 tons (Koonce et al., 2008). The study collected vehicle data using a Sony Camcorder and tripod from three through lanes on one approach at each site during the afternoon peak period (4 pm-6 pm). Two camcorders recorded vehicle queues and signal indications for data collection, and three observers recorded driver distractions, as shown in Figure 2. The camera angle captured the moment that a vehicle bumper crosses the stop bar on the three through lanes as shown in Figure 1. This process ensured that the research team could calculate vehicle headways crossing the stop bar when post-processing the videos.

This study used the 'Visual-Manual on NHTSA Driver Distraction Guidelines for In-Vehicle Electronic Devices' published by NHTSA (NHTSA, 2012) to develop a data collection plan and train observers. Before beginning the actual data collection, the researchers trained three observers using the NHTSA guidelines and conducted a trial data collection at a similar intersection. During the trial data collection, the observers identified distracted drivers for the first three vehicles in a queue and the type of distraction. The observers cross-validated their data to evaluate whether all the observers reported the same distracted behaviors. This repeatability test showed 86 percent matching rate (repeatability) in

detecting the same distraction type and 97 percent matching rate in detecting a distraction.

During the actual study, the first person observed the first and second vehicles of the queue for the three through (main) lanes, and the second observer covered the third and fourth vehicles in the queue while the third person observed the remaining vehicles in the queue (if any). The observers recorded (i) the types of distraction behavior during a red phase and (ii) whether the distraction persisted into a green phase. To mark the driver's location for later identification, the observer marked the car's location, color, and type. If the distraction recorded during the red interval persisted after the signal turned green, the observers added another mark to the observation sheet to document if this distraction resulted in extra startup delay. The study included six types of distractions – using technology such as cell phones or other electronics, eating or drinking, talking to a passenger, handling objects in the vehicle, grooming, and watching outside person. The cell phone or other electronics included hand-held and hand free devices and other activities such as using stand-alone navigation devices and changing radio stations. This study focused on through lanes only to isolate the impact of distraction from any exogenous factors such as traffic or extra decision-making time by drivers. For example, due to crossing or intersecting traffic movements, vehicles in the right turn lane must determine when to turn and ensure their safe movement, which can cause delays unrelated to distractions. The researchers did not collect any identifiable images (i.e., the face of drivers or passengers, license plate, etc.) to protect drivers' privacy rights. The study also stored video and pictures on password-protected encrypted hard drives supported by the university.

Previous studies adopted three different data collection/analysis methods; these included manual observation (Alshabibi, 2021; Huth et al., 2015), video playback (Roy and Saha, 2017) and image conversion or processing using a software (Hurwitz et.al., 2013, Brumfield and Pulugurtha, 2011; Shawky et al., 2017) to calculate time headway between vehicles. Several researchers pointed out that using video footage to identify time headway between vehicles was cumbersome and prone to miscalculation (Brumfield and Pulugurtha, 2011; Shawky et al., 2017) since discerning milliseconds in the footage represented a challenge. Therefore, the study used open-source software, 'video to jpg', to generate still images from videos to reduce human error in reading timestamp from videos. The software generated 29 frames per second from the video. The team converted the video into images for every frame, which produced an image every 34.48 milliseconds. The team only kept the images that capture the moment when the front bumper of each vehicle passed the stop line.



a) Matlock road



b) Pioneer pkwy

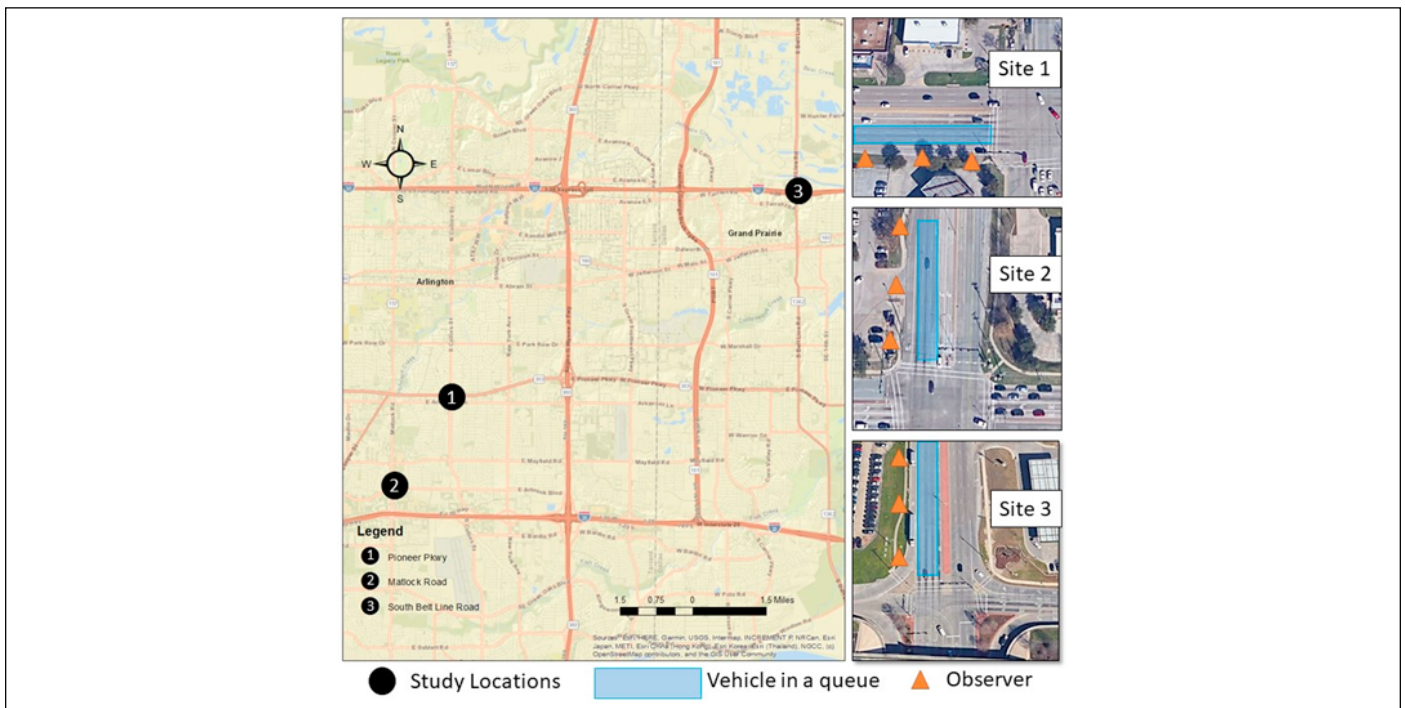
**Figure 1: Camera Set-up at Matlock and Pioneer**



Site No	Location	Intersection geography	Land use context	AADT* (year=2019)	Heavy Vehicle Percentage
Site 1	Pioneer Pkwy	<ul style="list-style-type: none"> <li>• Total 6 Lanes</li> <li>• 3 through lanes</li> <li>• 2 left lane</li> <li>• 1 right lane</li> </ul>	Mixed: commercial and residential	18,674	2.6%
Site 2	Matlock Road	<ul style="list-style-type: none"> <li>• Total 6 Lanes</li> <li>• 3 through lanes</li> <li>• 2 left lane</li> <li>• 1 right lane</li> </ul>	Mixed: commercial and residential	17,583	1.7%
Site 3	South Belt Line Rd	<ul style="list-style-type: none"> <li>• Total 5 Lanes</li> <li>• 3 through lane</li> <li>• 1 left lane</li> <li>• 1 right lane</li> </ul>	Industrial	29,381	11.4%

\* Annual average daily traffic data of year 2019 was collected from Statewide Traffic Analysis and Reporting System by Texas Department of Transportation (TxDOT, 2019)

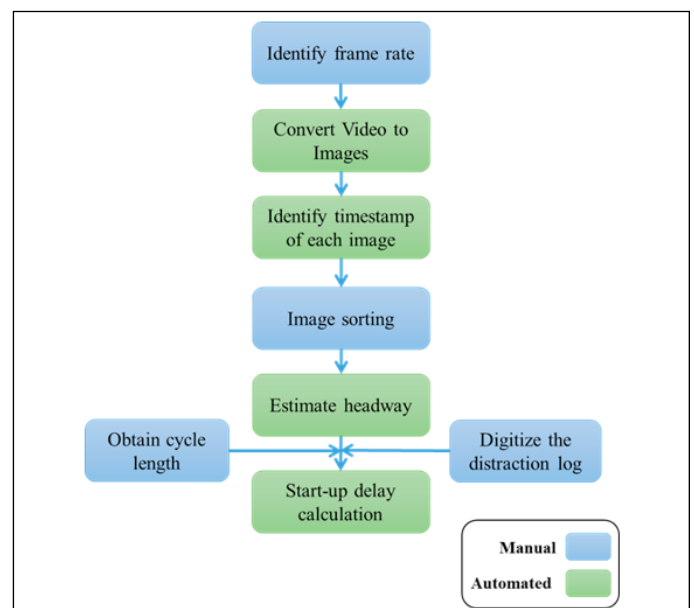
**Table 1. Study Location Description (Source: Texas Department of Transportation Statewide Mapping and Traffic Count Data)**



**Figure 2: Data Collection Location**

Then, the research team used R-programming to assign the timestamp of individual vehicles as a file name (e.g., an image taken at 12:00:0034 on April 4th at Matlock recorded as M10412\_120000034), and the programming read the file names to calculate the headway between vehicles. These automated processes helped the research team compute the start-up lost time quickly and accurately without repeatedly playing back videos. The analysis considered the images of the first nine vehicles in a queue.

The observers also identified the distracted drivers recorded in the field based on the timestamp of the images. Overall, the researchers processed 17 hours of video that converted and sorted almost 8,000 images capturing the moment vehicles passed the stop line. Field observers recorded 1,350 distraction behaviors at the study sites during 371 signal cycles. This study noted that not distracted drivers could be impacted by a distracted driver located in front of them in the queue. For example, a driver distraction in the 3rd position in the queue included drivers at the 4th and later queue positions to assess the impact of this distracted driver. Figure 3 showed the entire data processing and data analysis procedure.



**Figure 3: Data processing and data analysis procedure**

#### 4. DISTRACTED BEHAVIORS AND STARTUP LOST TIME

At least 13 percent of drivers appeared distracted while waiting during a red indication in this study; however, this distraction rate remained closer to 20 percent for the Pioneer and Matlock locations, as shown in Table 2. Among those distracted during the red indication, more than 25% remained distracted during the green indication and contributed to distraction delay at the signalized intersection. The total distraction during the green indication ranged between 5 and 7% at these three sites.

##### 4.1 Descriptive Analysis of Startup Lost Time

This study assessed the headways for the first nine vehicle positions to calculate the saturation flow. As previous literature suggested (HCM, 2010), this study estimated the saturation headway using the vehicles located at the 5th position and after in the queue without any distracted drivers. The average saturation headways for Pioneer, Matlock, and South Belt Line sites showed 1939, 2143, and 2143 milliseconds, respectively.

Startup lost time represented the additional headway of the first four vehicles in the queue. As shown in Figure 4, the average startup lost times for Pioneer, Matlock, and South Belt Line intersections without distracted drivers in the queue were 3083, 2213, and 2730 milliseconds, respectively. However, a distracted driver in the queue increased the mean lost time by about 600 to 950 milliseconds, and the standard deviation by about 300 to 550 milliseconds. South Belt Line showed a few excessive startup lost time values because the heavy vehicles present at this location caused extra startup loss time due to their slow acceleration.

To illustrate the differences in headways along the queue, this study analyzed and compared the individual vehicles'

startup lost time behind a distracted driver using one set of queues at three study intersections. Figure 5 illustrated a graphical representation of distraction scenarios and the observed startup lost time of the corresponding vehicles in the graphic. For example, a first red vehicle in the queue indicated a distracted driver. This distracted driver may cause additional delay for the drivers of the blue vehicles in a box because they started behind the distracted driver in the queue. Drivers of the blue vehicles without a box represented the undistracted drivers who remained unaffected by the distracted driver since they started in front of the distracted driver in the queue. Table 3 showed the impact results for trailing drivers due to distraction for all three intersections. A distracted driver in the first queue position created an average startup lost time of 1,417 ms. Undistracted drivers behind these distracted drivers in the first queue position showed an average startup lost time of 1,462 ms at Pioneer. The drivers at positions 3 and 4 in the queue (two and three behind the distracted drivers) showed an average startup loss time of 1,023 ms and 269 ms, higher than the average startup loss time of non-distracted drivers (533 ms and 258 ms for these positions). A driver behind a distracted driver in the second queue position experienced an average start-up lost time of 1,046 ms (513 ms greater than average non-distracted cases) at Pioneer. These results demonstrated that in many cases the driver behind a distracted driver showed an increase in startup lost time.

Moreover, the impact appeared to propagate along the queue and affected drivers far from the distracted driver. Similar patterns appeared for the rest of the positions, and a distraction at position 2 in the queue increased the startup lost time up to position five or more. Similarly, at South Belt Line, a distracted driver in the first queue position driver (startup loss time of 2427 ms) affected the drivers in the fourth and fifth queue positions affected since their headways (366ms

	Number of Cycles	Number of Vehicles observed	Number of distractions during red indications	Number of distractions during red indications persisting to green indication
<b>Site 1: Pioneer Pkwy</b>	98	1,876	419 (22% of Total)	103 (5% of total) (25% of total red)
<b>Site 2: Matlock Road</b>	131	2,960	555 (19% of Total)	200 (7% of total) (35% of total red)
<b>Site 3: South Belt Line Rd</b>	142	2,995	363 (12% of Total)	154 (5% of total) (42% of total red)

Table 2 Data Observed at Study Sites

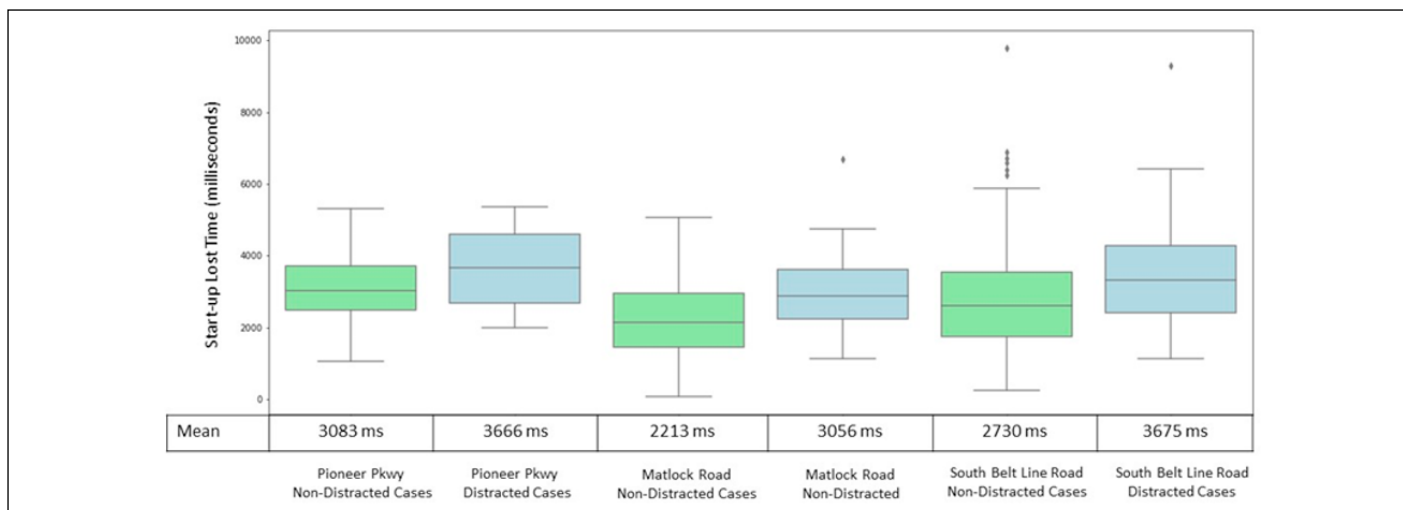


Figure 4: Start-up Lost Time

and 139ms) remained much higher than the drivers at the same positions without any distracted drivers in front of them (Table 3). At Matlock, even though not all vehicle positions showed similar headways to the other two intersections, drivers behind a distracted driver at positions two and four showed higher lost time than non-distracted drivers. These results indicated that the slow response of a distracted driver to a green indication affected the drivers behind them and increased their headways.

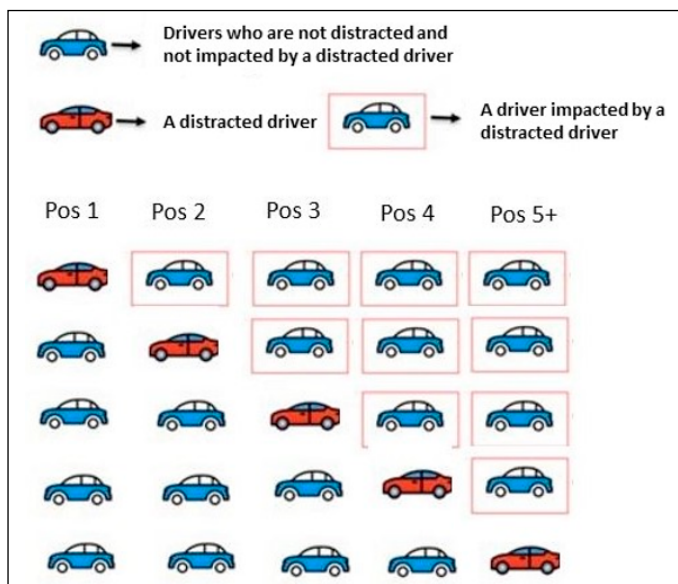


Figure 5 Impacts of distraction along the queue

#### 4.2 Statistical Analysis of Startup Lost Time

The study conducted two statistical analyses using t and F tests. The first analysis considered the increase in startup lost time due to distractive behavior, while the second analysis investigated a distraction's effect on the overall queue for distracted drivers in the first to the fourth position in the queue. This study also focused on distraction location and evaluated its role in increasing startup lost time. The t and F tests assumed the following hypotheses:

*t-test*

$$H_0 : \mu_1 \leq \mu_2$$

$$H_1 : \mu_1 > \mu_2$$

Where  $\mu_1$  = average headway for distracted cases;  $\mu_2$  = average headway for non-distracted cases

*F-test*

$$H_0 : \sigma_1 \leq \sigma_2$$

$$H_1 : \sigma_1 > \sigma_2$$

Where  $\sigma_1$  = standard deviation for distracted cases;  $\sigma_2$  = standard deviation for non-distracted cases

Table 4 showed the lost time analysis for the individual queue positions. The results compared the total sample size, descriptive statistics, t-test, and F test between the distraction and no distraction cases. The startup lost time was significantly higher for distracted drivers regardless of site location or vehicle position and had values as high as 1,570 ms. Either the first (Matlock and South Belt Line) or the second (Pioneer) driver in the queue displayed the highest distracted induced lost time. Statistical tests demonstrated that distracted drivers always showed higher lost time at a 90% confidence. The tests indicated that the distracted behaviors, even during a red indication, likely caused significant impacts on drivers' awareness and responses for all queue positions. The F-test confirmed that distracted cases showed a significantly higher standard deviation of the startup lost time except for position one at sites 1 and 2. This result might indicate that the increase in lost time in the first position experienced less variability even though the rise in the mean lost time remained significant.

The second analysis investigated the impacts of a single driver's distracted behavior on the entire queue. Table 5 displayed the aggregated startup lost times grouped by the distracted driver's position. For example, a case of vehicles 1 to 4 represented the aggregated startup lost time for the first four vehicles in the queue where the first driver was distracted, and the following three vehicles were affected by distraction. Similarly, a case of vehicles 2 to 4 indicated the aggregated startup lost time for these three vehicles where the second driver in the queue was distracted. In this case, the first vehicle in the queue was not used for the analysis since the distraction of the second driver did not affect the first vehicle. No distraction cases indicated that all drivers in the queue were not distracted. All nine cases showed that the aggregated lost times were significantly higher with a distracted driver at a 90% confidence level. The F test also showed higher standard deviations for the distracted cases at a 90% confidence level for all the locations. This result clearly described that a distracted driver, regardless of its location in the queue, significantly increased the total delay and delay variance.

#### 4.3 Distraction Types and Impacts

Figure 6 presented the proportions of the six different distraction types (1. Using technology such as a smartphone; 2. eating or drinking; 3. talking to a passenger; 4. handling objects inside the car; 5. grooming and 6. watching outside person) observed during a red indication at intersections by lane where the first lane referred to the rightmost lane. Technology-based distractions, such as cell phones and navigation, represented the most distractive behaviors in all three locations. Talking to other people in the car represented the second-most frequently observed (9% -15%) distraction while waiting in the queue. Eating or drinking occurred the third most frequently and ranged from 3% to 17%. These categorized patterns also showed that the lane position (inner or outer lane) had little to do with the distraction pattern; how-

Position	Site 1: Pioneer Pkwy					Site 2: Matlock Road					Site 3: South Belt Line Road				
	1	2	3	4	5+	1	2	3	4	5+	1	2	3	4	5+
1	1417	1462	1023	269	332	1584	742	296	524	131	2427	1189	505	366	139
2		1883	1046	403	355		1477	554	51	63		1596	505	285	67
3			1311	443	179			930	8	194			1176	356	100
4				952	549				765	68				1196	229
5					818					570					818
No Distraction	1066	1218	533	258	0	807	950	350	153	0	857	1096	466	184	0

Table 3: Start up lost time behind a distracted driver along the queue for all three intersections

		Site 1: Pioneer Pkwy		Site 2: Matlock Road		Site 3: South Belt Line Road	
Position Lost Time							
Vehicle Position	Stats	Distraction	No distraction	Distraction	No distraction	Distraction	No distraction
Position 1	Sample Size (N)	10	230	17	305	18	299
	S.D ( $\sigma$ )	$\sigma_1$ =719	$\sigma_2$ = 666	$\sigma_1$ = 750	$\sigma_2$ = 691	$\sigma_1$ =2099	$\sigma_2$ =728
	Mean ( $\mu$ )	$\mu_1$ = 1417	$\mu_2$ = 1065	$\mu_1$ = 1584	$\mu_2$ = 807	$\mu_1$ = 2427	$\mu_2$ = 857
	T test for different sample means						
	P value	0.08008*		0.00029**		0.00284**	
	F Test for different sample standard deviations						
	P value	0.31682		0.28307		0.00000**	
Position 2	Sample Size (N)	23	216	22	328	26	332
	S.D ( $\sigma$ )	$\sigma_1$ = 892	$\sigma_2$ = 454	$\sigma_1$ = 869	$\sigma_2$ = 654	$\sigma_1$ = 961	$\sigma_2$ = 668
	Mean ( $\mu$ )	$\mu_1$ = 1883	$\mu_2$ = 1218	$\mu_1$ = 1477	$\mu_2$ = 950	$\mu_1$ = 1596	$\mu_2$ =1096
	T test for different sample means						
	P value	0.00091**		0.00513**		0.0074**	
	F Test for different sample standard deviations						
	P value	0.00000**		0.02151**		0.00231**	
Position 3	Sample Size (N)	24	198	21	310	21	292
	S.D ( $\sigma$ )	$\sigma_1$ = 663	$\sigma_2$ = 481	$\sigma_1$ = 984	$\sigma_2$ = 511	$\sigma_1$ =1049	$\sigma_2$ =613
	Mean ( $\mu$ )	$\mu_1$ = 1311	$\mu_2$ = 533	$\mu_1$ = 930	$\mu_2$ = 350	$\mu_1$ =1176	$\mu_2$ =466
	T test for different sample means						
	P value	0.00000**		0.00704**		0.00296**	
	F Test for different sample standard deviations						
	P value	0.01002**		0.00000**		0.00004**	
Position 4	Sample Size (N)	15	162	40	282	7	269
	S.D ( $\sigma$ )	$\sigma_1$ = 624	$\sigma_2$ = 463	$\sigma_1$ = 1168	$\sigma_2$ = 537	$\sigma_1$ = 297	$\sigma_2$ = 609
	Mean ( $\mu$ )	$\mu_1$ = 952	$\mu_2$ = 258	$\mu_1$ = 765	$\mu_2$ = 153	$\mu_1$ = 1196	$\mu_2$ = 184
	T test for different sample means						
	P value	0.00039**		0.00111**		0.00003**	
	F Test for different sample standard deviations						
	P value	0.03988**		0.00000**		0.23753	

\*\*significant at  $p<0.05$ ; \*significant at  $p<0.1$

Table 4 Lost Time Analysis for the First Four Positions in the Queue

		Site1: Pioneer Pkwy		Site2: Matlock Road		Site3: South Belt Line Road	
Aggregated Lost Time							
Types	Stats	Distraction	No distraction	Distraction	No distraction	Distraction	No distraction
Vehicle 1-4	Sample Size (N)	14	118	17	218	16	278
	S.D (σ)	σ1=1129	σ2= 883	σ1=1342	σ2=1057	σ1= 1960	σ2= 1384
	Mean (μ)	μ1=3666	μ2=3083	μ1=3056	μ2= 2213	μ1= 3675	μ2= 2730
	T test for different sample means						
	P value	0.04071**		0.00904**		0.03495**	
	F Test for different Sample standard deviations						
P value	0.08535*		0.06738*		0.01506**		
Vehicle 2-4	Sample Size (N)	21	117	22	218	21	271
	S.D (σ)	σ1= 1412	σ2= 743	σ1= 1216	σ2= 904	σ1=1442	σ2= 1083
	Mean (μ)	μ1= 3394	μ2=2062	μ1= 2145	μ2= 1313	μ1=2257	μ2=1825
	T test for different sample means						
	P value	0.00018**		0.00239**		0.09617*	
	F Test for different Sample standard deviations						
P Value	0.00000**		0.01916**		0.02342**		
Vehicle 3-4	Sample Size (N)	24	117	21	218	19	271
	S.D (σ)	σ1= 767	σ2= 614	σ1= 1244	σ2= 721	σ1=1197	σ2=831
	Mean (μ)	μ1= 1752	μ2= 845	μ1= 1185	μ2= 486	μ1= 1408	μ2=695
	T test for different sample means						
	P Value	0.00000**		0.00968**		0.00978**	
	F Test for different Sample standard deviations						
P Value	0.06493*		0.00004**		0.00716**		

\*\*significant at  $p<0.05$ ; \*significant at  $p<0.1$

Table 5 Aggregated Start-up Lost Time



ever, lane one experienced greater distractions from outside persons or objects than other lanes, mostly because of its proximity to sidewalks and pedestrians.

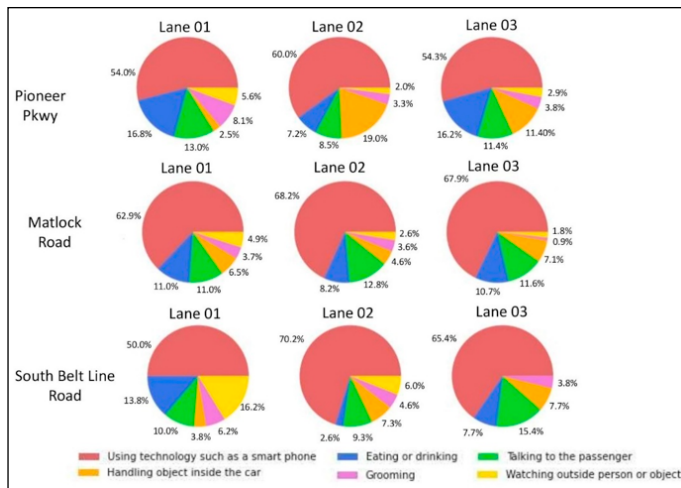


Figure 6: Distraction Proportion in Different Lanes

Figure 7 compared the headway distributions of distracted drivers observed from the study sites. This study used the most commonly observed distraction types, including using technology, eating or drinking, talking to a passenger, and non-distracted cases for comparisons. The headway distributions of handling objects in a car, grooming, and watching outside person were not included in the analysis as they had very few observations compared to the other three types of distraction. In general, drivers engaging with technology showed higher average headways while the drivers who talked to other passengers showed a higher variance of headway based on a wider interquartile distribution of the boxplot. Interestingly, technology-related distraction showed many outliers outside the interquartile range between 5000 to 9000 milliseconds. This indicated that technology distraction might affect startup delay and possibly cause unusually higher delays. Some outliers occurred for the no distraction cases, but these outliers resulted from the heavy vehicles at South Belt Line Road, which might create larger headways due to slow accelerations.

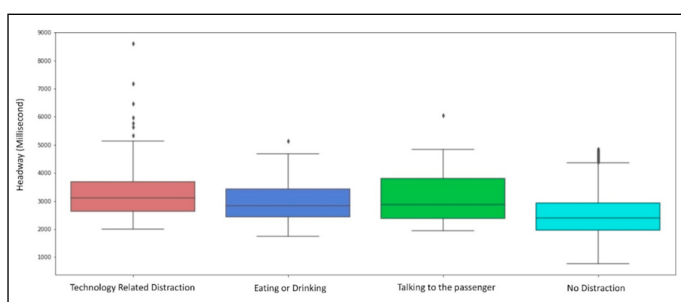


Figure 7: Headway Distributions of the Most Common Distractive Behaviors

This study used the South Belt Line location to investigate the effect on distraction behaviors behind a heavy vehicle in a queue. A driver in a passenger car right behind a heavy vehicle showed more distracted behavior. On average, 14% of drivers showed distracted behaviors behind a passenger car; however, the distraction increased to 20% for a vehicle behind a heavy vehicle. This study found only two types of distractions at this location, including using technology and talking to passengers for the driver's behind a heavy vehicle. Over 85% of these drivers appeared to use their cell phones or electronic devices (Figure 8). However, this result might not reflect the whole population of distraction types because the limited data

collection within the study only noted two distraction types at one intersection (South Belt Line Road).

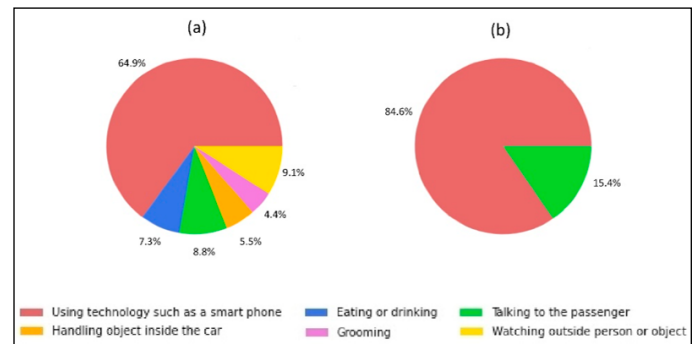


Figure 8: Distraction Proportion at South Belt Line Road (a) with no heavy vehicle in front of the driver, (b) driver is waiting behind a heavy vehicle in the queue

## 5. DISCUSSION AND FUTURE RESEARCH

Signal designers sought to maximize the capacity of intersections by identifying an optimum cycle length and phase timing, since the percentage of effective green time and saturation flow rate determined the capacity of signalized intersections (HCM, 2010). Traffic engineers largely adopted a standard startup lost time in their signal design like two seconds (HCM, 2010), and most practical guidelines did not factor in drivers' distraction to estimate start up delay. Most US cities recognized distracted driving as a significant cause of low performance at signalized intersections (Tefft, 2018). Although the startup lost time might not significantly differ from practitioner assumptions, this research clarified that distraction could be considered when designing signal timing plans and should be considered when evaluating the benefits of retiming signals since distraction might prevent achieving the modeled values. This appeared particularly important when determining the green band for a corridor because the higher variance in delays would make the green bandwidth more stochastic. This study conducted data collection at three intersections in Texas and performed statistical analysis to understand the types of distractive behaviors and their effects on saturation flow and startup lost time at an intersection. While two seconds represented the typically assumed startup lost time under ideal condition, this study observed three seconds of startup lost time on average and as high as 6.6 seconds. This study showed that distraction clearly affected the intersection's lost time and saturation flow. The results indicated that, on average, 15% of drivers were distracted during a red indication, and more than 60% of these drivers were distracted due to a cell phone. Statistical analysis showed that distraction caused significantly higher headway and total lost time than non-distraction conditions, which clearly affected saturation flow rates and intersection capacity. The study also found that drivers behind a heavy vehicle in the queue experienced distraction more often than drivers behind another passenger vehicle. The result showed that people behind a truck tend to have more cell phone-related distractions (85%) than a driver who sits behind a car (50-65%). This did not conclusively showed that drivers used cell phones more when they waited behind a truck because of limited data, but these drivers might use their phones more often when their view was blocked by heavy vehicles.

This study showed that the distraction type varied by vehicle location in the queue. The level and the depth of impacts also varied by the distraction types. Therefore, understanding the frequency and effect on lost time and intersection capacity by distraction type appeared critical to properly calibrate the phase timing and maximize operational efficiency. The



technology-induced delay showed a higher standard deviation, which implied technology-induced delay varied from case to case more than non-technology-induced delay. Distracted drivers might continue to increase in the future as technology such as cell phones and in-vehicle entertainment continue to evolve.

A few limitations in the study design and data collection existed. The visual inspection involved a few limitations, such as the presence of heavy vehicles, which impeded the view of the adjacent vehicle, and tinted windows, which made observations of the drivers' behavior difficult. The raised elevation of the truck seating position could be challenging for observers to identify driver distractions. However, the observers saw most of the distracted behaviors of truck drivers because most of the trucks used the leftmost through lane. The sufficient distance between the trucks and the observers allowed the observers to see the truck drivers' distracted behaviors. Apart from this, the observer location on the right side of the street made discerning the drivers' actions on the innermost lane difficult. The study's observers and cameras might have induced driver distraction. The research team installed the cameras close to a traffic pole or in a nearby shaded area to not attract attention from drivers. Based on these findings, this study made some recommendations for future research.

1. Data collection required careful implementation to cover all approaches at the intersection (i.e., left lane and two-lane approach) to understand the distraction behaviors and their impacts on different approaches. This analysis would help understand how distracting behaviors impact the overall intersection capacities for different intersection types.
2. Technology distraction caused higher startup lost time. More importantly, technology distraction showed high variations in startup lost time. Future studies should investigate the impacts of uncertainty and high variance of startup lost time, particularly from technology distraction, on intersection efficiency and performance measures.
3. This study also recommended additional analysis to understand the impacts on platoon dispersion and progression. The team found that distraction caused longer delay and startup lost time, which might affect downstream intersections. This study recommended a corridor-level data collection and analysis to investigate whether the green band decreased when considering progression through multiple intersections and other network-level delay impacts. We also recommended investigating differences for fixed and actuated signal timing.
4. Heavy vehicles significantly impacted distractive behaviors. This study recommended collecting more heavy vehicle data to characterize their impact on distraction type and frequency and startup lost time.
5. Distracted drivers in an intersection queue might result in safety and environmental impacts that require further study because startup delays also impacted vehicle emissions. Emissions from motor vehicles contributed to ground-level ozone and other toxic gases, which triggered many health problems. Previous studies also found that hard accelerations due to distraction could contribute to higher emissions.

Driver distractions appeared likely to increase as companies created more new technologies in the future; therefore, increasing education and awareness about the negative impacts of using electronic devices while driving appears critical. A good example would be educating children from an early age so that future generations became more aware of the impacts of distraction. Government agencies could im-

pose stricter laws and develop public awareness campaigns about technology-induced distractions.

## AUTHOR CONTRIBUTIONS

The authors confirmed contribution to the paper as follows: study conception and design: Hyun, Mattingly; data collection: Boni; analysis and interpretation of results: Boni, Hyun, Mattingly; draft manuscript preparation: All authors. All authors reviewed the results and approved the final version of the manuscript. The author confirmed sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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