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Acceleration of Left Turning Heavy Trucks

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Abstract

Accidents involving heavy trucks turning left across travel lanes of a roadway are common subjects of investigation in the field of accident reconstruction. The distance traversed during a turn and lateral and tangential accelerations of the left turning heavy truck can be used to model its motion and determine timing as it relates to a collision. As a follow up to the 2019 SAE Accident Reconstruction section paper by the authors (2019-01-0411), this paper will investigate the longitudinal and lateral accelerations of heavy trucks during small, medium, and large radius turns and analyze peak and average lateral accelerations as they relate to turn radius and vehicle speeds. This study analyzed 70 tractor-trailers, 19 straight trucks and 15 bobtail tractors for a total of 104 heavy trucks. The tractor-trailers had various trailer configurations ranging from flat bed, box and tanker, while the straight trucks are defined as non-articulated heavy trucks with various body configurations such as box, garbage, and cement trucks.

Introduction

This paper intends to expand upon the heavy truck acceleration analysis presented in 2019 written by these authors, which analyzed available heavy truck acceleration testing results and developed a two-phase acceleration model for various configurations of tractor-trailers for use in accident reconstruction [1]. The two-phase acceleration model for heavy trucks was based primarily on data collected during straight line acceleration testing, as this type of testing was performed and published extensively over the years in SAE technical papers [2,3,4,5,6,7,8]. The model presented in the 2019 paper utilized two phases of steady state acceleration from a stop of heavy trucks: one phase of 3-4 seconds at the start of higher acceleration, followed by a second phase of 8-9 seconds of lower acceleration. This model included several breakdowns of different configurations of heavy trucks, including tractors with and without trailers, automated or manual transmissions, and whether the trailers were empty, half-loaded, or fully loaded, as this detailed information was provided in the reviewed acceleration testing publications. An accident reconstructionist can utilize information from an accident-involved heavy truck to determine the specific acceleration ranges for the two phases of acceleration from a stop in order to analyze time-space relationships in an accident.

The two-phase acceleration model was found to be applicable to the field of accident reconstruction for not only straight line acceleration, but also of left turning heavy trucks, by analysis of the 2010 SAE publication on tractor-trailer left turns and lane changes written by Raymond Merala and Kristen White [9]. The acceleration data collected through video analysis and published in the Merala paper came from a single intersection with tractor-trailers traversing a turn with radius between 32-45 feet. This presented a limited data set for comparing left turning trucks to the straight line acceleration data which has been more thoroughly tested. However, the data from the 2010 Merala paper was found to fall within the published ranges of straight line acceleration data discussed by these authors' 2019 paper, however, further research was decided upon to expand the left turning heavy truck data and analysis.

The thesis at the start of research for this paper was that although heavy trucks have a maximum lateral acceleration at which they may tip or reach a loss of control, there was a typical peak lateral acceleration threshold at which drivers would normally perform a left turning maneuver below the capabilities of the truck. The normal lateral acceleration reached during a left turn would limit the truck to a maximum speed through a given turn radius.

For this analysis, acceleration data needed to be collected from a variety of tractor-trailer makes, types, and combinations, to present a sufficient sample size for developing average and peak lateral accelerations for left turning heavy trucks. A new data collection method for vehicles was presented in the 2019 SAE publication by Neal Carter, Steven Beier, and Rheana Cordero, in which they developed a video tracking technique for automated tracking of left turning vehicles from overhead video footage, which was recorded with a small unmanned aerial system (sUAS) [10]. The 2019 paper validated the video tracking process with VBOX data to verify its accuracy.

Furthermore, the 2019 Carter paper presents average peak lateral accelerations for passenger vehicles at intersections where either one, two, or three lanes must be traversed to complete the left turn. For the purpose of this study, we contacted the authors of the 2019-01-0421 paper to inquire if they could review their data and analyze the lateral acceleration for the passenger vehicles for each turn radius. Based on our request, Carter, Beier, and Cordero produced Table 1, which summarizes the average and peak lateral accelerations for passenger vehicles for each turn radius.

TABLE 1 Summary of average and peak lateral accelerations for passenger cars from the author of SAE Technical Paper 2019-01-0421

Radius (ft)	Number of Vehicles	Average Lat. Accel. (g)	Peak Lat. Accel. (g)	Standard Deviation Lat. (g)	Standard Deviation Peak Lat. (g)
<20	2	0.07	0.09	0.01	0.01
20-30	16	0.09	0.12	0.03	0.03
30-40	33	0.10	0.14	0.03	0.04
40-50	10	0.13	0.19	0.07	0.09
50-60	9	0.18	0.27	0.06	0.05
60-70	4	0.22	0.27	0.02	0.02
70-80	3	0.17	0.28	0.05	0.08
>80	8	0.09	0.15	0.07	0.08
Average		0.13	0.19	0.04	0.05

Review of the data in Table 1 shows that although the turn radius ranges from 20 to 80 feet, the lateral accelerations do not change significantly relative to the turn radius, with standard deviations of 0.05 g and 0.07 g for average and peak accelerations, respectively. The data in Table 1 shows the average peak lateral acceleration reached by passengers cars is approximately 25% of roadway friction. This paper will analyze and present the average peak lateral accelerations for heavy trucks obtained through further testing; comparison of heavy truck lateral acceleration data to that of passenger cars from Carter's paper can be relevant in accident reconstruction.

The aerial video tracking process was utilized for this research to collect data from three urban intersections, which captured over 100 left turning heavy trucks for analysis of time, distance, speed, and lateral and tangential accelerations.

Data Collection

Eight intersections in the greater Denver metropolitan area were inspected for suitability for data collection; three were selected using the following criteria: sufficient heavy truck traffic (specifically turning left), intersection and turn radius size category (small, medium, large), and no airspace restrictions for longer duration sUAS flights for video capture. The three intersections that were selected for data collection are listed below in Table 2.

Figure 1, Figure 2, and Figure 3 show aerial images of each intersection taken from a DJI Mavic 2 Pro sUAS during data collection.

96th Ave and Alton Ct is a small uncontrolled intersection in Commerce City, CO, which has a posted speed limit of 30 mph for eastbound and westbound traffic. There is one travel lane for both eastbound and westbound directions, and there is a center lane with turn pockets for both directions at Alton Ct.

5101 Quebec St is a left turn across southbound Quebec St to enter a truck stop on the west side of the road. There are two northbound travel lanes with a left turn pocket in the median, and there are three travel lanes southbound on Quebec. The posted speed limit on northbound and southbound Quebec St is 40 mph.

TABLE 2 Three intersections selected for data collection

Intersection Size Classification	Intersection Location	Controlled Intersection	Lanes Traversed
Small	96th Ave and Alton Ct	No	One (east-west to north-south) Two (north-south to east-west)
Medium	5101 Quebec St	No	Three
Large	56th Ave and Quebec St	Yes	Three/Four (double turn lanes)

56th Ave and Quebec St is a large controlled intersection with a posted speed limit of 35 mph for eastbound 56th Ave and 40 mph for all other directions of travel. There are three travel lanes northbound and southbound on Quebec, each with two left turn lanes. There are two travel lanes eastbound and westbound on 56th, also with two left turn lanes present in both directions.

Data was collected at each intersection with a DJI Mavic 2 Pro sUAS. All flights were operated in Class G airspace in

FIGURE 1 Small Intersection - 96th Ave and Alton Ct

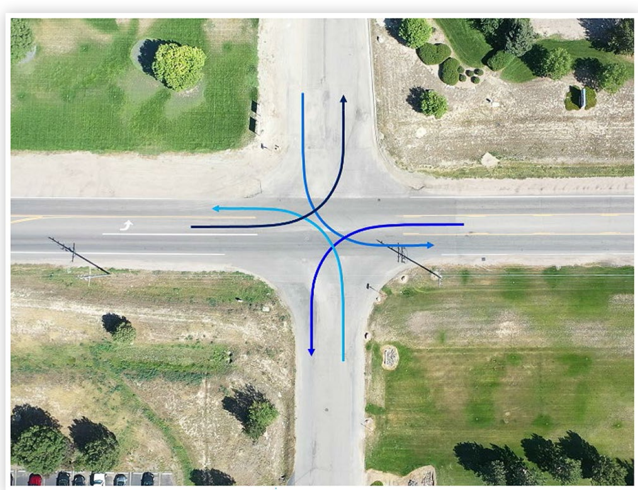


FIGURE 2 Medium Intersection - 5101 Quebec St

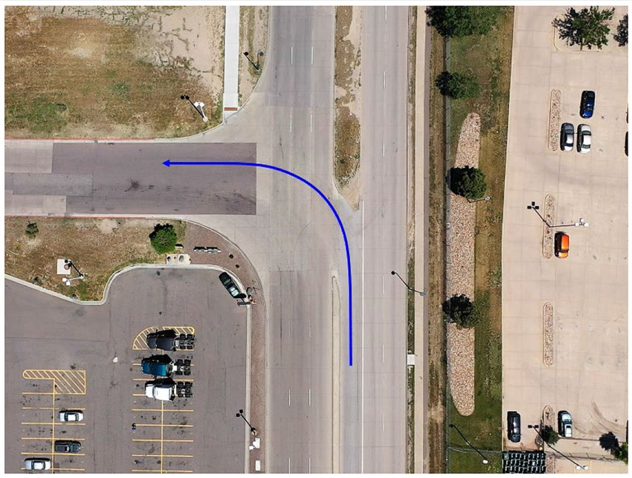
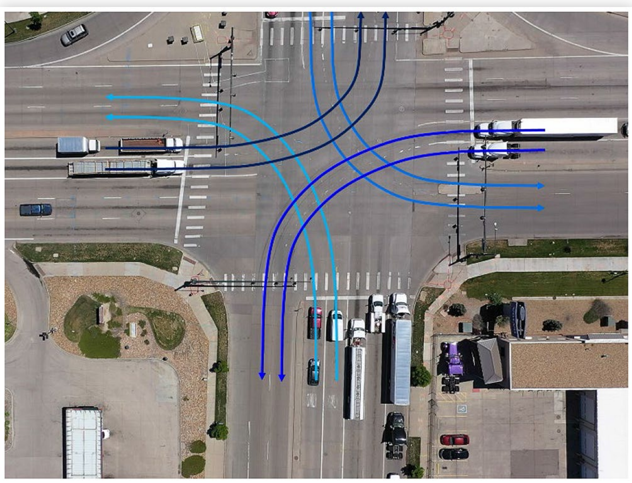


FIGURE 3 Large Intersection - 56th Ave and Quebec St

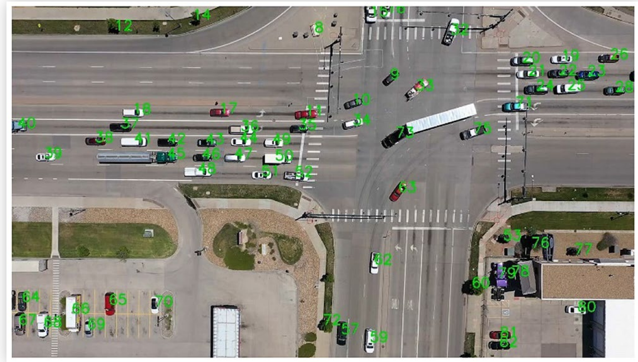


accordance with the Federal Aviation Administration (FAA) Small Unmanned Aircraft Regulations, Part 107, by a licensed remote pilot. The sUAS was flown at 400 feet above ground level and video was recorded at 60 frames per second with the camera facing 90 degrees downward, to generate video as close to perpendicular to traffic flow as possible. Secondary ground-level video was also captured at each intersection utilizing two GoPro Hero 6 video cameras, positioned to capture as much information about tracked heavy trucks as possible, such as make, model, trailer configuration, and partial VIN if present on the tractor.

Data Processing

Overhead video captured from each intersection was combined with ground-level video in Adobe Premiere Pro video editing software. The aerial footage was synced with

FIGURE 4 Video frame from video tracking output video with object labels



ground footage for identification of tracked vehicles, and then clips were exported of each heavy truck for input into the video tracking process. The start of a given tracked run was determined either when the heavy truck proceeded from a stop at the stop bar into the intersection, or when a rolling heavy truck reached the stop bar. The end of a run was chosen when the entire vehicle cleared the oncoming lanes of travel. The video tracking process outputs are a video labeled with objects tracked and a text file containing X and Y pixel coordinates per frame for each tracked vehicle. The point at which heavy trucks are tracked is approximately centered over the cab of the vehicle. Figure 4 shows a frame from the video output with labeled tracked objects from the large intersection.

The tracking data for each heavy truck was then processed utilizing the same techniques as presented in SAE 2019-01-0421, such as a two-pass Butterworth filter, scaling from pixels to feet, and calculating radii throughout the tracked vehicle's turn motion. Turn radius, speed, and lateral acceleration were plotted against time for the duration of the runs; sample charts are presented in Appendix A.

Data Analysis

All runs were processed and calculations were performed to generate distance, speed, acceleration, and radius data. The average and peak lateral accelerations were calculated for the cab of each heavy truck, along with an average turn radius. While the path of a given heavy truck through a left turn is not of constant radius, an average radius can be calculated by excluding radius data from the beginning and end of a turn to eliminate the straight portions of the path. Figure 5, Figure 6, and Figure 7 show the paths of heavy trucks plotted in red traveling through each intersection, with circles drawn in blue showing the average radius for each intersection overlaid on the plotted paths. Only one or two directions of travel are shown for clarity; however all left turn directions were tracked and analyzed at each intersection.

As seen in the above graphics, there are variations in paths traversed through the same turn for different trucks, traffic situations, and driving styles. Some drivers start their

FIGURE 5 Small Intersection - Average Turn Radius (47 feet)

FIGURE 6 Medium Intersection - Average Turn Radius (78 feet)

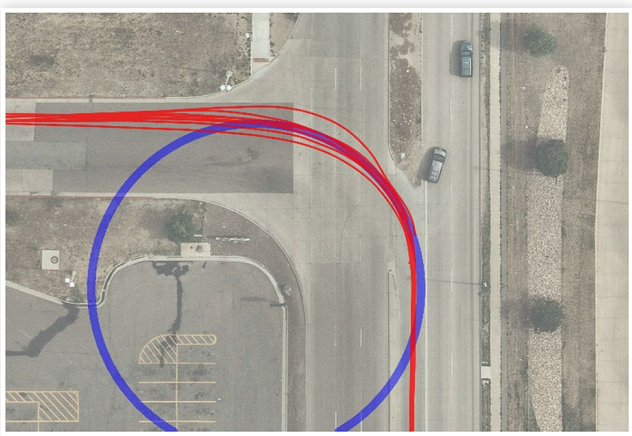
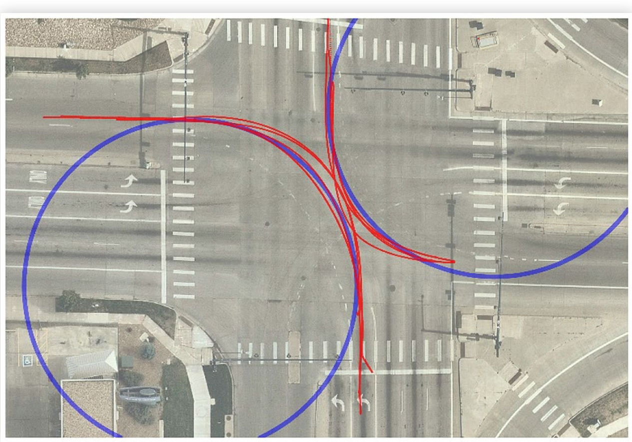


FIGURE 7 Large Intersection - Average Turn Radius (79 feet)



turns early and traverse a larger radius across travel lanes; others roll forward further then initiate the turn later, generating a smaller radius. When analyzing an accident, the exact path of the heavy truck may not be known, therefore using an average radius from known vehicle paths can be utilized.

Once the average and peak lateral accelerations and average radii were determined for each dataset, these values were plotted against all other runs to analyze the affects of intersection size and turn radius on average and peak lateral accelerations. Figure 8 and Figure 9 show plots for all runs showing the average and peak lateral acceleration, respectively, versus turn radius, including color coding for each run's intersection size (small/blue, medium/red, large/green). It should be noted that driver actions can contribute to outlier data points: the heavy truck generating accelerations of 0.26 g and 0.32 g for average and peak lateral accelerations, respectively, entered the turn at the medium intersection at 32 mph and only slowed to 18 mph through the turn. These high accelerations were not found to be typical during the analysis of collected data, and should be considered outliers based on the driver's aggressive actions entering the turn. However, if a reconstructionist has knowledge of the driving style of the heavy truck driver, such outlier data can be considered as valid should the situation require, as the heavy trucks are physically capable of reaching higher lateral accelerations than seen during normal driving.

FIGURE 8 Average Lateral Acceleration vs. Turn Radius

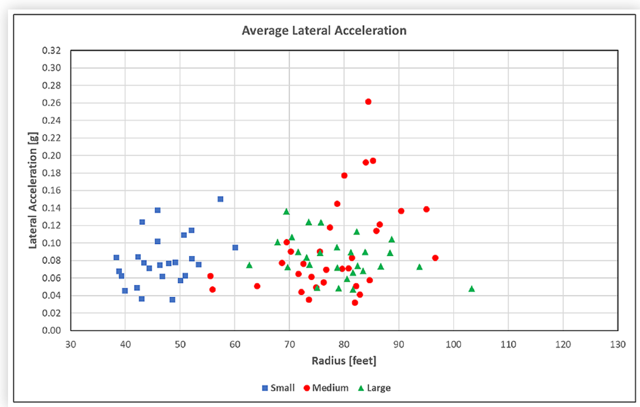
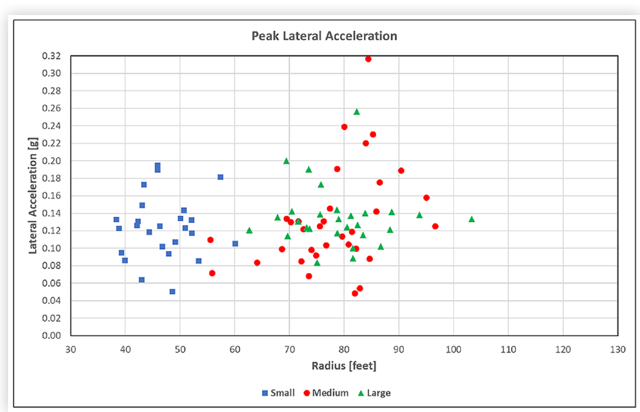


FIGURE 9 Peak Lateral Acceleration vs. Turn Radius



Discussion

Average and Peak Lateral Accelerations

At first inspection, these plots have a wide overall range of minimum and maximum average and peak lateral accelerations; however, the data is grouped in such a way that the turn radius of the heavy truck does not appear to have a significant affect on magnitude of lateral acceleration. Furthermore, when the data is separated into groups based on whether or not the truck was stopped before entering the intersection, the data shows a clearer trend reinforcing initial impressions. Figure 10 and Figure 11 show the average and peak lateral accelerations of only vehicles that were stopped prior to beginning their left turn.

The heavy trucks that were stopped prior to entering the intersection have a close grouping of average and peak lateral accelerations, regardless of turn radius size. To classify the resulting average and peak lateral acceleration data, averages of each with one standard deviation were calculated. Table 3 and Table 4 summarize the average and peak lateral acceleration values by intersection size (small, medium, large) and heavy truck starting condition (stopped, almost stopped, did not stop), respectively.

FIGURE 10 Average Lateral Acceleration vs. Turn Radius (Vehicles were stopped)

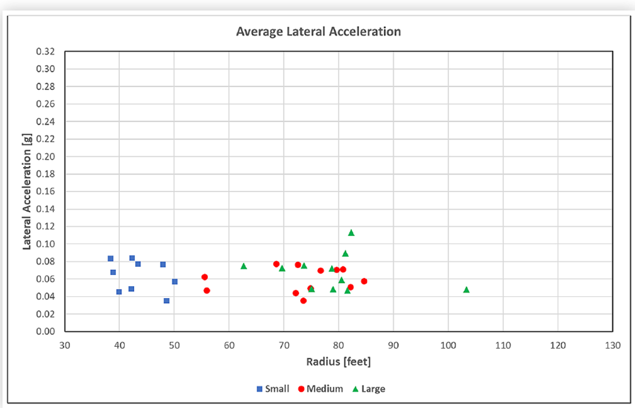
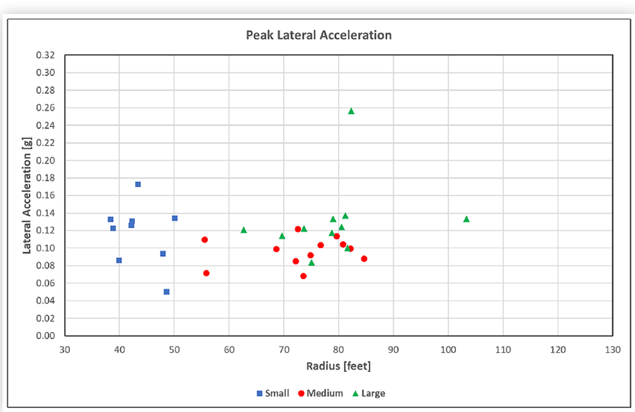


FIGURE 11 Peak Lateral Acceleration vs. Turn Radius (Vehicles were stopped)



Charts including averages and one standard deviation up or down were generated for each classification; Figure 12 and Figure 13 show the same groupings as Figure 10 and Figure 11 for stopped heavy trucks, but have the average and one standard deviation lines overlaid on the data. The complete complement of charts for all classifications are included in Appendix B.

The peak and average lateral acceleration data shows that turn radius has a negligible effect on average and peak lateral accelerations reached by heavy trucks during a turn. Whether the intersection is small or large, turn radius 40 feet or 100 feet, the average and peak lateral accelerations remain at a consistent level. Furthermore, the driving factor in variation of average and peak lateral accelerations is whether the heavy truck was stopped at the stop bar prior to entering the intersection, or it was rolling when beginning its left turn. The data shows that average lateral accelerations are lower when the heavy truck begins from a stop, with an average of 0.064 g, and higher when the truck does not stop and rolls into the turn, with an average of 0.109 g. The difference between stopped and rolling trucks in peak lateral accelerations is smaller, with stopped trucks reaching an average peak acceleration of 0.114 g and rolling trucks reaching 0.150 g.

Speed Reached in Intersection

The second consideration of the left turn tracking data was the peak speed reached during the intersection, and how the longitudinal or tangential acceleration compared to straight line heavy truck acceleration trends presented in SAE 2019-01-0411. Speeds of heavy trucks that were stopped prior to entering the left turn were plotted over time, and compared with the two-phase acceleration model developed from straight line acceleration testing. Figure 14 shows all tracked runs of tractors with trailers from the left turn intersection tracking data with the range of accelerations for all tractors with trailers from SAE 2019-01-0411. Left turning tractor-trailer runs are colored as shown previously (small/blue, medium/red, large/green); the solid black line is the average of two-phase acceleration model for tractors with trailers, and the dashed black lines represent the 85th percentile above or below the average. Appendix C includes the tables from the SAE 2019-01-0411 paper showing the two-phase acceleration for various tractor-trailer configurations.

As shown above, the accelerations of left turning trucks that entered the intersections from a stop align with the accelerations and speeds of straight line testing. The left turning trucks have similar accelerations in the first phase of acceleration from straight line testing (0-3 seconds), and the acceleration tends to decrease or approach zero after four seconds in most left turn runs. The trend shows that during the second phase of the longitudinal acceleration, the tractor-trailer reaches their peak lateral acceleration threshold and therefore decreases their longitudinal acceleration.

A second trend in speed over time data was apparent in the left turn tracking data: regardless of intersection size or starting condition, heavy trucks rarely reached peak speeds of 15 mph

TABLE 3 Average and Peak Lateral Accelerations (classified by intersection size)

Intersection Size	All Intersections		Small Intersection		Medium Intersection		Large Intersection	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Turn Radius [feet]	69.2	16.5	46.9	5.7	77.8	9.3	79.0	8.5
Average Lateral Acceleration [g]	0.086	0.039	0.081	0.029	0.093	0.053	0.084	0.024
Peak Lateral Acceleration [g]	0.131	0.045	0.124	0.036	0.132	0.058	0.136	0.035

TABLE 4 Average and Peak Lateral Accelerations (classified by heavy truck starting condition)

Heavy Truck Starting Condition	All Starting Motion		Stopped		Almost Stopped		Did Not Stop	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Turn Radius [feet]	69.2	16.5	66.8	17.1	72.4	13.0	70.1	17.1
Average Lateral Acceleration [g]	0.086	0.039	0.064	0.017	0.072	0.029	0.109	0.042
Peak Lateral Acceleration [g]	0.131	0.045	0.114	0.036	0.114	0.040	0.150	0.047

FIGURE 12 Average Lateral Acceleration vs. Turn Radius including average and standard deviation (Vehicles were stopped)

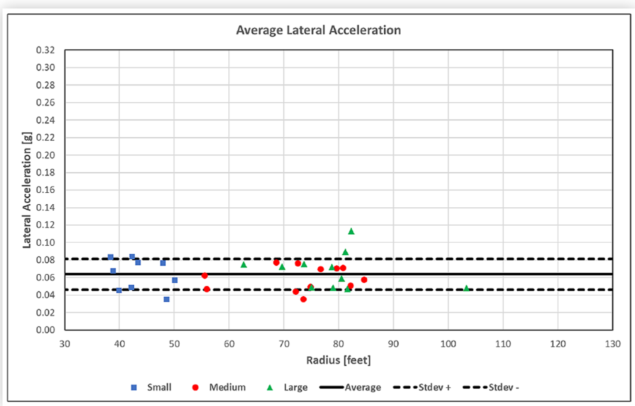


FIGURE 13 Peak Lateral Acceleration vs. Turn Radius including average and standard deviation (Vehicles were stopped)

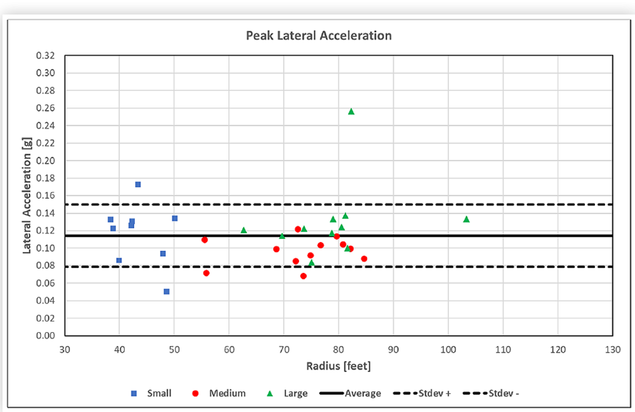
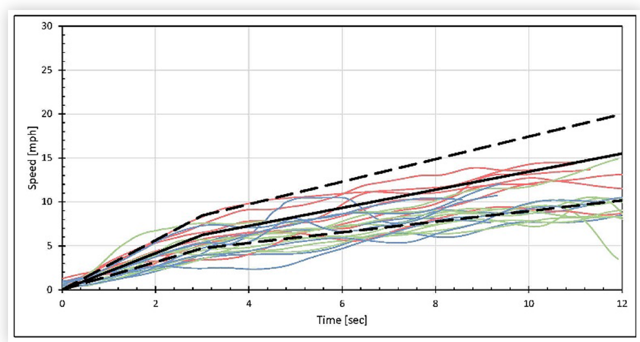


FIGURE 14 Speed vs. Time Plots (Left turn data overlaid upon straight line acceleration data for all tractors with trailers)



or higher while within the intersections. Given the consistent peak lateral accelerations reached throughout the left turn intersection data, a peak speed can be estimated for a given intersection or turn from peak lateral acceleration and estimated turn radius.

Summary/Conclusions

Trends relating to both lateral accelerations and speeds were evident upon analysis of left turning heavy truck video tracking data, as shown in this paper. The average turn radii analyzed in this paper are as follows: small 46.9 feet, medium 77.8 feet, and large 79.0 feet. The analysis shows that the radius of the turn has little to no effect on the lateral acceleration of heavy trucks, as seen in the range of average lateral accelerations which were 0.081 g, 0.093 g, and 0.084 g for the small, medium, and large intersections, respectively. The same can be said for the peak accelerations as well: 0.124 g for the small intersection, 0.132 g for the medium intersection, and 0.136 g for the large intersection.

There were differences in the lateral accelerations, however, when the initial starting conditions of the heavy truck differed. The average lateral acceleration of a heavy truck that was stopped was 0.064 g, while the rolling vehicles saw an average lateral acceleration of 0.109 g. There was also a difference in the peak lateral acceleration (0.114 for stopped and 0.150 for rolling), however the difference was not as significant compared to the average lateral acceleration.

The heavy trucks in all turn radii reached an average peak lateral acceleration of 0.131 g. A commercial vehicle is only capable of reaching 70% to 85% of the sliding coefficient of friction compared to a passenger vehicle [11]. Based on the average reduction in friction of 77.5% and using a passenger roadway friction of 0.76 g, the heavy trucks' peak lateral acceleration achieves approximately 22% of available roadway friction. This finding is consistent with the peak lateral accelerations found in left turning passenger cars.

Furthermore, the heavy trucks reached a peak speed under 15 mph in nearly all tracked runs, which indicates that the peak lateral accelerations reached during a left turn can be utilized to calculate a peak speed reached by a heavy truck during a left turn. The speed data indicates that straight line acceleration data can be utilized to estimate speed during left turns as well, up to a peak speed determined using the turn radius and peak lateral acceleration. These calculations can be applied to accident reconstruction directly in order to determine the time, distance, and speed required for a heavy truck to traverse a left turn across traffic.

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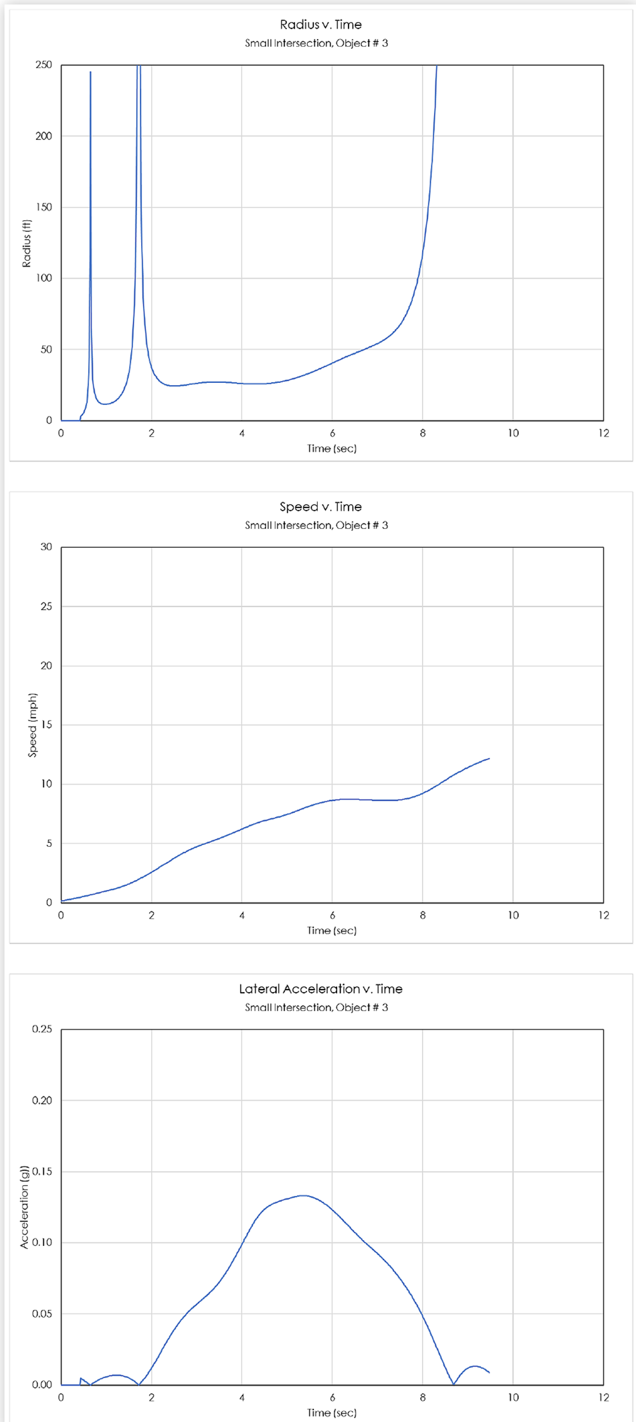
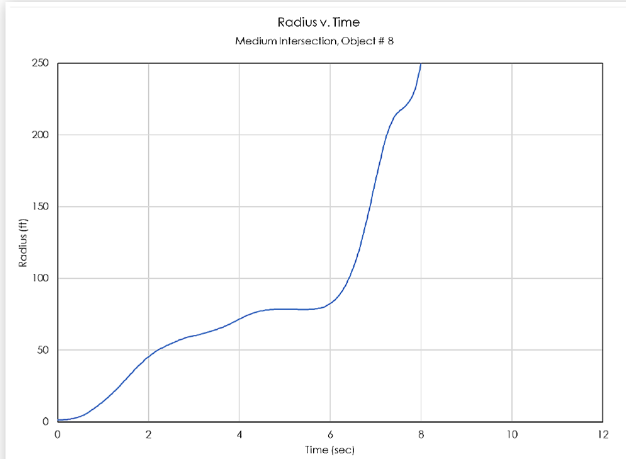
Appendix A

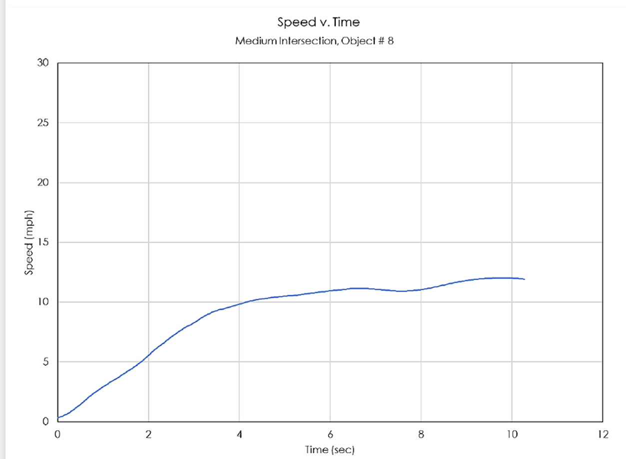
Appendix A contains sample radius, speed, and lateral acceleration charts plotted over time, which are representative of the output data from the video tracking process.

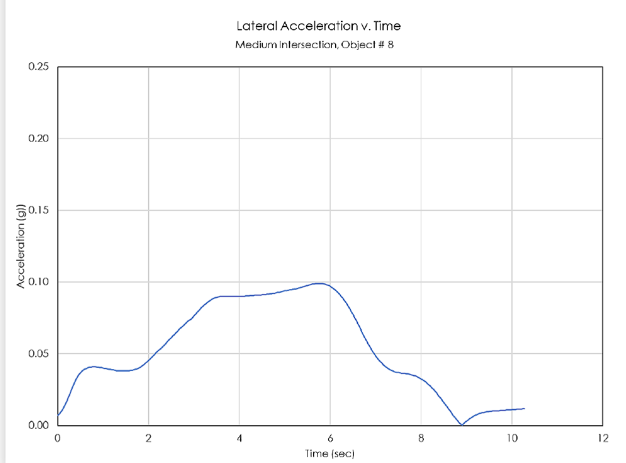
Small Intersection - Freightliner Cascadia, dry van trailer, stopped prior to entering intersection:



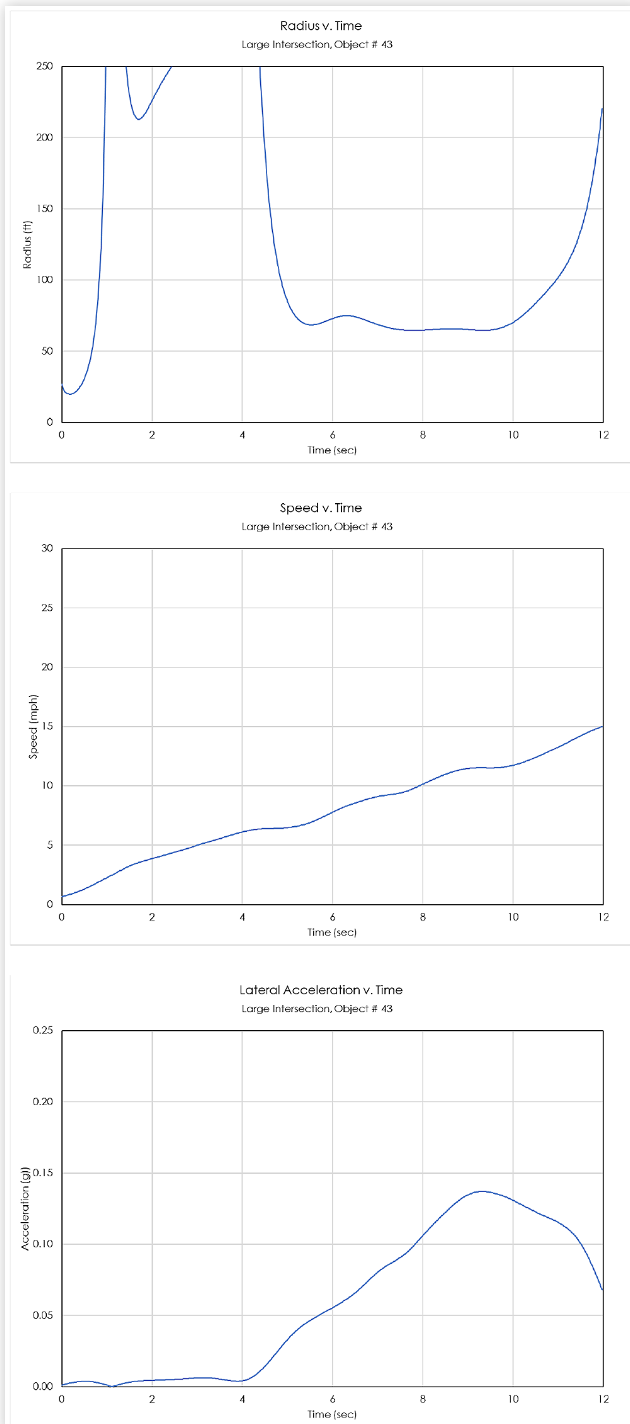
Medium Intersection - Peterbilt 386, dry van trailer, stopped prior to entering intersection:







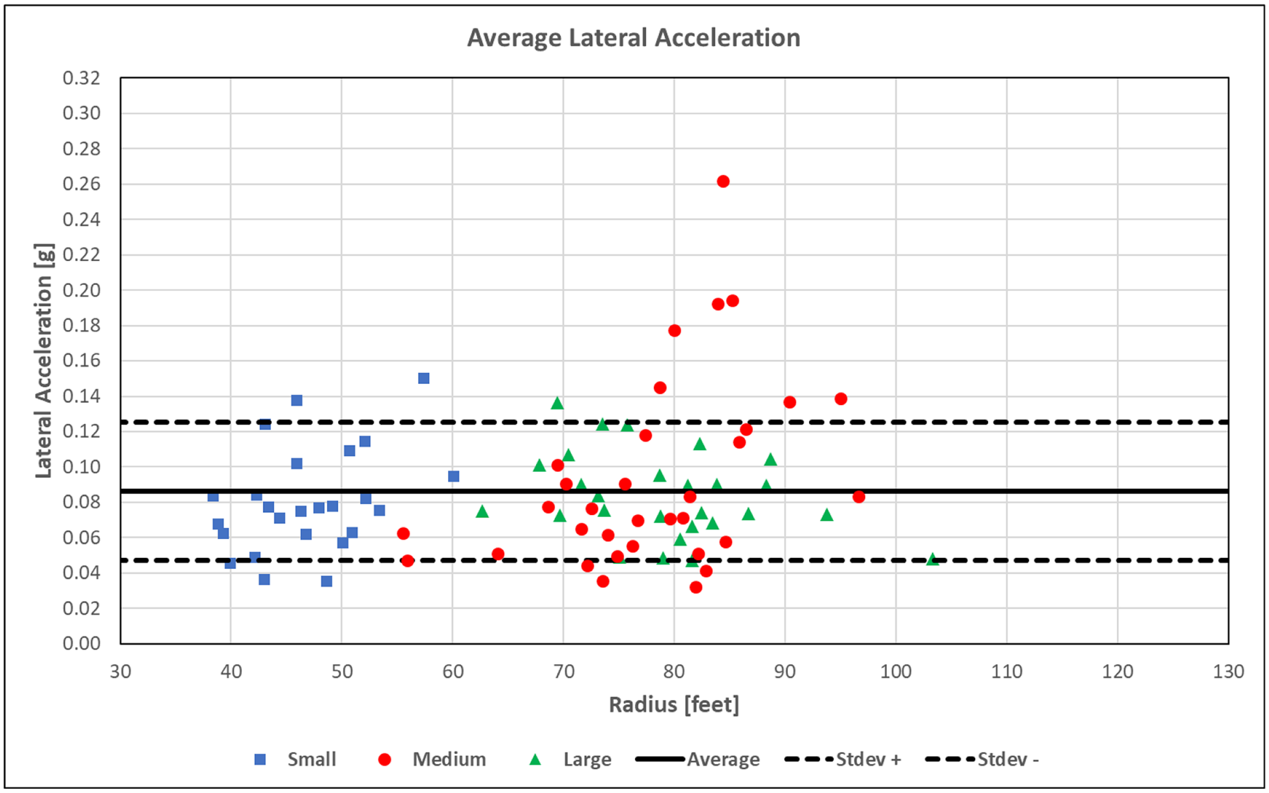
Large Intersection - International tractor, flatbed trailer, stopped prior to entering intersection:

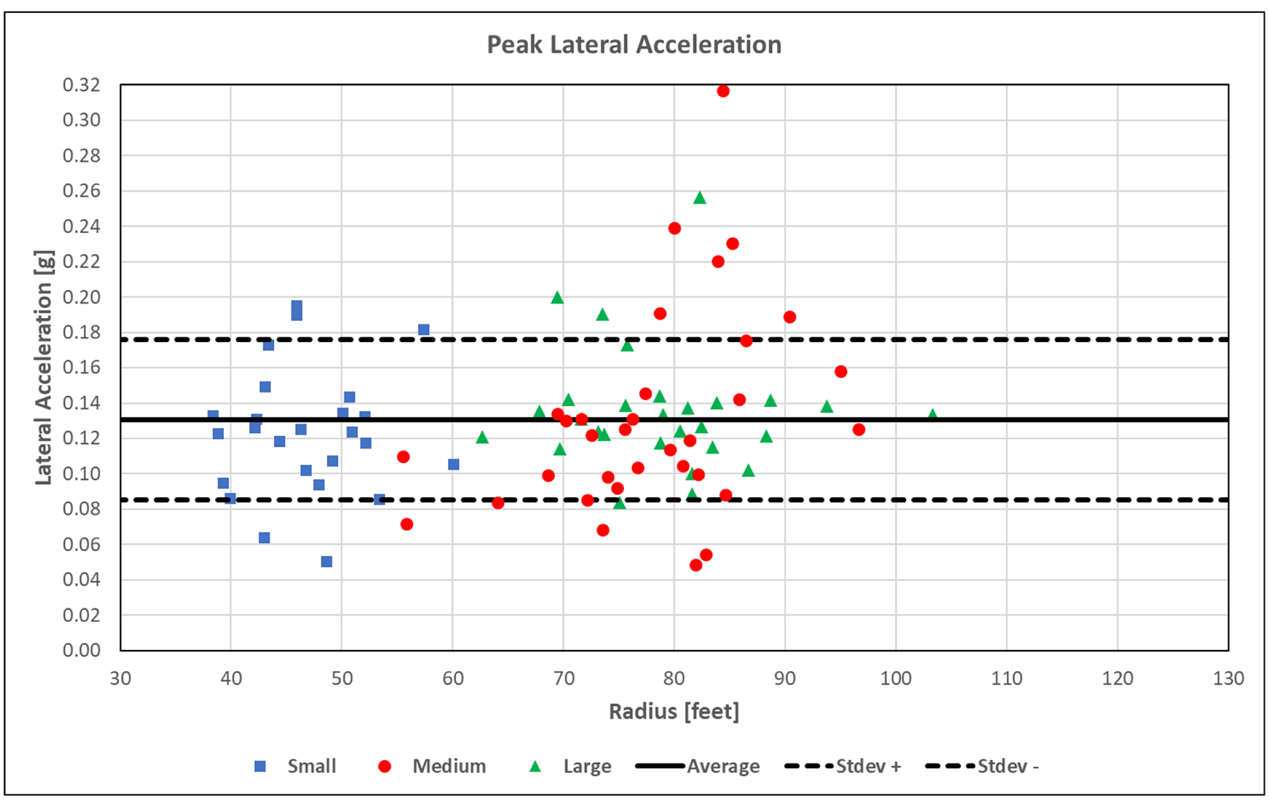


Appendix B

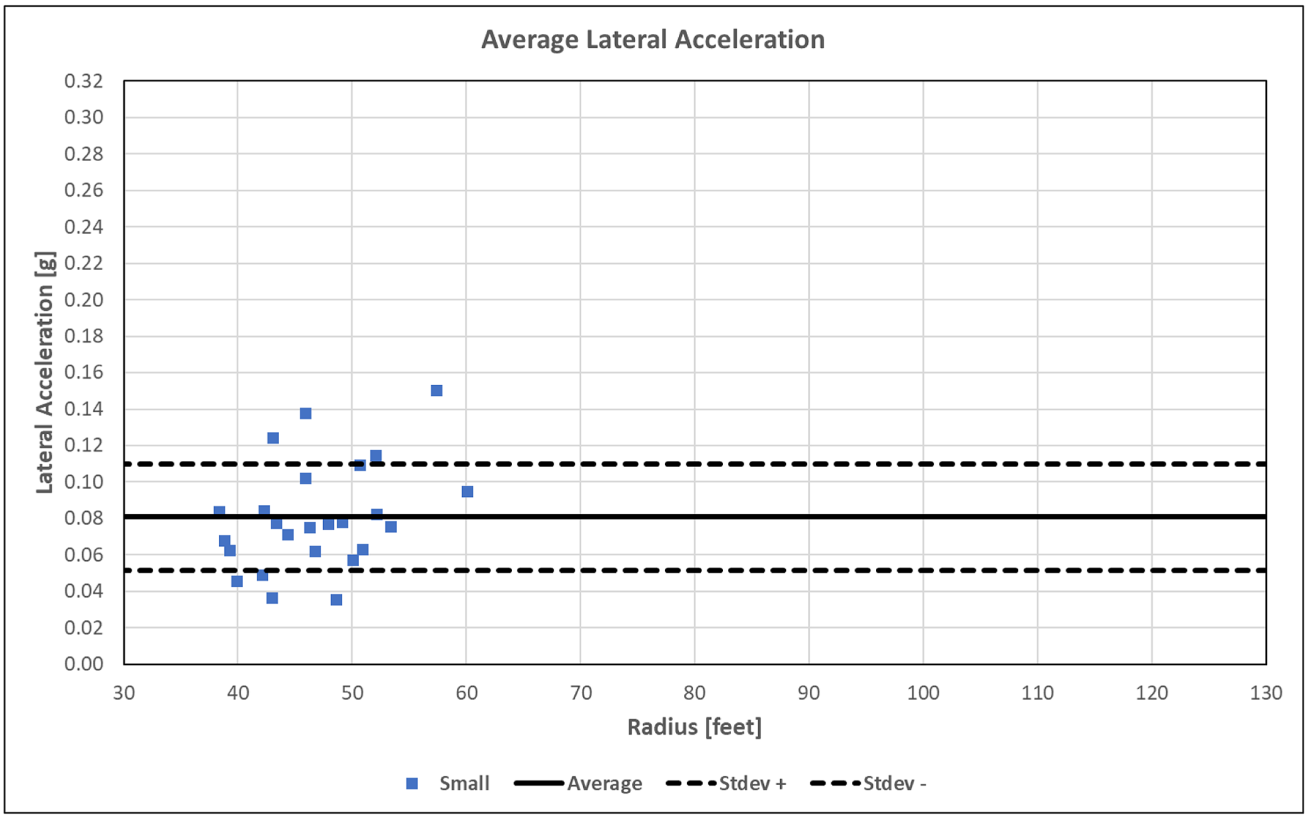
Appendix B contains charts of average and peak lateral accelerations of left turning heavy trucks, classified by intersection size and starting condition.

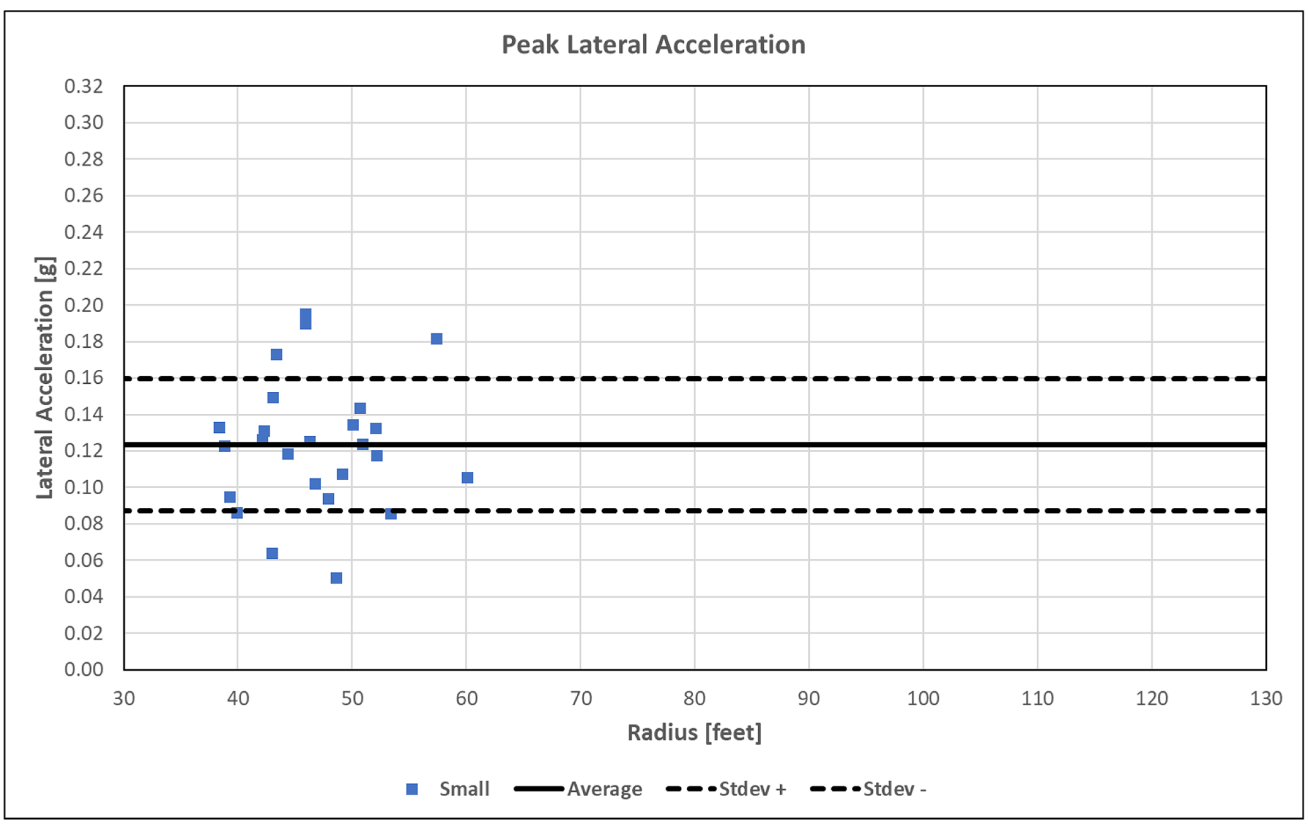
All Left Turning Heavy Trucks



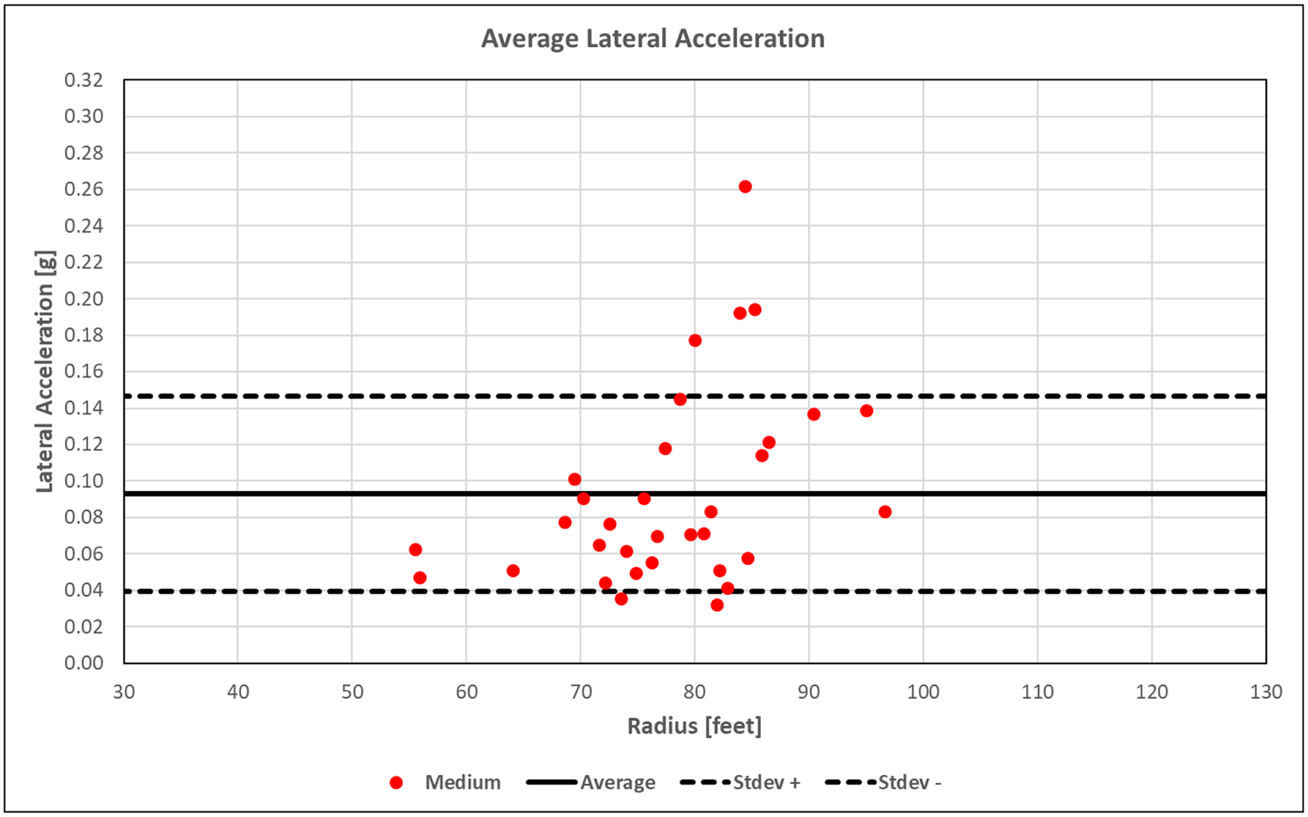


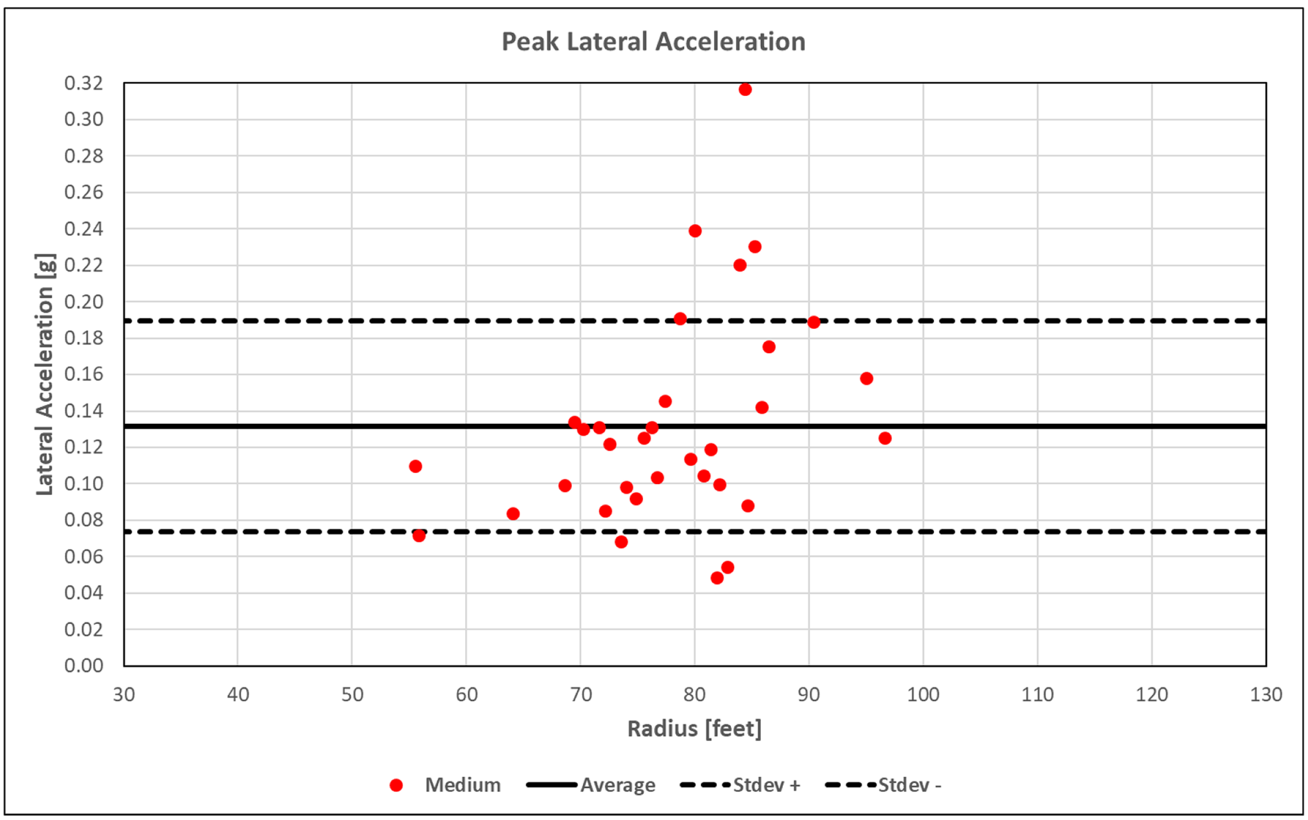
Small Intersection



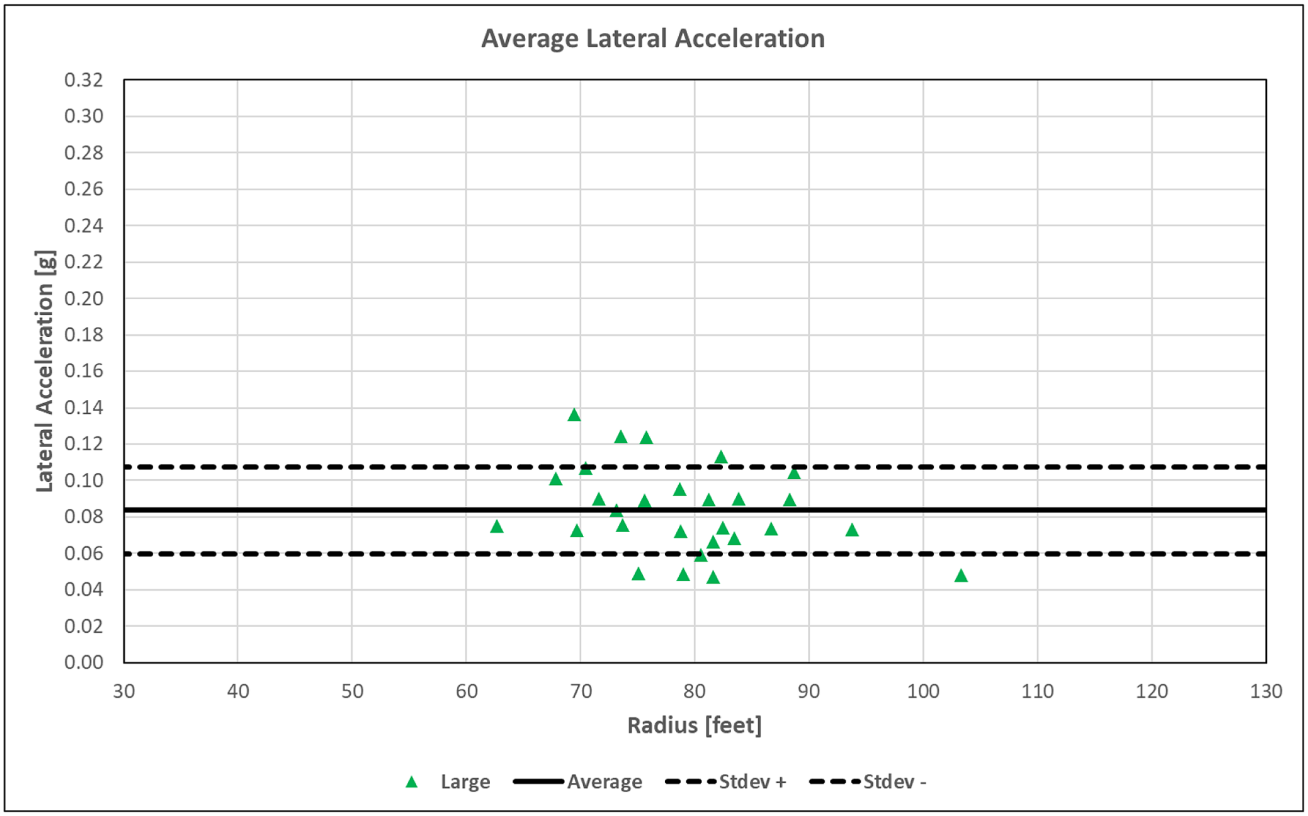


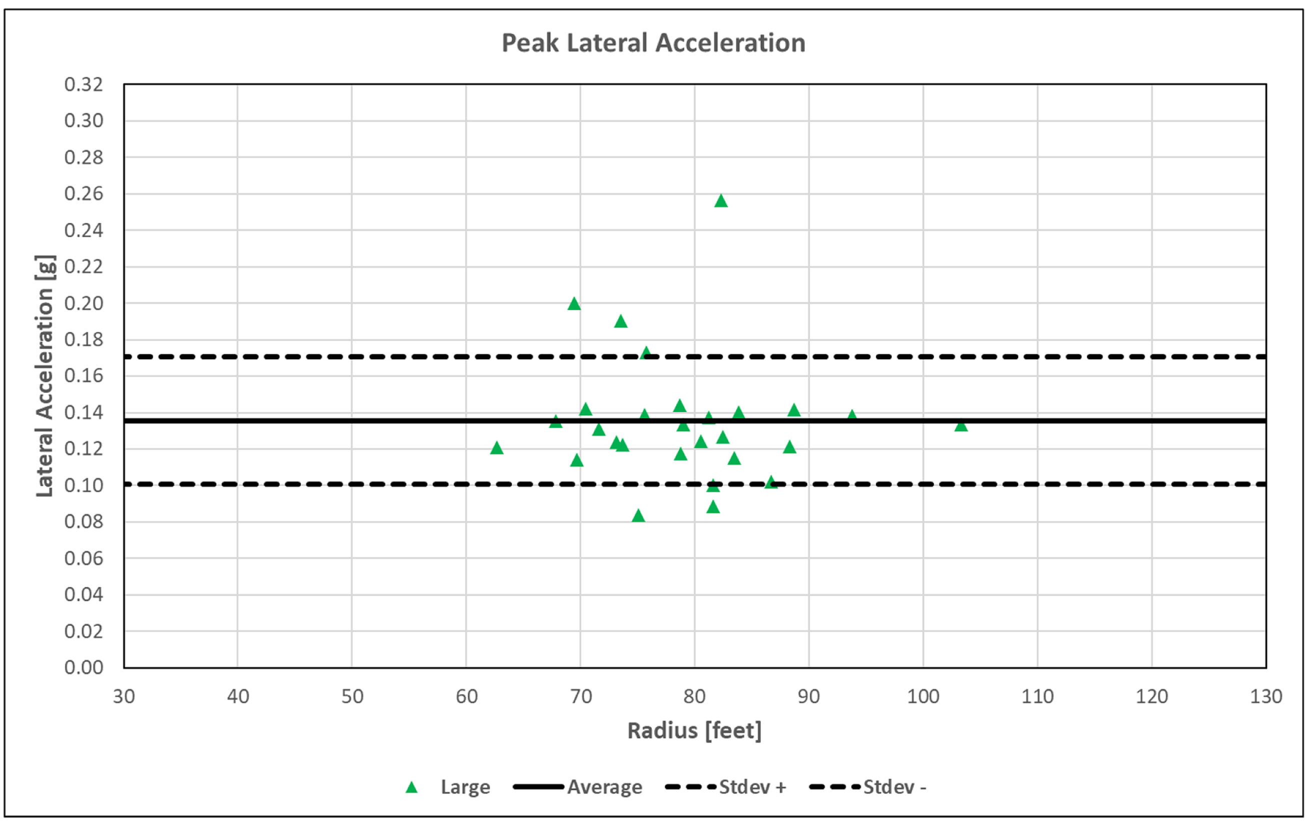
Medium Intersection



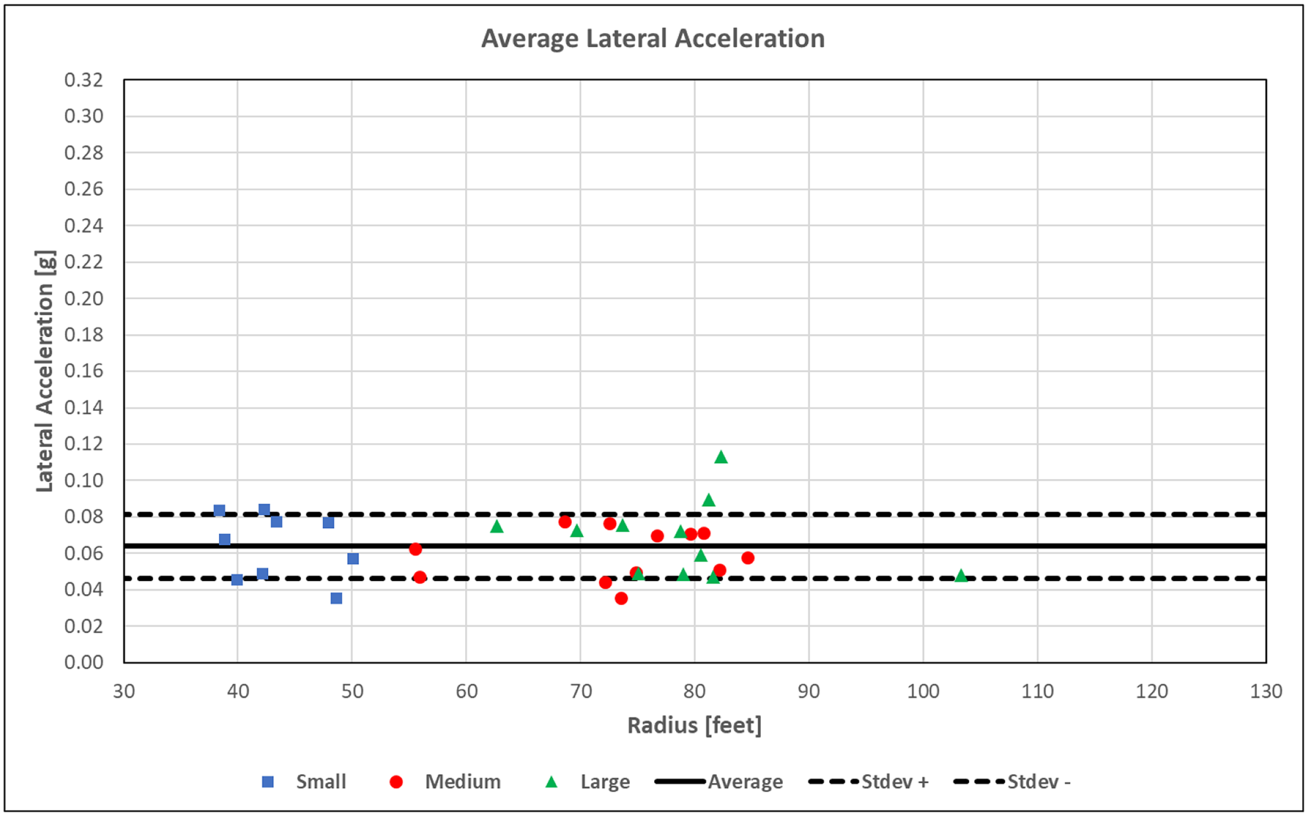


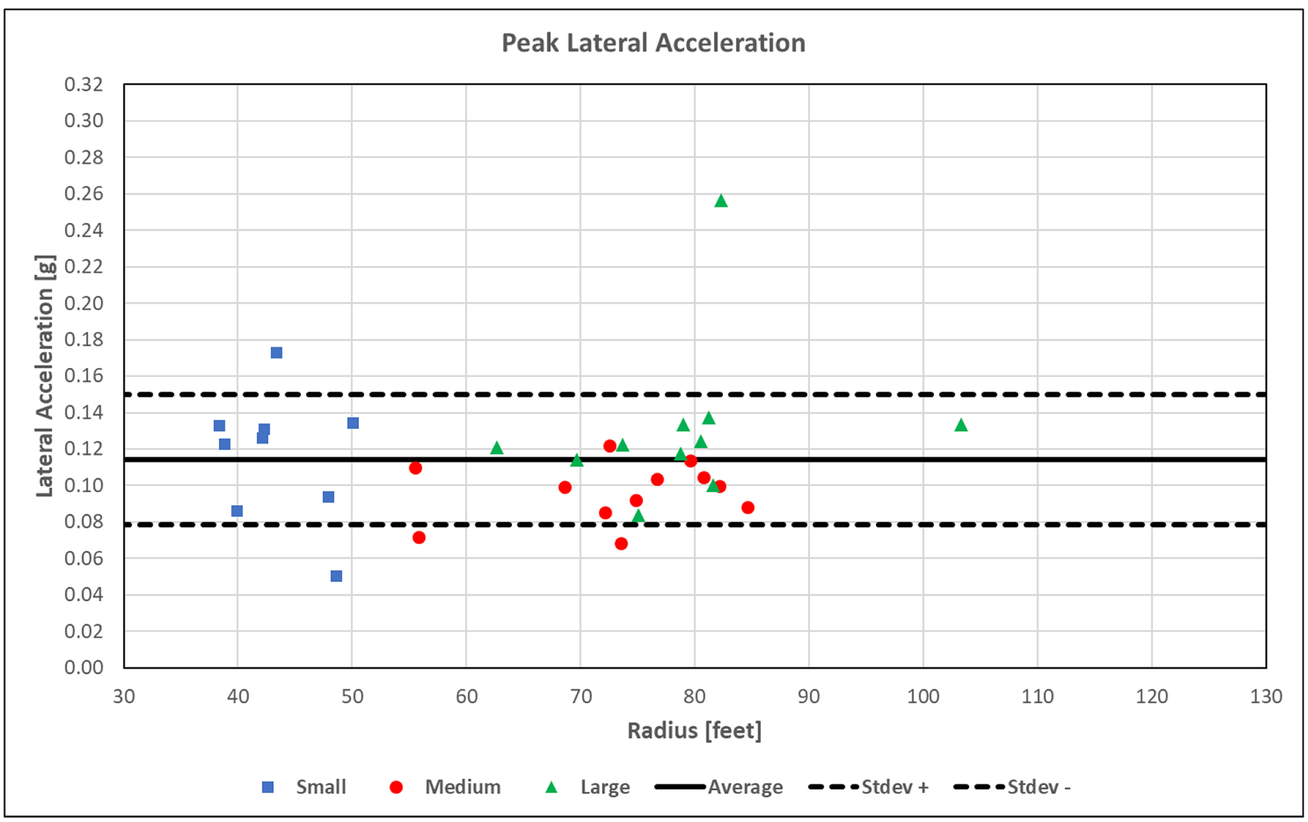
Large Intersection



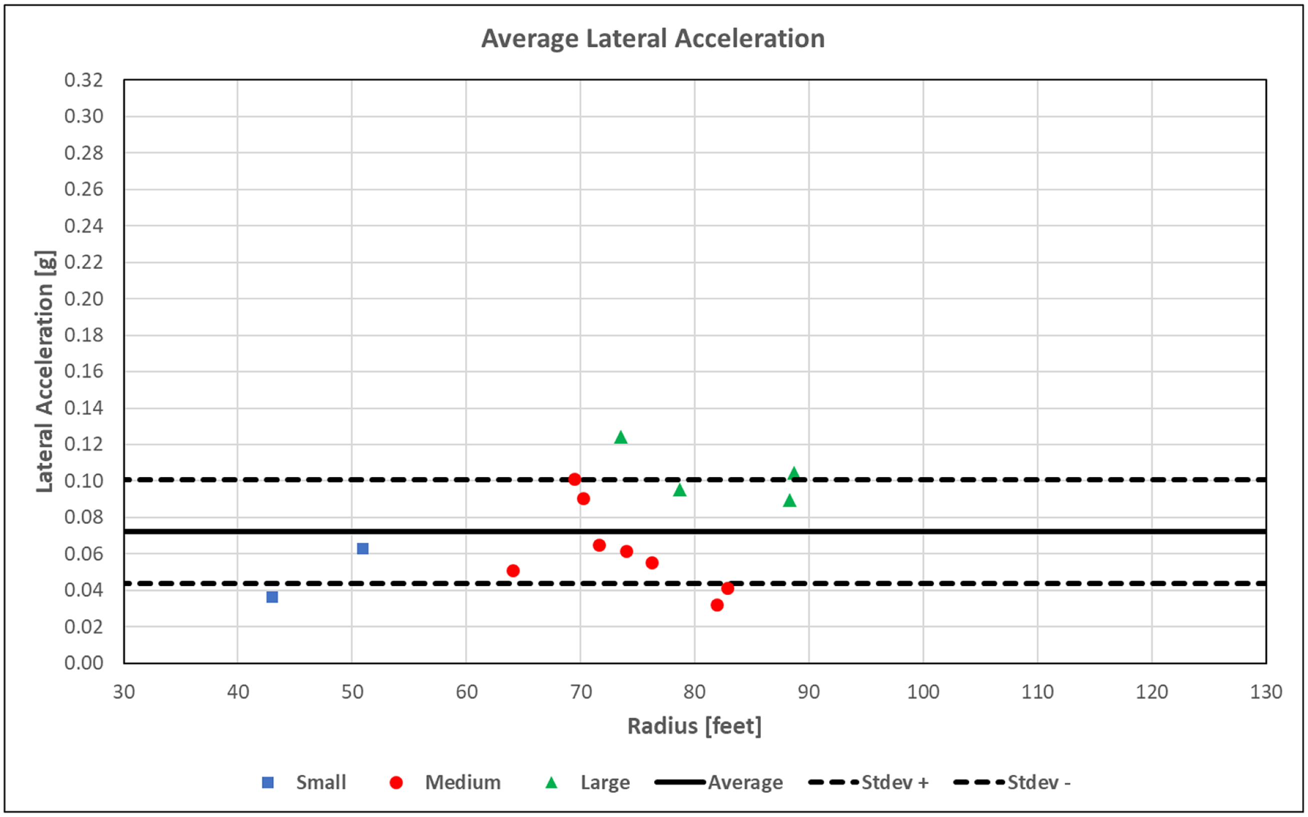


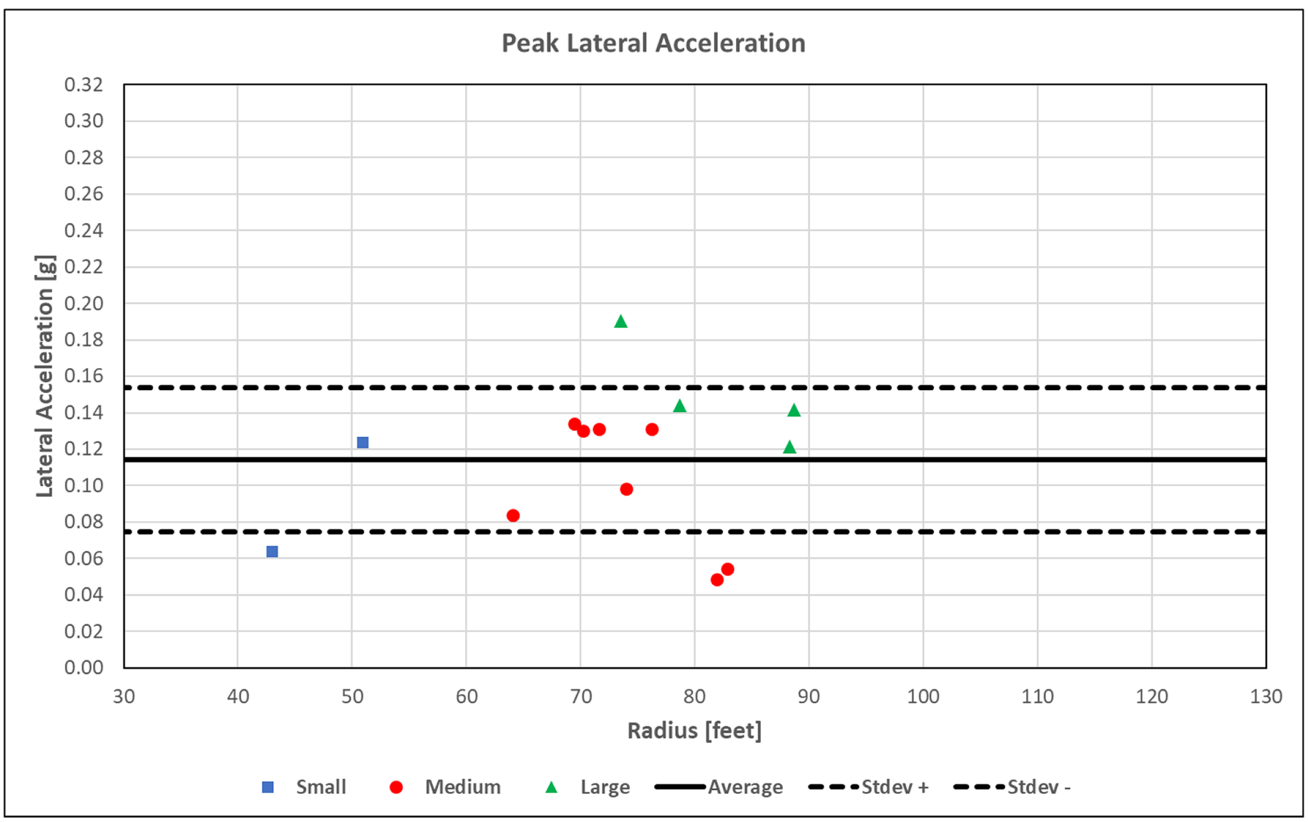
Stopped Prior to Starting Left Turn



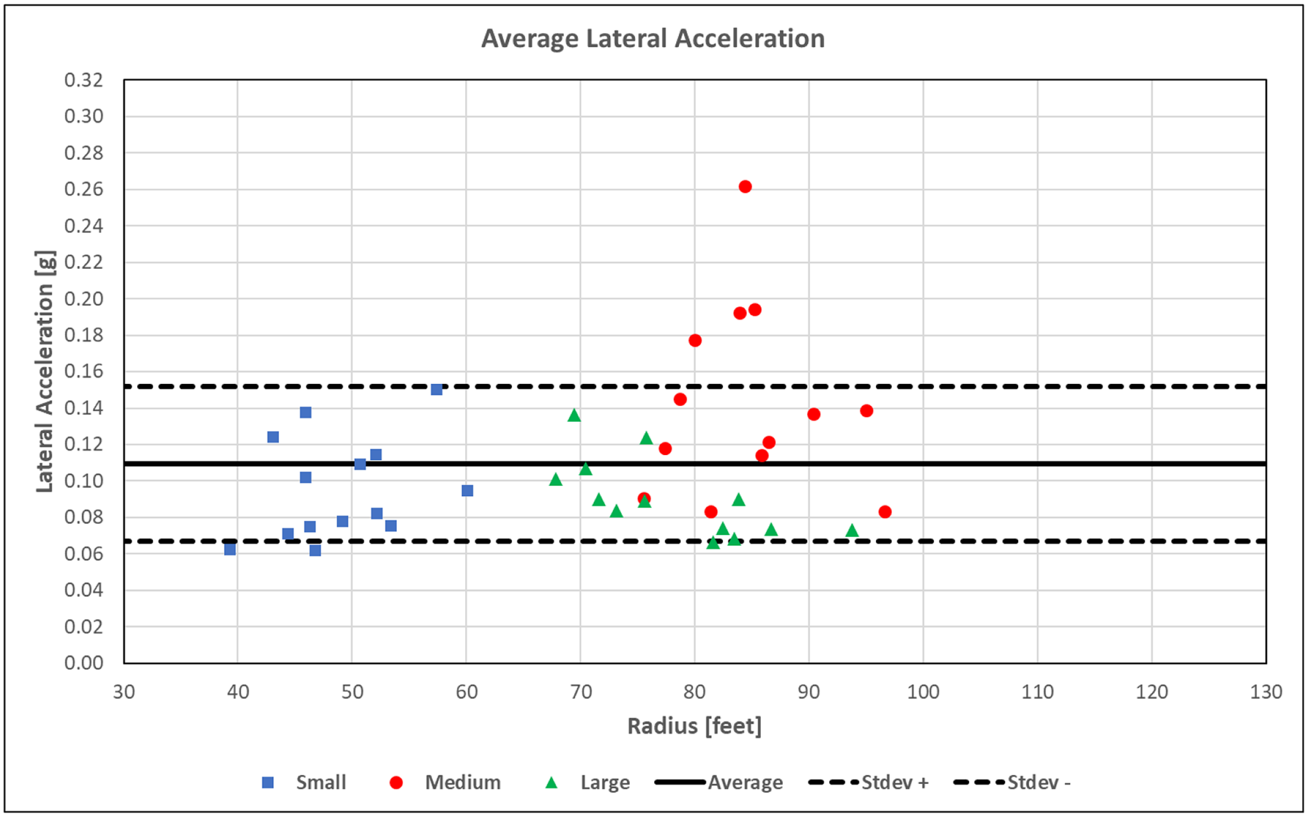


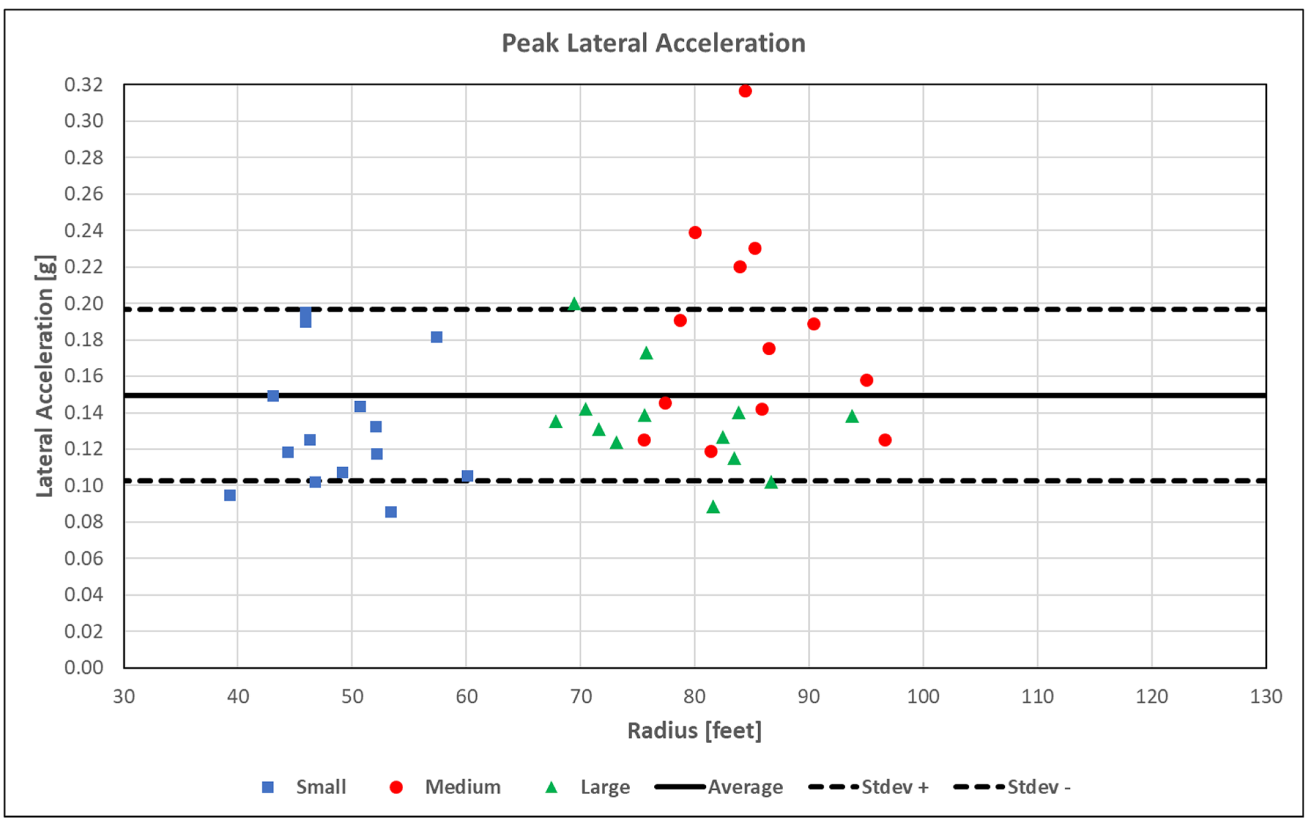
Almost Stopped Prior to Starting Left Turn





Did Not Stop Prior to Starting Left Turn





Appendix C

Appendix includes tables from 2019-01-0411 of the two-stage acceleration model for each tractor-trailer configuration with 85th percentile confidence interval, which was used to plot the lines in the charts in Appendix A.

Two Phase Acceleration - Trailer vs. No Trailer

	Phase 1			Phase 2		
Configuration	Time [sec]	Accel [g]	Range [g]	Time [sec]	Accel [g]	Range [g]
All	0-3	0.098	± 0.034	3-12	0.048	± 0.024
All with trailer	0-3	0.095	± 0.028	3-12	0.047	± 0.015
All without trailer	0-3	0.121	± 0.022	3-12	0.064	± 0.011

Two Phase Acceleration - Automated vs. Manual Transmission

	Phase 1			Phase 2		
Configuration	Time [sec]	Accel [g]	Range [g]	Time [sec]	Accel [g]	Range [g]
All with trailer	0-3	0.095	± 0.028	3-12	0.047	± 0.015
All Auto with Trailer	0-3	0.094	± 0.028	3-12	0.051	± 0.013
All Manual with Trailer	0-4	0.088	± 0.022	4-12	0.037	± 0.012

Two Phase Acceleration - Empty, Half-Loaded, and Fully Loaded Trailer

	Phase 1			Phase 2		
Configuration	Time [sec]	Accel [g]	Range [g]	Time [sec]	Accel [g]	Range [g]
All Auto with Traileriler	0-3	0.094	± 0.028	3-12	0.051	± 0.013
Auto, Empty Trailer	0-3	0.100	± 0.028	3-12	0.057	± 0.012
Auto, Half Load Trailer	0-3	0.094	± 0.020	3-12	0.048	± 0.014
Auto, Full Load Trailer	0-4	0.083	± 0.009	4-12	0.044	± 0.013
All Manual with Trailer	0-4	0.088	± 0.022	4-12	0.037	± 0.012
Manual, Empty Trailer	0-4	0.099	± 0.019	4-12	0.042	± 0.005
Manual, Half Load Trailer	0-4	0.087	± 0.014	4-12	0.040	± 0.008
Manual, Full Load Trailer	0-4	0.078	± 0.008	4-12	0.034	± 0.010

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