GPS/GIS Analysis of Tennessee Truck Trips

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Executive Summary

Freight transportation planning is largely limited by the amount, quality and detail of truck trip data. Most truck movement data is reported at the inter-county level and is represented as aggregated tonnages that must be broken down to truck trips. Additionally, intra-county flows can be largely under-represented and commercially available commodity flow databases (e.g., TRANSEARCH) are prohibitively expensive. Surveying truck drivers (such as at truck stops or at terminal gates) and following trucks from terminals is time-consuming and requires a great amount of labor to geocode the trip origins and destinations. Truck trip traffic generated from these aforementioned sources relies on outdated and insufficient traffic generation data and models, shortest path algorithms and spot counts and the results are seldom validated.

The American Transportation Research Institute (ATRI), with the Federal Highway Administration (FHWA) developed the Freight Performance Measures Web-Based (FPMWeb) tool. FPMWeb continually measures operating speeds (using GPS device data) of a large sample of trucks along 25 interstate highways. While the data available on the web consists mainly of processed average speed information, Vanderbilt will subcontract with ATRI and will perform the research using some of the raw GPS data. The raw data consist of truck GPS positions recorded once every 5-15 minutes with a unique ID number for the truck, a timestamp and speed. The unique ID numbers may be linked together to identify the route(s) taken by a given truck on a given day.

The University of Memphis in collaboration with the ATRI and Vanderbilt University have developed methods to utilize truck GPS data provided by ATRI and the FHWA to provide insight into freight movement throughout the state of Tennessee. This is a unique opportunity to integrate relatively new technologies in order to further understand the effects of freight on the state and to apply this information to the country. The proposed research fits the Tennessee Department of Transportation (TDOT) Strategic Management Plan in the “Address Customer Needs and Priorities” emphasis area. This research directly addresses difficulties encountered by TDOT personnel in effectively integrating freight transportation into the long-range transportation planning process. Additionally, the use of raw GPS truck data presents rewarding opportunities for understanding travel times and trip distribution on Tennessee roadways. Finally, the research will enable the identification and prioritization of key trucking corridors in Tennessee.

The report is organized into five sections. Section 1 outlines the process developing performance measures and models that can accurately represent the effects of volume on intermodal facilities within the Memphis area through the use of GPS data. Section 2 contains the analysis of corridor travel time along major shipping routes within the state. Section 3 develops a process of determining the location of interstate truck border crossings as well as the beginning and end of trucks trips within Tennessee. Section 4 uses the GPS data to determine the location of truck stops and rest periods demands for truck operators along freight routes. Section 5 reviews the classification of low clearance bridges and excessive curvature to validate truck-prohibitive geometrics in Tennessee.

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1. MEMPHIS INTERMODAL FACILITY TURN TIMES MODEL DEVELOPMENT

1.1 Introduction

Freight movement is one of the most important aspects of economic development in the country and the world. The 1991 transportation bill, ISTEA changed the focus of transportation developments and improvements from the "blind" expansion of the road network to an emphasis on planning to increase efficiency of the current network. Research into understanding the movement of freight is an important aspect to road network efficiency. Understanding of the industries performance measures (PM's) is key to defining methods of not only measuring the effectiveness of the system, but also developing methods to make the system more efficient (*1,2*).

This report will analyze intermodal (road-rail), warehouse, and distribution facilities to determine associated PM's for the Memphis, Tennessee area. Unfortunately, there is currently little study being conducted on the PM's that are associated with facility turn times unrelated to intermodal yards. This is unfortunate because road-rail intermodal facilities are predominate intermodal freight facilities in Memphis. According to a study completed by Huynh and Walton, one of the key PM's for an intermodal terminal given today's increased level of freight is a ports truck turn time. This is the time is takes the truck to enter the facility, perform the task (loading/unloading), and exiting the facility. By affecting the length of a truck turn time; the port can limit the "environmental impacts, reduce landside shipping cost, and improve national economy" (*3*). California requires ports adopt either gate appointments or off-peak hour arrivals to reduce queuing lengths (*4*). Gate appointments and off-peak hour arrivals have been shown too effectively decrease turn times within port terminals (*5*).

The complicated process of "turning" a truck requires a great deal of understanding of the inner workings of not only intermodal facilities, but warehouses and distribution facilities. Effective scheduling of trucks to doors is a method used by specialized warehouse facilities known as cross-docks. A cross-dock minimizes the amount of time that a product is stored (*6*) which requires significant door allocation planning. Finding an optimal allocation process and thusly reducing turn time is important to reducing overall cost (*7*).

Due to the proprietary nature of private facility PM's such as turn times, it is difficult to develop performance models for the different types of facilities. Research on the matter must then be relegated to turn times produced by modeling algorithms. This research however utilizes GPS location data to give a unique insight into truck turn times at a level of precision that would be difficult to accomplish with the current method.

1.2 Data

Data from the American Transportation Research Institute (ATRI) in congress with the Federal Highway Administration (FHWA) collected truck GPS location data along 25 of the nation's highways. These data contains a unique truck ID number, a time stamp as well as speed and direction for each truck in the program for the state of Tennessee.

The information is recorded for each truck every 5-15 minutes through the Freight Performance Measures Web-Based (FPMWeb) tool. It was collected over a two month period in 2011 between September 1 and October 31 and consists of more than 13 million data points. The study area consists of the Greater Memphis Area as defined by the Memphis Metropolitan Planning Organization excluding DeSoto County, Mississippi due to the fact that data is not available for this area. Figure 1 is a map of the study area.

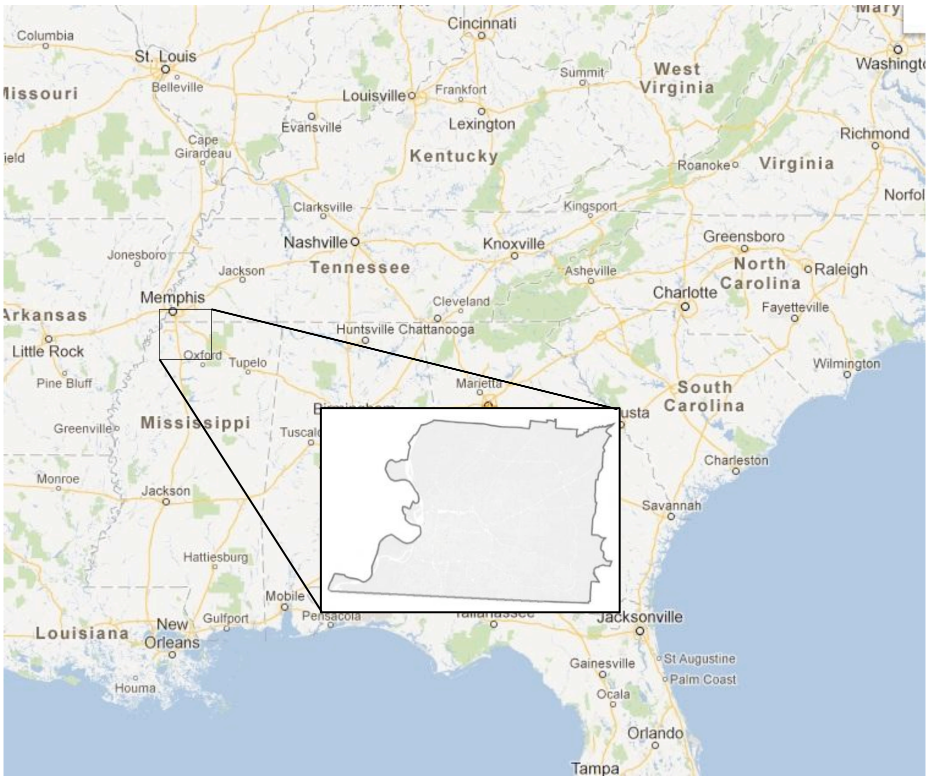

FIGURE 1 Memphis Study Area

1.3 Methodology

A Geographic Information Systems (GIS) program was used to analyze the spatial location of the data. To determine the truck turn times for facilities within the Memphis area, the data specific to those locations needed to be assigned a unique value for comparison to the surrounding data. This approach allows for a program to written that determines the length of stay within the facility for any given truck.

These data is can be used to determine truck turn times and truck volumes within the facilities that are being studied. However, due to the fact that the data provided is a small sample of the total truck volume, the information that is provided by these data is limited to general inferences rather than detailed analysis and the development of turn time prediction models.

1.4 Facilities of Interest

Memphis comprises of hundreds of facilities that aid in the steady movement of goods through the mid-south given the strategic location and infrastructure surrounding the city. In order to get a reasonable snapshot of the daily operations of these facilities, they first needed to be broken into facility type. The process yielded four facility types: Intermodal, Warehouse, Private Warehouse, and Distribution Centers. Then each facility type had several facilities that were chosen from a GIS map of different freight facilities in the Memphis Area. The facilities selected were determined to have enough data to produce significant results for the analysis.

Each of these facility types provides a unique service to the transfer of goods through Memphis. The intermodal facility expedites the transfer of goods between modes of transportation. While Memphis utilizes over water transport, via barge, and air transport, this study does not include these facilities due to the limited data available for ports and the possible legal issues associated with facility operations.

"Public" warehouses and private warehouses perform the same task, however, the defining characteristic between the two facilities are the specialization of goods flow through the facility. Private warehouses are defined in this study as a facility type is managed and run by a singular company. The trucks that enter and exit are owned and operated by the company, making delays caused by unfamiliar routine less impactful. Warehouses typically store products for several businesses and some provide cross-docking facilities. While the facility may be operated by one company, the truck operators may be unfamiliar with facility specific routines or door locations causing delay in the loading and unloading process. Compounding the matter, the amount of goods and the consistency of flow of goods can vary for this type of facility.

Distribution centers perform a similar duty to private warehouses, but the type of goods being moved (size and weight) change very little. The facilities in this study are privately owned and move products such as electronics and clothing.

1.5 Results

The analysis of the GPS data was used to determine two specific performance indicators: turn times and the relationship between the number of trucks entering a facility and the average turn time of that facility on a given day. Table 1 displays the descriptive statistics of the turn time analysis for each facility.

The large standard deviations that can be seen in Table 1 are present for many of the facilities can be attributed to the number of trucks that remained in the facility over night or parked for the day. This may not be time that the facility is using to load or unload the truck, but it is occupying space within these facilities, and is worth including in this analysis.

Figures 2, 3, 4 and 5 show the distribution of the data for each facility. Figure 2 shows that the majority of the turn times are between 10 and 40 minutes. Figure 3 and Figure 4 have significant disparity between the turn times. There does not appear to be any pattern amongst the facilities in these figures. Figure 5 shows slightly more similarity between the different facilities. A majority of the turn times in these facilities occur between 10 and 90 minutes. The large deviation and significant number of outliers make prediction capabilities difficult for these data.

TABLE 1 Descriptive Statistics of Turn Time Results for Facilities

Facility Type	Facility Name	Total Trucks	September Avg. Turn Time (min)	Stan. Dev. (min)	Total Trucks	October Avg. Turn Time (min)	Stan. Dev. (min)
Intermodal		6366	33	44	6749	34	46
	A	3515	28	29	3792	26	29
	B	1181	31	35	1181	34	35
	C	1001	26	59	888	30	59
Distribution		1452	60	171	1533	73	226
	A	334	35	44	225	32	47
	B	28	50	54	50	54	62
	C	632	15	22	734	20	42
	D	623	126	246	757	171	300
	E	467	29	48	501	35	69
Warehouses		9553	52	234	8645	81	217
	A	7972	63	49	8120	68	55
	B	7	13	6	41	31	32
	C	310	151	319	N/A	N/A	N/A
	D	263	26	18	14	84	202
	E	140	71	113	166	74	120
	F	845	26	20	304	147	291
	G	16	16	19	N/A	N/A	N/A
Private Warehouses		3686	179	349	9348	173	341
	A	1242	223	321	6623	229	325
	B	2344	238	368	2635	183	379
	C	100	76	101	90	105	170

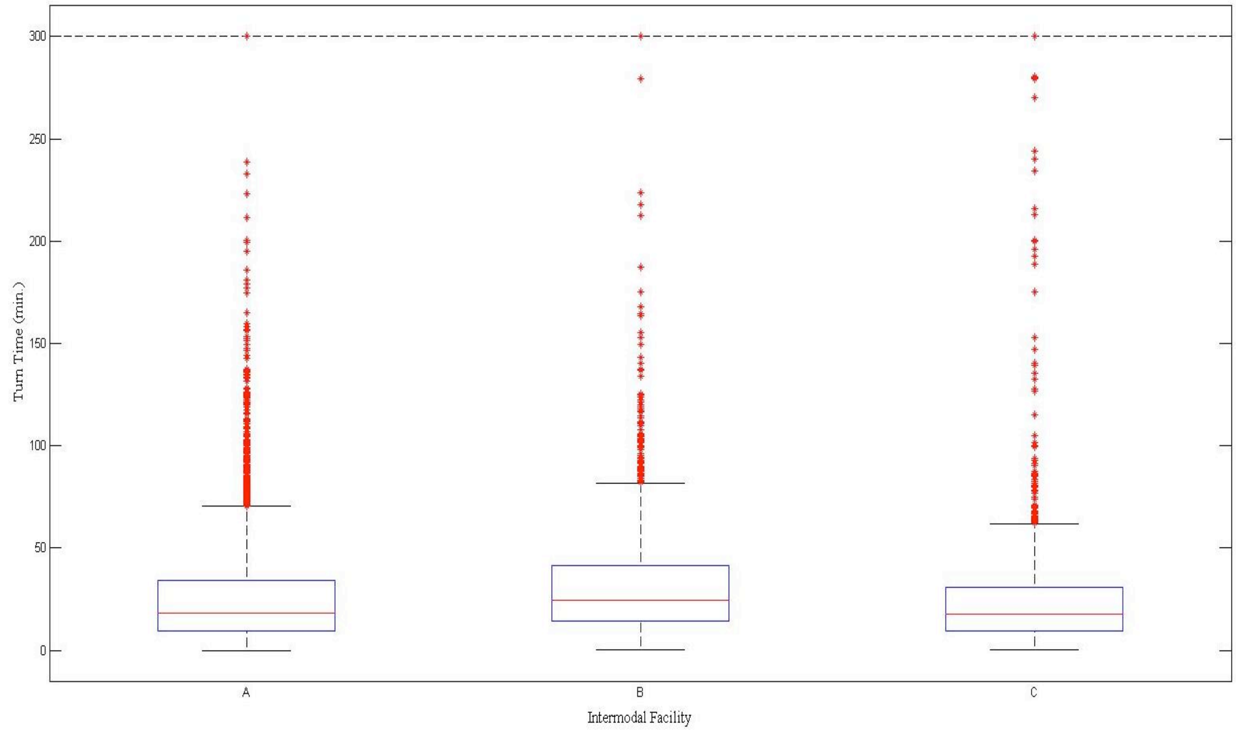

FIGURE 2 Turn Time Data Distribution for Intermodal Facilities

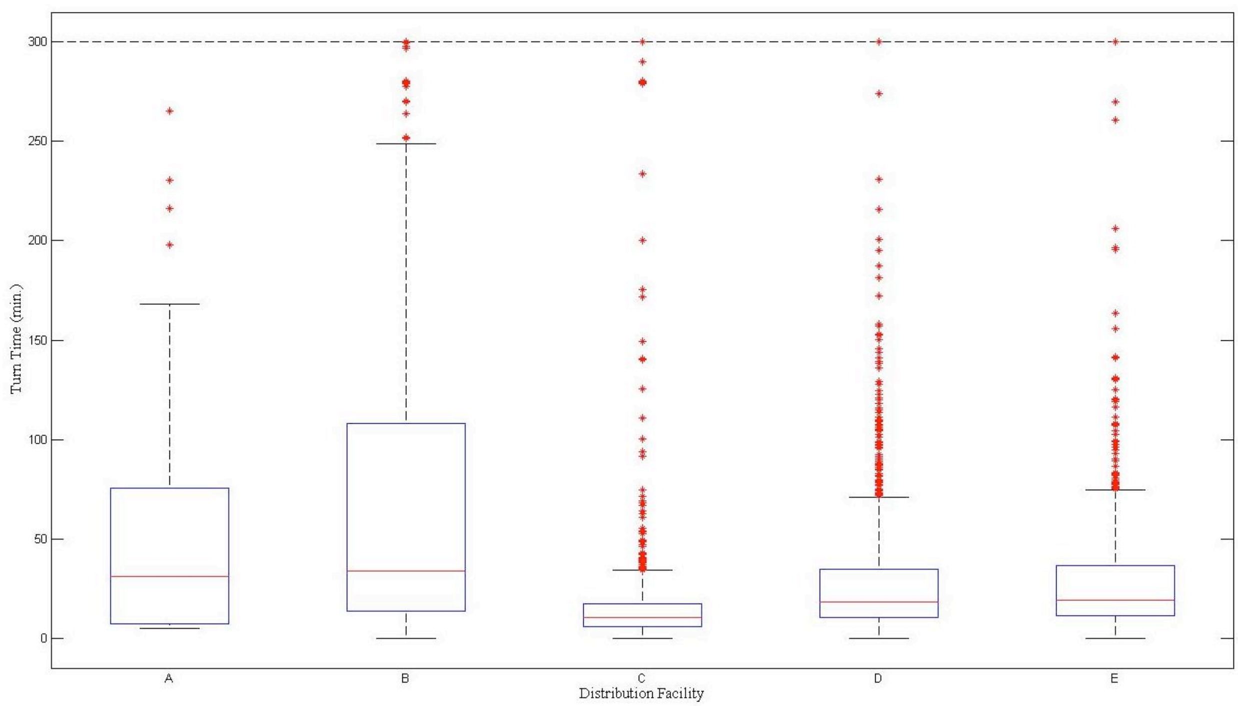

FIGURE 3 Turn Time Data Distribution for Distribution Facilities

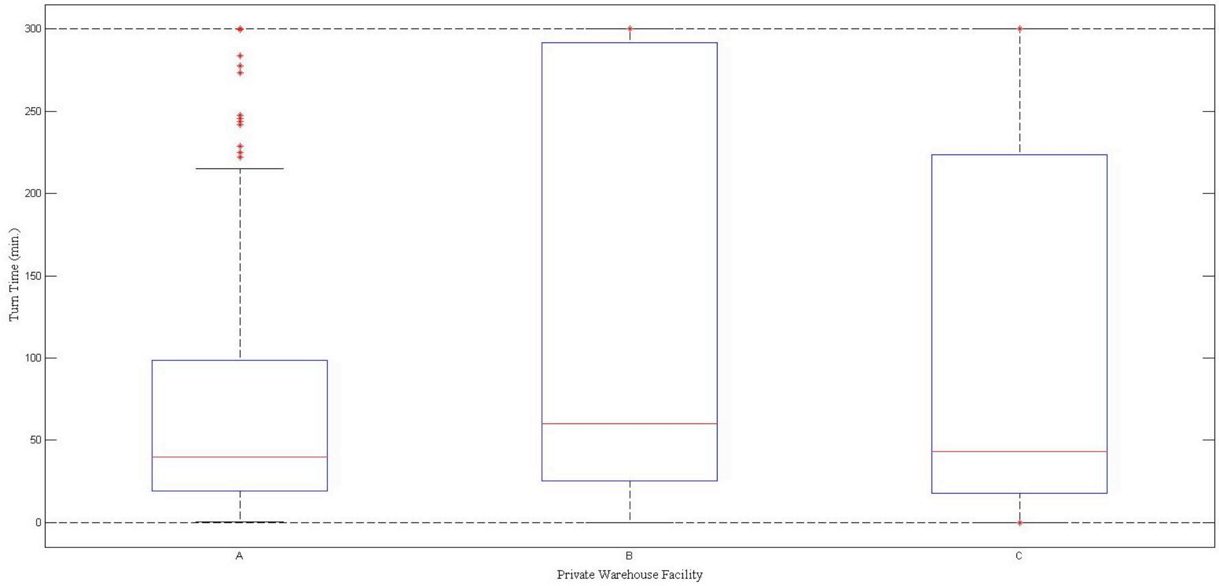

FIGURE 4 Turn Time Data Distribution for Private Warehouse Facilities

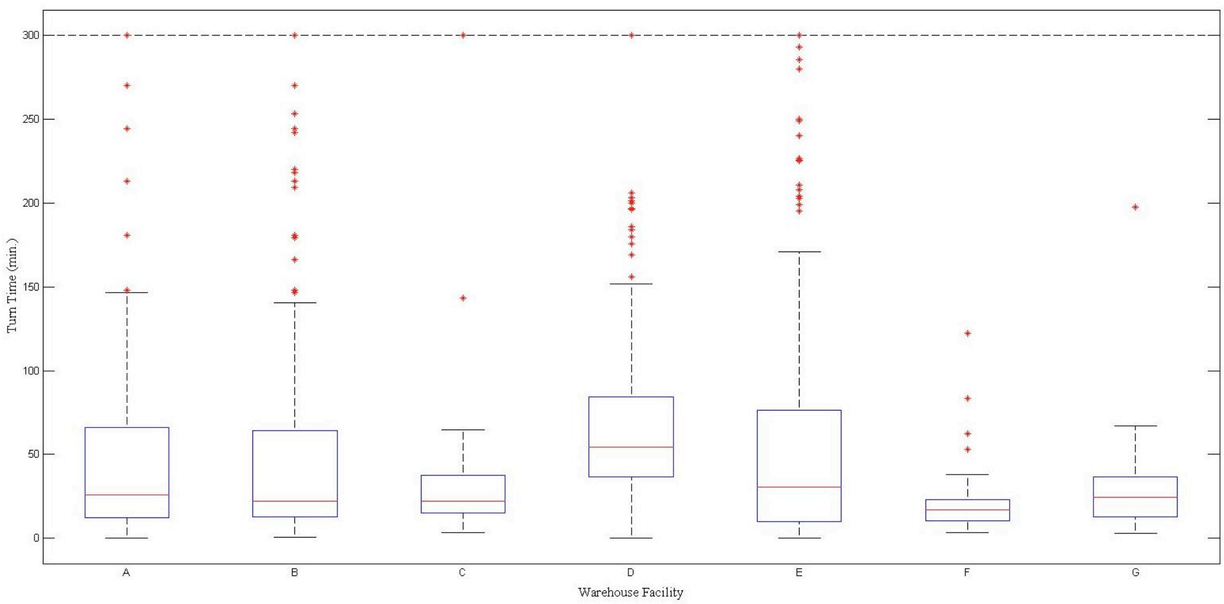

FIGURE 5 Turn Time Data Distribution for Warehouse Facilities

1.5.1 Turn Times

Figures 6 and 7 display the outcome of the analysis for the facility types studied. The results showed a skewing to the left with the frequency of turn time decrease drastically the longer the truck is within the facility.   Warehouse and Private Warehouse facilities have a larger percentage of the turn time occurrences happen in the 15-30 minute window, were as Distribution Centers and Intermodal facilities have lower truck turn times with a majority occurring within the 0-15 minute window. This can be attributed to the purpose of the facility meaning that Intermodal facilities handle large containers of standard size and Distribution facilities typically manage similar goods with similar, if not identical, loading and unloading processes. This is contrary to Warehouses and Private Warehouses where the type of product and the loading configuration can change with each truck load.

The large frequency of trucks remaining in the facility for longer than 300 minutes is an indicator for efficiency issues, but also how a specific facility type is used by the operators. Figures 6 and 7 both show that the Private Warehouse facilities have a significantly higher percentage of trucks remaining with in the facility. This could be attributed to the storage of vehicles overnight and/or the lengthened loading/unloading process that occurs at these types of facilities. Warehouses have the second highest percent of trucks remaining with in the facility longer than 300 minutes followed by distribution centers. All three of these facilities require a loading/unloading process that involves entering the container, which can take time. The Intermodal facilities however have very few vehicles that remain within the facility for longer than 300 minutes. The practices of Intermodal facilities are to turn a truck as quickly as possible. Unlike Warehouses, Private Warehouses, and Distribution Centers, whole containers on trucks removed and placed on the chassis to speed the movement of goods between modes.

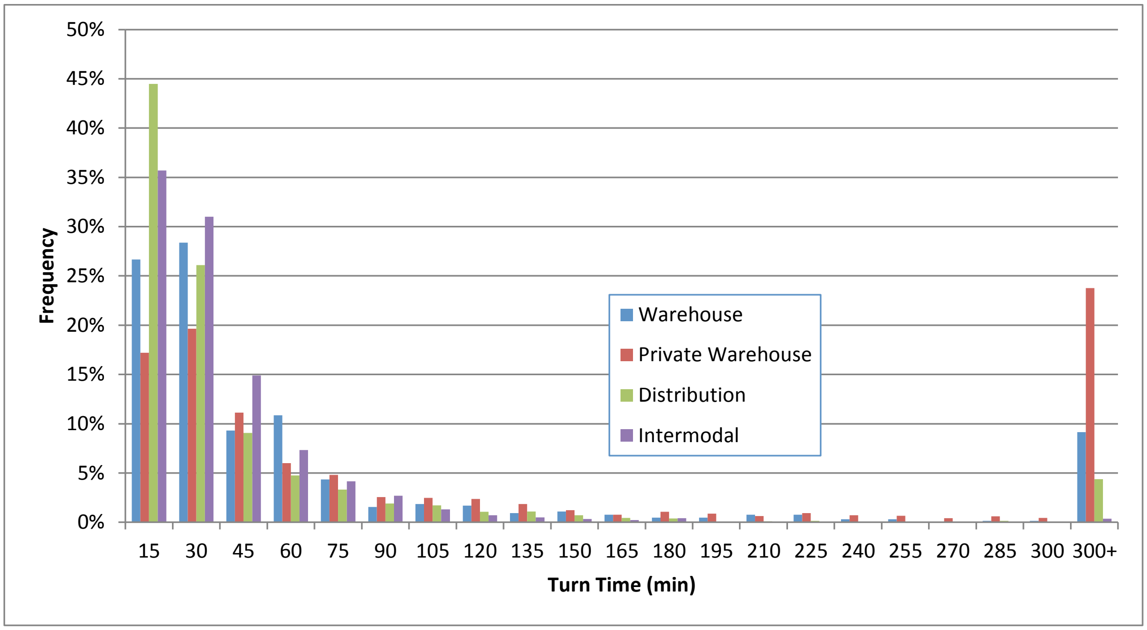

FIGURE 6 Histogram of Turn Times for September

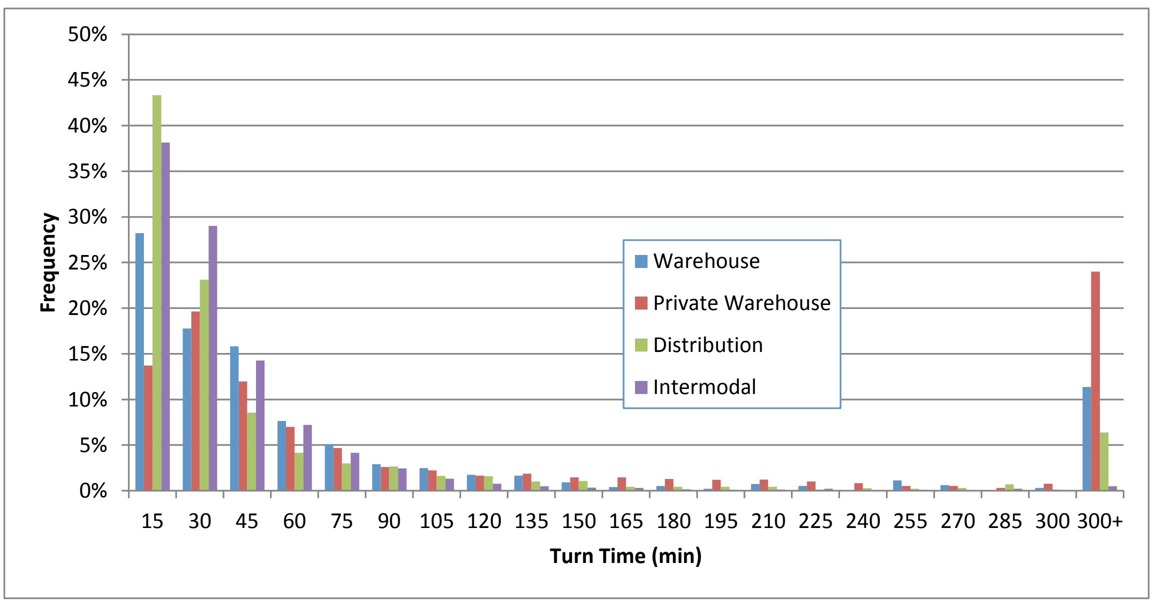

FIGURE 7 Histogram of Turn Times for October

1.5.2 Development of Turn Times Model

Using the data from ATRI has the potential to provide a unique understanding of truck turn times that is unavailable through any other means of data collection. However, the data is only a small sample of the actually truck traffic in the study area. Not knowing the exact number of trucks that were in each facility at the time the data was recorded limits the prediction capabilities of the model. This is due to a level of uncertainty that is created when building a model based on incomplete data and unknown arrival frequency for each facility. A study in Oregon attempted to utilize count data and GPS data to determine an expansion factor, but found that there was no discernable relationship between the two (8). In order to solve the problem, information on actual truck volumes must be gathered from the facilities researched. This information is typically proprietary and it is unlikely that the information will be obtained.

The insufficient nature of these data requires an alternative approach to determining a facility turn time model. Assuming that the volumes, produced in Section 4.3, and the number of trucks entering, produced in Section 4.4, are representative of the facilities actual demand pattern, interval percentages based on average total daily volume for each facility can be used. The variables of turn time and 15-minute interval percentages for daily facility volume and entry volume were regressed to develop models.

Intermodal Facilities (R^2=0.24)

$$Y = 20 + 275x_1 + (-390)x_2 \qquad (1)$$

Distribution Facilities (R^2=0.18)

$$Y = 11 + 993x_1 + (-576)x_2 \qquad (2)$$

Private Warehouse Facilities (R^2=0.01)

$$Y = 137 + 1x_1 + (-259)x_2 \qquad (3)$$

Public Warehouse Facilities (R^2=0.06)

$$Y = 52 + (-155)x_1 + 1266x_2 \qquad (4)$$

where:

$Y = turn\ time$

$x_1 = \%\ daily\ volume\ per\ 15\ min.\ interval$

$x_2 = \%\ daily\ entrance\ volume\ per\ 15\ min.\ interval$

The R^2-values for each facility type are too low to suggest that the model produces a significant fit for the data. Several of the coefficients for volume (Eq. 4) and entering (Eq. 1,2, and 3) percentages are also negatives which is contrary to known information that as volumes increase, turn times also increase. The negative coefficients suggest that as the volume increases the turn times will decrease. These results reinforce the insufficient effects of the limited data on the development of a model.

1.5.3 Truck Volumes

By analyzing the volumes of trucks within a facility, it is possible to determine a facilities peak hour for use in traffic analysis and possibly for mitigation tactics. The volume graphs located in Appendix A show the combined volumes within the facilities during a 15-minutes period of time over the course of an average 24-hour day. The days are broken down into weekdays, Saturday and Sunday. It is important to remember that this is only a sampling and the actual truck volume can be assumed to be much greater.

Figure A-1 shows the average weekday volumes of a Private Warehouse. It is important to notice that there is significant volume with in the facility during the early part of the morning until midafternoon, when the volumes drop significantly. Figure A-2 shows the average volumes for a Warehouse. There is a noticeable spike in traffic between 1PM and 9PM. Figure A-3 shows that the average volumes for the Distribution Centers tend to be consistent throughout the day. Around 6AM there is a spike in traffic volumes for Facility B and D which could represent the start of the work day for the facility. There are several other minor spikes that could represent the typical times that these trucks are loaded and unloaded for the facility. Figure A-4 shows a drastic increase in volume between noon and midnight.

Private Warehouse and Warehouse facilities remain fairly consistent throughout the weekend. This could be associated to the facilities not being operational during the weekend and allowing trucks to remain in the facility as a parking area. Distribution Centers however are very inconsistent on Saturdays and appear basically inactive on during the morning on Sunday. Interestingly however, the volume decreases to nearly zero in the afternoon. There appears to be significant traffic on Saturday mornings for Intermodal facilities, but decreases by midday. Around noon there is an increases traffic which again slowly decreases. On Sundays, the Intermodal traffic looks like a typical weekday with a majority of the traffic entering during the afternoon.

1.5.4 Truck Entry and Exit Times

The entry and exit times of trucks for each facility can more accurately represent possible effects that these facilities have on traffic as well as detail the peak hours around the facility entrance. The volumes are averages for weekdays, Saturday, and Sunday. The actual number of trucks entering and exiting will most like be higher as the results are based on limited data (roughly 5 to 10% of the total truck volumes). The figures for entry and exit volumes are located in the Appendix B.

Figure B-2 shows several spikes that occur about every hour with large spike occurring at 6AM, 12PM, and 6PM. This is a common pattern for entering and exiting times for Private Warehouses (Figures B-1 to B-3). The patterns are much different for Warehouse facilities (Figures B-4 to B-10). Though the number of trucks entering the facilities is small, the bulk of the volume occurs between noon and midnight. This is consistent with the increased volumes within the facility. Distribution facilities (Figures B-11 to B-15) entrance and exit volumes show a decrease in traffic in the mornings followed by significant increase between noon and midnight. Intermodal facility (Figures B-16 to B-18) entrance and exit times are consistent with the volumes within these facilities. Most of the traffic appears to take place between noon and midnight.

Weekend entry and exit volumes for Private Warehouse facilities (Figures B-19 to B-22) look similar to the weekday volumes. There are large spikes that occur at 6AM, noon, and 6 PM with smaller spikes occurring about every hour. Interestingly, Warehouse facilities (Figure B-23 to B-26) have relatively little volume on Saturdays, but increased activity on Sunday. This is the same case for Distribution facilities (Figures B-27 to B-30). For both, Warehouse and Distribution facilities, there is a large increase in entry and exit volume between noon and 6PM on Sundays. Intermodal facilities (Figures B-31 to B-34) also show an increased activity level on Sundays as compared to Saturdays. The entry and exit volumes follow the pattern for the volumes within the facility on these days.

1.5.5 Average Turn Times and Volume Trends

Though developing an effective model to determine the effect on turn times by percent volume and percent entry volume of different facilities was not possible, it is possible to see trends that volumes have on average turn times. A visible inspection of the graphs showed that with increased volumes in the facility, the average turn times would increase as well.

The weekday graphs (Appendix C) for all the facility types show that as the volumes increased the turn times also increase. Unfortunately, due to the sparse nature of the data, the average turn time's line has several spikes. These spikes can be attributed to many factors, including the method of data collection via timed GPS "pings" rather than geospatial "pings" which would more accurately represent the vehicles entry and exit times. However, even with the large spikes in average turn times, it is possible to see a trend as it relates to volume. This provides greater evidence that the development of a model based on facility volumes to predict turn times would be feasible given information to help fill the gaps that the data cannot provide.

The Saturday and Sunday graphs (Appendix C) show the same relationship between volumes and turn times, but it is important to restate that many of these facilities do not operate on the weekends (specifically Warehouses). No graphs are available for facilities that are closed. If the turn time's line is on zero, it means that there was insufficient data to determine and average turn time.

1.6 Discussion and Conclusion

The research conducted on the GPS data has developed methods to effectively use GPS location data to determine truck turn times for use as a performance measure, however, the variance and uncertainty in these data population makes it nearly impossible to produce an efficient model for field use. Without increasing the number of trucks that are involved in the data collection process, obtaining a true representation of facility truck volumes will be impossible. As GPS systems become more widespread among truck companies, the ability and accuracy of prediction models for turn times, drayage operations and more will become feasible and useful.

Though the preliminary research shows promise, it should be stated that the precision of this GPS research is limited by the number of times location data is recorded. Given the distances that can be covered between 5-15 minutes of every recording can significantly affect the outcome of the research. Due to the method of extracting turn times from these facilities, the reported turn times could be less or more than true turn times. This false reporting can negatively impact the results. It may be prudent to decrease the time between location recordings to further increase the precision of the data.

Truck turn times are a significant measure of efficiency for a freight handling facility. By knowing the time it takes for a truck to enter and exit a facility, it will be possible to more effectively plan for traffic generated around the facilities which can lead to safer and more efficient traffic conditions. This information can be used by not only traffic planners, but also businesses and governments to further the understanding of freight movement.

2. CORRIDOR TRAVEL TIME ANALYSIS

2.1 Introduction

Travel time along a corridor can vary significantly throughout the course of the day due to congestion and environmental conditions. When analyzed over time, historical travel time data can provide insight into the best and worst times to traverse a particular corridor. This type of information is extremely valuable for facilitating efficient freight movement. A savings of ten minutes, while insignificant to an individual vehicle, becomes quite large when compounded across thousands of vehicles daily. Historical truck GPS data can be used to calculate travel times across a corridor by time of day to determine, on average, when to depart for the quickest possible trip. The following describes how this type of analysis was performed for Interstates 40 and 65 in Tennessee using ATRI's database of truck GPS positions.

2.2 Methodology

ATRI's truck GPS database contains hundreds of thousands of unique trucks, which generate billions of GPS position reads annually. A portion of these database, representing points in Tennessee during September and October 2011, was isolated to perform this analysis. Each position read contained information on the vehicle location (latitude and longitude), timestamp, and vehicle speed. A polyline GIS shapefile was created for each direction of travel on Interstates 40 and 65 and those polylines were divided into segments of approximately one mile each. Every segment was assigned a unique identifier. A 35 foot buffer was extended from each one mile segment to create a polygon shapefile for each segment. Any GPS position read that fell within a polygon was then associated with that particular one-mile highway segment. The points within each polygon were then aggregated according to the hour of the day each point occurred and the average speed for each of the 24 one-hour time bins was calculated. These average speed values were then converted into travel times that were adjusted for the precise length of each segment.

With this information, an algorithm was used to simulate a vehicle traversing the corridor based on 24 different starting times. The simulated time was adjusted by compounding the travel times of each one-mile segment based on the hour of the day. Once a vehicle crossed into a new one-hour time bin (e.g. from 12:59 PM to 1:00 PM) the corresponding average travel time for that one-hour time bin was utilized. At the conclusion of each corridor, the ending time was noted and the starting time was subtracted from the ending time to yield total trip time. This resulted in 24 travel times based on different trip start times.

2.3 Results

Figure 8 shows the results of the I-40 analysis (note: all times are in Central Daylight Time). The travel time on I-40 eastbound ranged from a minimum of 7 hours and 22 minutes (8 PM departure), to a maximum of 7 hours and 39 minutes (2 PM departure); a difference of 17 minutes. The westbound trip was similar, with a minimum of 7 hours and 20 minutes (10 AM departure), and a maximum of 7 hours 35 minutes (4 AM departure); a 15 minute difference. The peak travel hours in the Nashville area appeared to contribute the most to the increased travel times, although Memphis congestion likely impacted travel as well.

Figure 9 presents the I-65 analysis (note: all times are in Central Daylight Time). The travel time on I-65 southbound ranged from a minimum of 1 hour and 57 minutes (5 AM departure), to a maximum of 2 hours and 23 minutes (4 PM departure); a difference of 26 minutes. The northbound trip had a somewhat smaller differential, with a minimum of 1 hour and 57 minutes (11 AM departure), and a maximum of 2 hours and 18 minutes (7 AM departure); a 21 minute difference. Clearly, Nashville congestion during peak travel periods are contributing to the increased travel times in this corridor. Interestingly, while the I-40 trip covered three times as many miles and two major metropolitan areas, the shorter I-65 trip had a larger variability in average travel times.

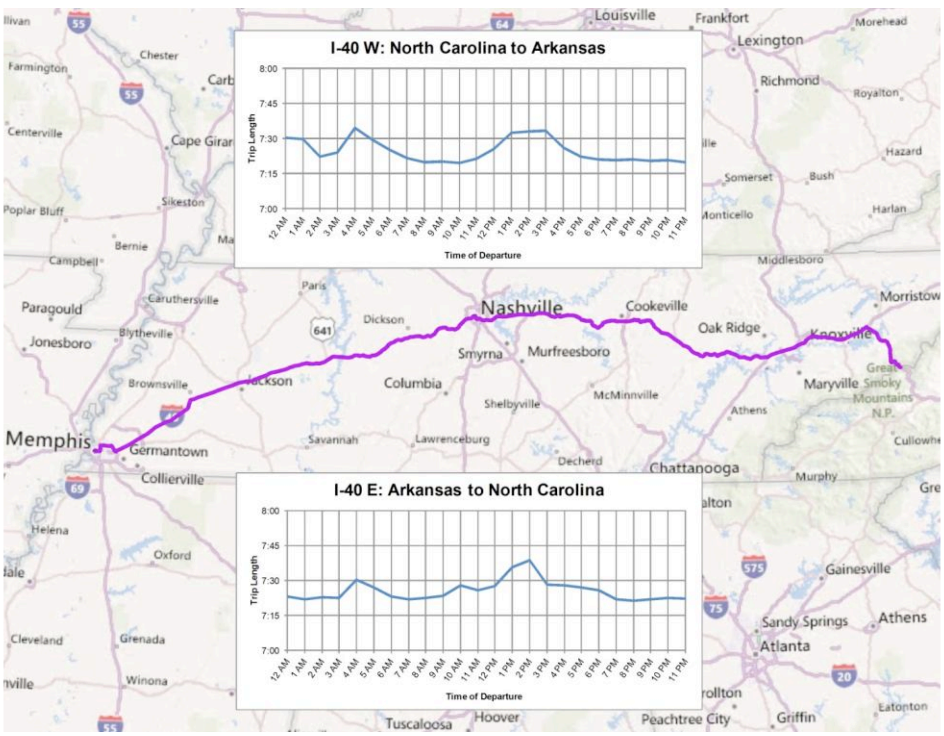

FIGURE 8 Travel Time on Interstate 40 by Time of Departure

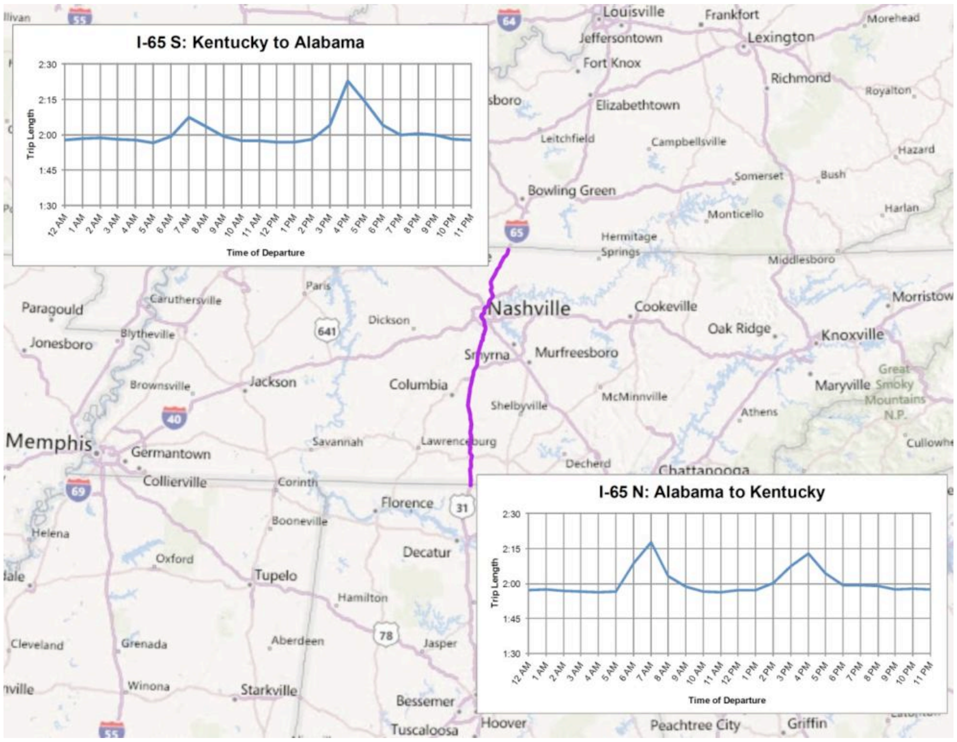

FIGURE 9 Travel Time on Interstate 65 by Time of Departure

3. IDENTIFY AND ANALYZE TENNESSEE'S PRIMARY TRUCK FREIGHT ROUTES

3.1 Introduction

In support of the University of Memphis-led GPS/GIS Analysis of Tennessee Truck Trips Study, the American Transportation Research Institute (ATRI) has investigated innovative methodologies for measuring truck activity in the State Tennessee. The following section summarizes the research activities undertaken by ATRI as part of this effort.

3.2 Methodology

3.2.1 Development of Truck Trip Tables

The first step of this research was the development of truck trip tables. Data used in the development of these tables was for activity during a two month time period that spanned September 1, 2011 through October 31, 2011. The data was limited to points within the State of Tennessee and 50 miles outside of the TN border. A series of 65 exit station polygons were created along key corridors to more specifically identify where trucks entered and exited the state.

The GPS data was sorted by the time/date of the position read to identify when trucks entered or exited the state. Any position read that was outside of TN but was subsequently followed by a position read that was inside TN was coded as "ENTER." All prior out-of-state points were then deleted from the dataset. Conversely, any position read that was inside TN but was subsequently followed by a position read that was outside TN was flagged as an "EXIT." All subsequent points that were out-of-state were then deleted from the dataset. One exception to these enter/exit rules was that if a vehicle exited the state but re-entered the state within 30 minutes, it was not counted as an entrance or exit. This was done due to the large amount of freight activity that occurs in Tennessee near the state line, particularly in the Memphis and Chattanooga areas.

Daily truck trip tables were developed for each individual week and for the entire two month period. The tables linked exit station or zip code level origin/destination activity into the following categories:

1. External-External: Exit Station to Exit Station
2. External-Internal: Exit Station-to-Zip Code
3. Internal-External: Zip Code-to- Exit Station
4. Internal-Internal: Zip Code-to-Zip Code

Once the analysis dataset was created, it was sorted first by unique truck identifier and then by the time and date of the position read. Within the points of each unique vehicle, the distance between points (calculated using the great-circle distance method), the time between points, and the space mean speed between points was calculated. A series of logical tests were applied to the data to determine trip origins and destinations. It is important to note that it is impossible to correctly identify 100 percent of the trip origins and destinations from the dataset. The algorithm used for this research can easily be modified, however any modifications will likely affect the results in both positive and negative ways.

The first set of logical tests determined whether or not the vehicle was stopped or moving. If the spot speed was "0", the vehicle was coded as "STOPPED." Space mean speed was also used to determine when the vehicle stopped. There were two logical tests used: "near-certain stop" and "likely stop." A near-certain stop was identified if the time between position reads was greater than 12 minutes and the space mean speed was less than one mile per hour. As for likely stops, if the space mean speed was less than 5 miles per hour, the vehicle was coded as "STOPPED." Generally the time between position reads was five minutes or greater, so it was assumed that if a vehicle was travelling less than five miles per hour over at least a five minute period, it most likely was stopped during a portion of that time. All other position reads were coded as "MOVING."

The next set of logic tests focused on determining whether a "STOPPED" code is due to a trip destination or other extraneous factors. Since truck rest stops are not true truck origins or destinations an attempt was made to recode a stopped vehicle at a truck rest stop as "MOVING" (i.e. the trip is continuing). To do this, a GIS polygon shapefile was created for every major truck rest stop in TN. Any position read that intersected that polygon was recoded from "STOPPED" to "MOVING". While the truck rest stop shapefile was not an exhaustive inventory of every rest stop, the number of incorrectly coded destinations was significantly reduced through this effort.

Another situation that created false origins/destinations was when a vehicle was at a true destination, but moved around within that destination (e.g. moving from different sides of a large distribution center). This issue, referred to as "micro-trips" in this research, results in a large number of very short trips if not mitigated. There were two logic tests sequentially employed to reduce the impact of this issue: "near-certain micro-trip" and "likely micro-trip". For near certain micro-trips, if a vehicle was coded as "MOVING" and either the immediately preceding or subsequent position read was coded as "STOPPED", the vehicle was recoded as "STOPPED", provided the space mean speed was less than five miles per hour and the vehicle was not at a truck rest stop. The likely micro-trip algorithm recoded a vehicle from "MOVING" to "STOPPED" when the immediately preceding trip was coded "STOPPED", the distance travelled was less than 0.25 miles, the space mean speed was less than 20 miles per hour, and the vehicle was not at a rest stop.

One of the most common scenarios that created false origins/destinations was when vehicles where stopped as a result of traffic conditions (traffic signals, congestions, etc.). A position read was recoded from "STOPPED" to "MOVING" if the total duration of the stop (i.e. the time between the first and last "STOPPED" position read) was less than 15 minutes.

The next set of logic tests was applied to identify the times between the end of one trip and the beginning of the next trip, known as "dwell time." Often vehicles may reach a destination and continue to generate position reads sporadically for hours, if not days. After a vehicle was identified as reaching a destination (i.e. coded as "STOPPED" after all logic tests have been performed), all subsequent position reads were coded as "DWELL" until the vehicle moved more than 0.25 miles between two consecutive points.

The final step of the trip algorithm was to identify the trip origins and destinations. An “ORIGIN” code was generated when a vehicle went from being coded as “DWELL” to “MOVING” (made a stop but began a new trip), “ENTER” (when vehicle enters the study area), or the first time “MOVING” is recorded for a unique truck. A “DESTINATION” code was generated when a vehicle went from being coded as “MOVING” to “STOPPED” or when coded as “EXIT” (left the state). At every position read coded “ORIGIN”, the trip start time was recorded, and a unique trip identifier was generated, based on the unique truck identifier and the trip start time. Once the “DESTINATION” position read was reached, the total trip distance and duration was recorded.

The origin and destination points were subsequently uploaded into GIS software and overlaid with the aforementioned exit station polygon and a polygon shapefile of zip codes within TN. A spatial join was conducted between the origin and destination points and the exit stations and zip codes. Each origin and destination point was assigned a zip code identifier if it was an instate origin/destination or an exit station identifier if it was an out-of-state origin/destination. These points were then exported to spreadsheet software where a pivot table was used to create an origin-destination table (O-D Table), with rows representing origins, columns representing destinations, and the subsequent matrix representing the number of trips for each O-D pair. Additional O-D tables were generated for each of the eight weeks of the two-month study period, using the trip start time as the indicator of which week a trip was located. Figure 10 shows O-Ds within the truck trips that have the greatest level of truck activity.

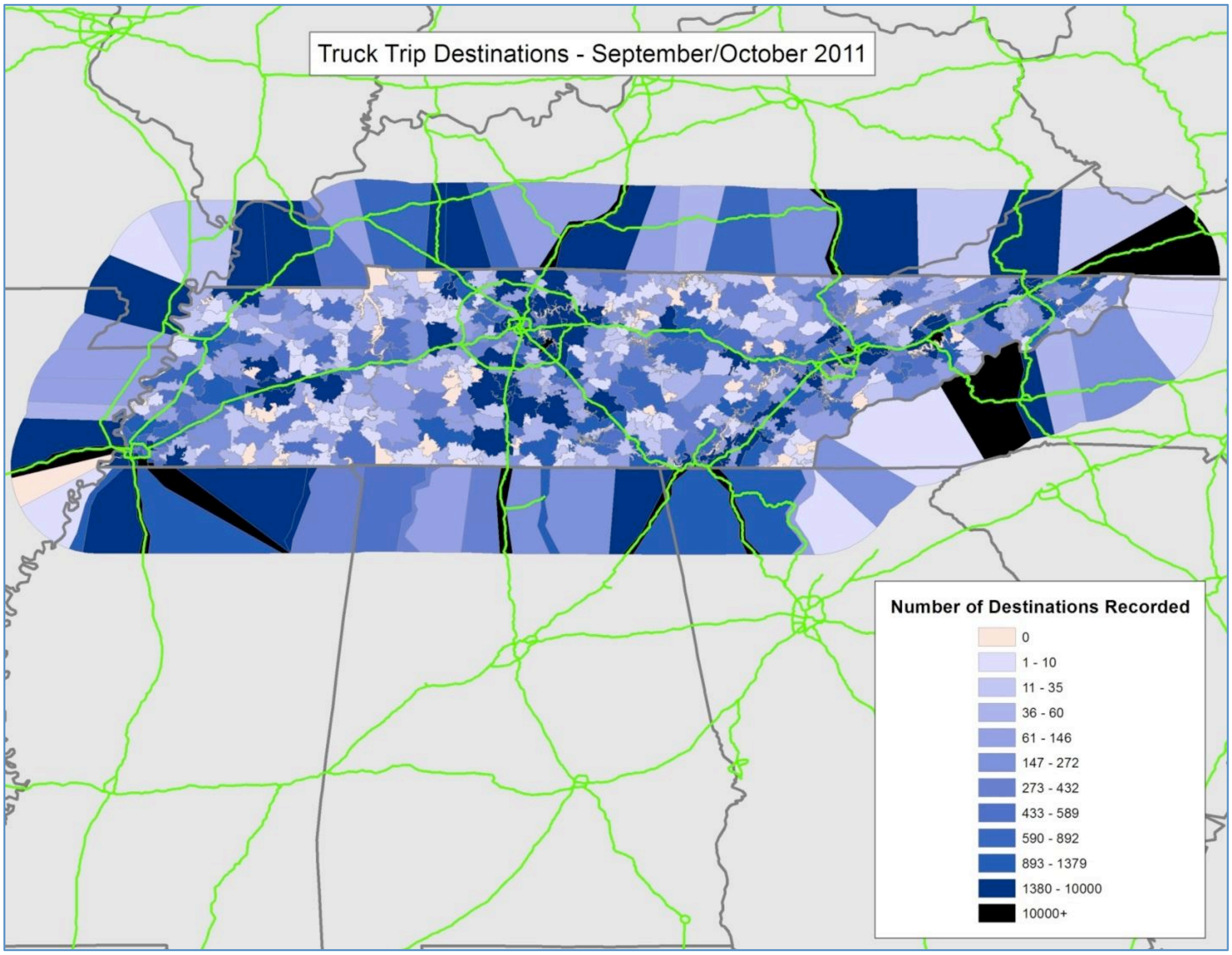

FIGURE 10 Destinations by Zip Code and Exit Station in Tennessee

3.2.2 Truck Flow Development

ATRI selected data from the aforementioned origin-destination table-source dataset for the truck flow analysis. In past research, this type of analysis had been conducted for vehicles that simply have a nexus in a specific geographic region; this process was improved upon as part of this effort by using data from the O-D dataset; thus vehicle trips that originated or terminated in a specific location can be identified.

As a proof of concept, ATRI selected data from the first one week period in the two month data set for vehicles that had an origin or destination (based on the aforementioned methodology) in Shelby County (Memphis) or Davidson County (Nashville). Data for these unique vehicles were then selected from a national database for the one week time period, and the data points were linked to create a GIS database of truck flows to/from the Memphis and Nashville locations. Figure 11 represents a map depiction of the results of the proof of concept, and the underlying shapefile was made available to the research team. Movement from approximately 4,000 trucks is included in shapefile depicted in Figure 2. This type of analysis could be applied to data from other time periods or data that has an O-D in other locations.

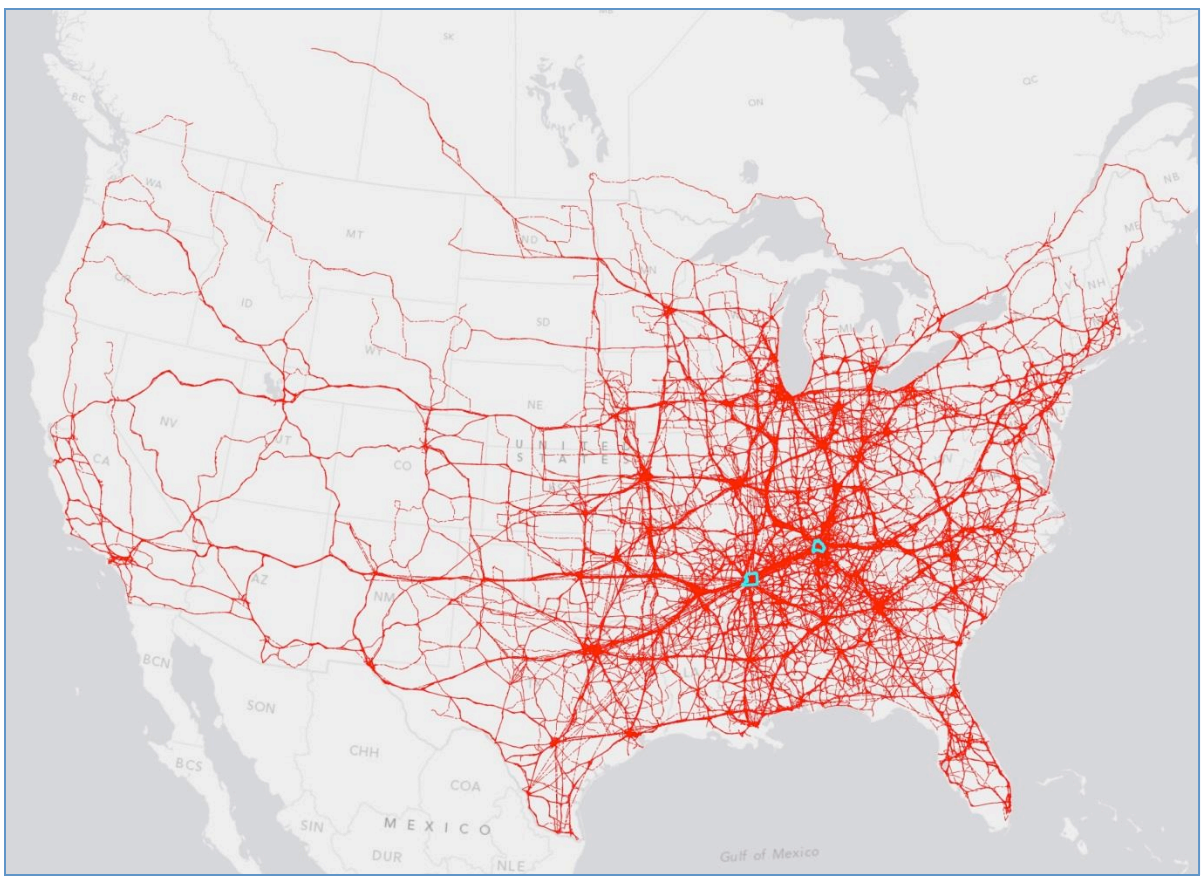

FIGURE 11 Truck Flows from Shelby and Davidson Counties

3.2.3 Truck Route Identification

Next, a proof of concept for an additional and unique GIS-based dataset was produced that allows for truck routes to be identified directionally. This was done by utilizing GIS and database management tools to estimate and aggregate truck trips that occurred within the state of Tennessee.

As a first step, activity for each one week time period within the two month sample dataset was averaged on a daily basis. Next, the truck movement derived from the sample dataset was linked to a polyline GIS layer provided by members of the research team which represented freight-significant highways in Tennessee.

ESRI's Network Analyst allowed the research team to dynamically model truck trips within the GIS environment. When loaded into Network Analyst as a "stop," each point associated with a unique truck trip was spatially assigned to a portion of the underlying road network. This network was created from ESRI base-files, which were already modified to model realistic truck travel. The network represents the line geometry used to transform the disparate point data (stops) into connected truck paths/routes. With a sophisticated network dataset, the Network Analyst was able to determine which streets were most likely traveled between two known truck positions using information such as one-way travel restrictions and road hierarchy to make decisions. This process is known as the "solve" function and produces the routes as line features. Two major benefits of using Network Analyst to model the truck trips were that the truck routes follow the flow of traffic (and can be mapped by direction for a single corridor) and that the routes replicate actual street geometry as opposed to "as the crow flies" or "straight-line" geometry produced through the less refined "point to line" tool. When simulation of truck trip travel is not confined to roads, the actual travel distances and paths may be under-represented and inaccurate.

Once the routes were created for a one-week period Spatial Join Analysis determined the number of truck trips on each roadway segment. The Spatial Join Analysis is available through the Overlay Toolbox; such tools are used to determine which features are "on top" of other features and where this layering occurs. When the truck trip routes are modeled with Network Analyst, the resulting line geometry is nearly identical to the underlying road network, except that the road network segments maintain their length and the routes lengths vary based on the characteristics of the trip. Road segments may be merged and split during the solve process in order to display the trip as a single line. Therefore, all of the various routes from the truck trips "overlay" the network in the GIS. The Spatial Join Analysis counts how many truck trips overlay a specific segment and reports that number in a separate output. The daily averages for those segments were determined by dividing the total number of truck trips identified through the Intersect Analysis (for one week) by seven (days of the week). Each week's daily averages are recorded in the resulting GIS shapefile and underlying dataset.

The Figure 12 map displays truck trip counts and the corresponding GIS polyline shapefile along freight significant highways and interstates by direction for nearly 2,000 truck trips that occurred during the first week of the two month sample dataset. It should be noted that due to the size of the network, it is not feasible to display all of the truck trip count attributes in a static map image). The symbology of the polyline has been set so that segments with the highest truck trip counts are displayed in dark blue with a thicker weight and descending values are displayed in lighter shades of blue with thinner weights. When deployed in GIS, the user is able to click on any segment of any freight significant corridor and identify the truck trip counts through the data contained in the attribute table. The thickest and darkest blue lines are the routes most used by the sampled 2,000 trucks during the first week of analysis.

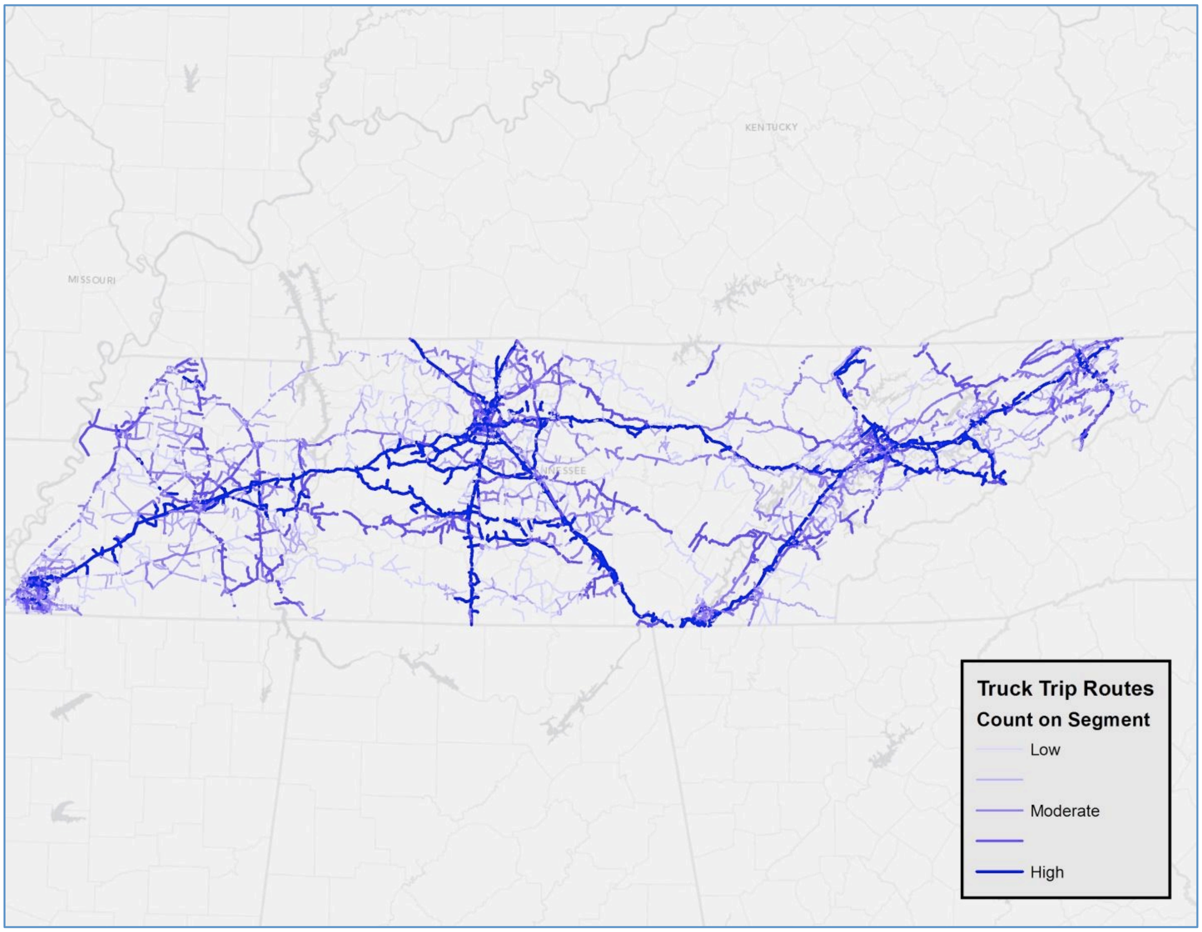

FIGURE 12 Truck Trip Proof of Concept

3.2.4 Urban Performance and Road Use

Finally, a series of performance measures were calculated in Memphis and Nashville (Shelby and Davidson counties, respectively). The average speed on selected major highways during the morning peak (6:00-10:00 AM), afternoon (10:00 AM – 3:00 PM), evening peak (3:00 – 7:00 PM), and offpeak (7:00 PM – 6:00 AM) were calculated for every one-mile interval by direction. In cases where highways were not median divided, the average speed was calculated for both directions together.

The average speeds were calculated from the resulting truck trip data points found in the truck trip table, which included latitude/longitude, timestamp, and vehicle spot speed for September and October 2011. For each highway segment that was analyzed, a 35 foot buffer was extended from the centerline, and any point that fell within that buffer was assigned to that highway segment. The points were then sorted by time of day, and the average speed was calculated for each of the aforementioned time periods. Figures 13 and 14 show the evening peak average speed for Shelby and Davidson counties (respectively). Please note that average speeds only include weekday time periods.

A rough indication of volume was also calculated for each highway segment by determining the number unique truck trip identifiers that fell within each 35 foot buffer during the 2 month timeframe. Figures 15 and 16 below show an example output of the volume analysis for Shelby and Davidson counties (respectively), representing the total number of trips over the 2 month study period. The underlying shapefile contains separate fields for the total number of morning peak, midday, evening peak, and off-peak trips. Where appropriate, the information is recorded by direction. Most segments are roughly one mile in length, but should be normalized for any type of analysis. Furthermore, adjustments should be made to segments that have one polyline for both directions, as it is counting trips in both directions.

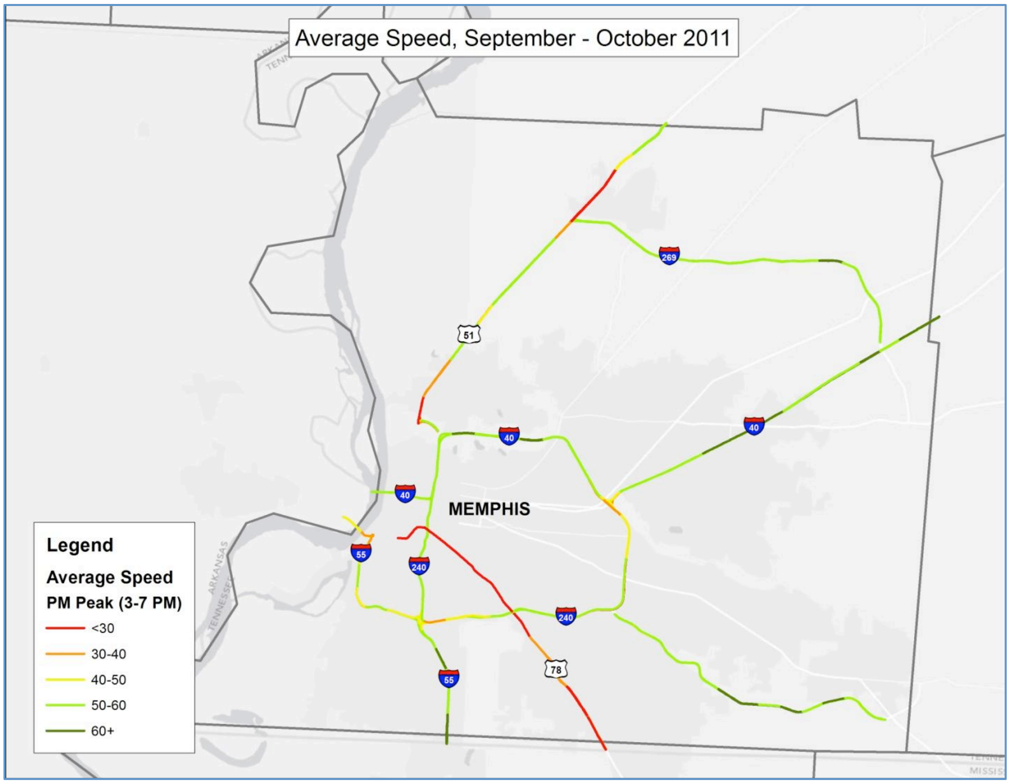

FIGURE 13 Average Evening Peak Speed, Shelby County

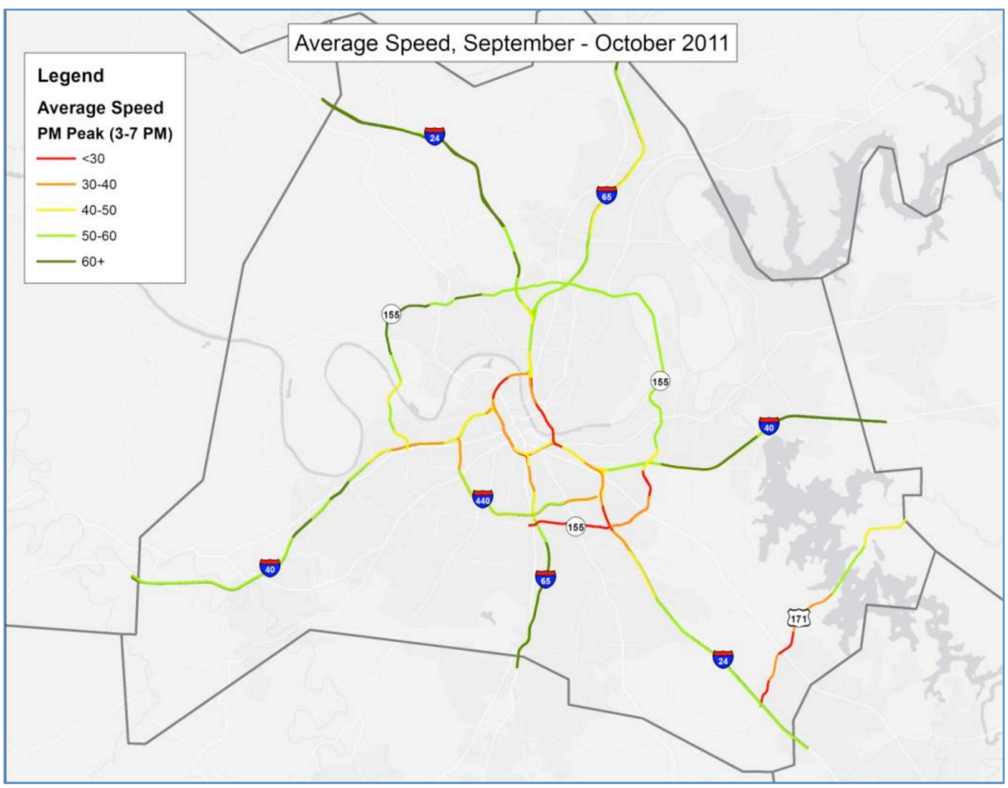

FIGURE 14 Average Evening Peak Speed, Davidson County

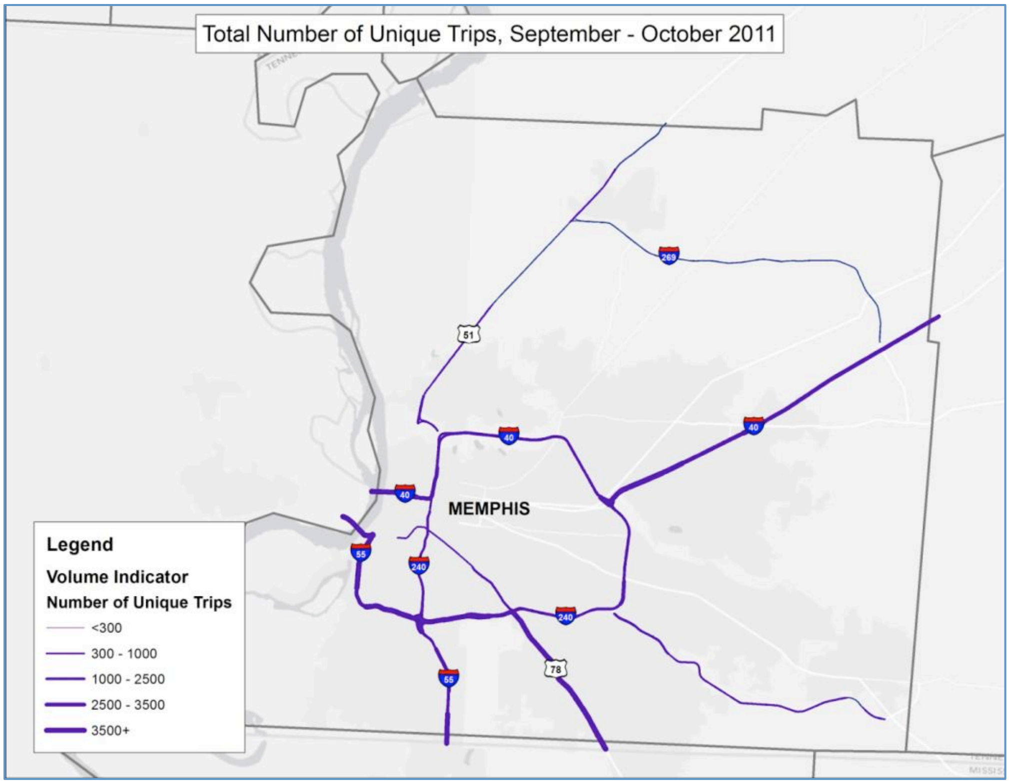

FIGURE 15 Total Number of Trips in Shelby County

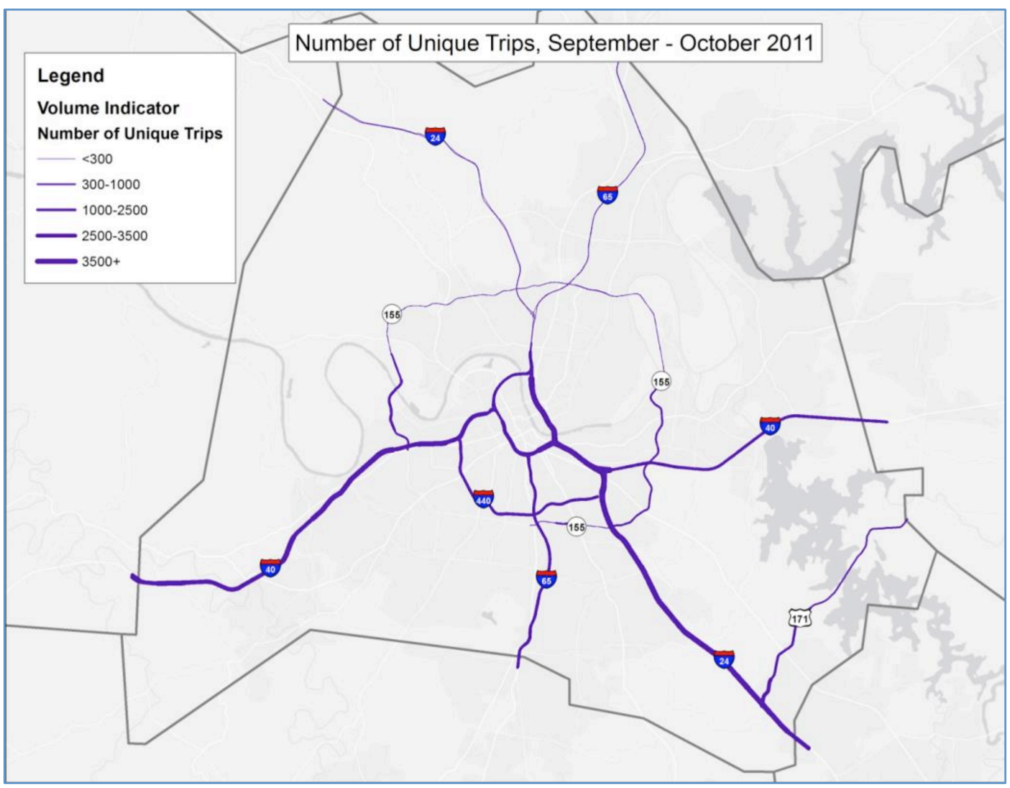

FIGURE 16 Total Number of Trips in Davidson County

4. TRUCK STOP AND REST STOP DEMAND ANALYSIS

4.1 Introduction

In the past the Tennessee Department of Transportation (TDOT) has expressed concern over the public safety issue related to the ability of trucks to find adequate parking capacity for rest and sleep. A trucker approaching an hours of service (HOS) limit may not be able to find available parking at the nearest rest stop. As a result, truckers usually either park on the side of the road or on an Interstate exit/entrance ramp or drive drowsy until they can find parking. This task is aimed at discovering more information about truck rest stops (e.g., peak demand hours), trucker rest/sleep patterns and the location of truck stops and rest areas in TN (by Interstate route).

4.2 Methodology

The first step in this research was to identify stopped vehicles which remained in the same position between 8-12 hours. This was done using Structured Query Language (SQL) statements within an Oracle database containing all 13 million plus truck positions. Using aggregate functions, coordinate pairs (latitude and longitude combinations) were identified with a common identification number (TRUCKID) where the speed was equal to zero miles per hour and the hours elapsed between the start and end time (or in database terms, the difference in hours between the minimum and maximum timestamps, respectively). Since GPS receiver readings can vary slightly, even for stationary objects, the precision of the latitude and longitude fields was rounded down by one decimal place (resulting in 6 decimal places rather than 7). The 7th decimal place of latitude/longitude represents a foot or less of geography precision. None of the trucks remained at the exact same latitude and longitude (to 7 decimal places) for 8-12 hours during the two month case study time period (between September 1, 2011 and October 31, 2011). However, there were 4,453 stops in TN lasting between 8-12 hours, 1,347 of these stops occurred within one half mile of the Interstate. These stops were considered to be occurring at Interstate truck stops/rest areas.

The following steps were used to determine where the rest areas and truck stops along TN Interstates are located:

1. Select all long-duration (8-12 hours) stop events within one half mile of the Interstate.
2. Identify clusters among these stops proximate to exit/entrance ramps.
3. Overlay these clusters on aerial photography within the geographic information system (GIS) to identify the area as a truck stop/rest area.
4. Create a polygon feature tracing the pavement of the rest area/truck stop. Buildings/structures and fuel islands were included in these polygons since it is assumed that each facility will need a proportional area to conduct operations. These structures often include fuel islands, restaurants, showers, convenience stores, truck/car washes, and/or small shopping areas.

5. Tag each long-duration stop event with the ID number and name of the truck stop/rest area in which it occurs.

Figure 17 shows the PETRO Truck Stop along I-40/I-75 in Knoxville, TN (exit 369). This figure shows all positions recorded during the case study period. Patterns can be detected, including trucks lined up for the truck wash at the northeast corner of the truck stop property. Figure 18 displays the same geographic area, with all stop events filtered out during the same time period. The clustered stop events align well with stopped trucks pictured in the underlying aerial photography, even indicating the heading of the truck by the location of the transponder. The stops occurring within the Knoxville PETRO station were compared to those occurring along Interstates. Figures 19 and 20 show a comparison of between the two aforementioned activity centers. Any number of similar analyses can be conducted using this framework (e.g., by region, route, day of week, etc.). Truck stops lasting less than 3 hours are likely representative of fueling operations and/or meals.

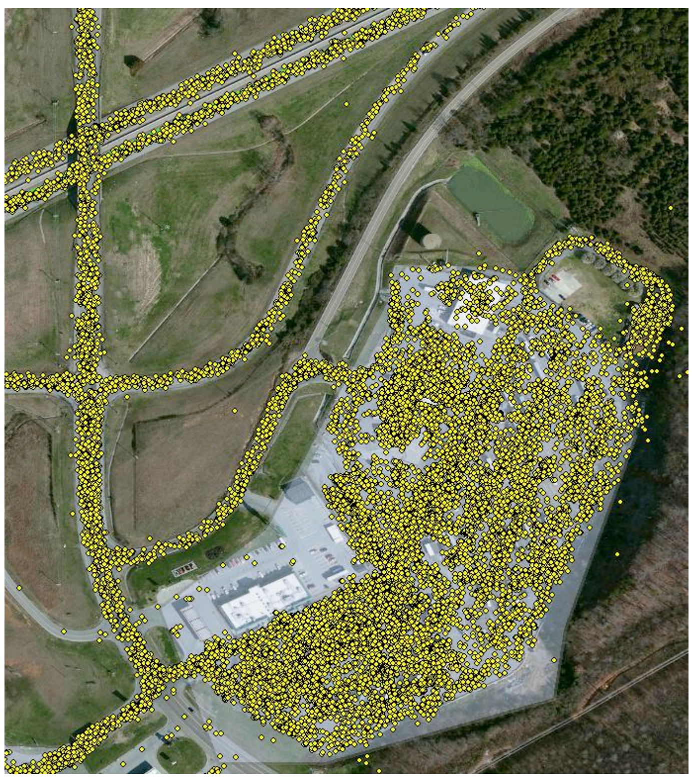

FIGURE 17 PETRO Truck Stop, Knoxville, TN, All Truck Positions

FIGURE 18 PETRO Truck Stop, Knoxville, TN, Truck Stop Events

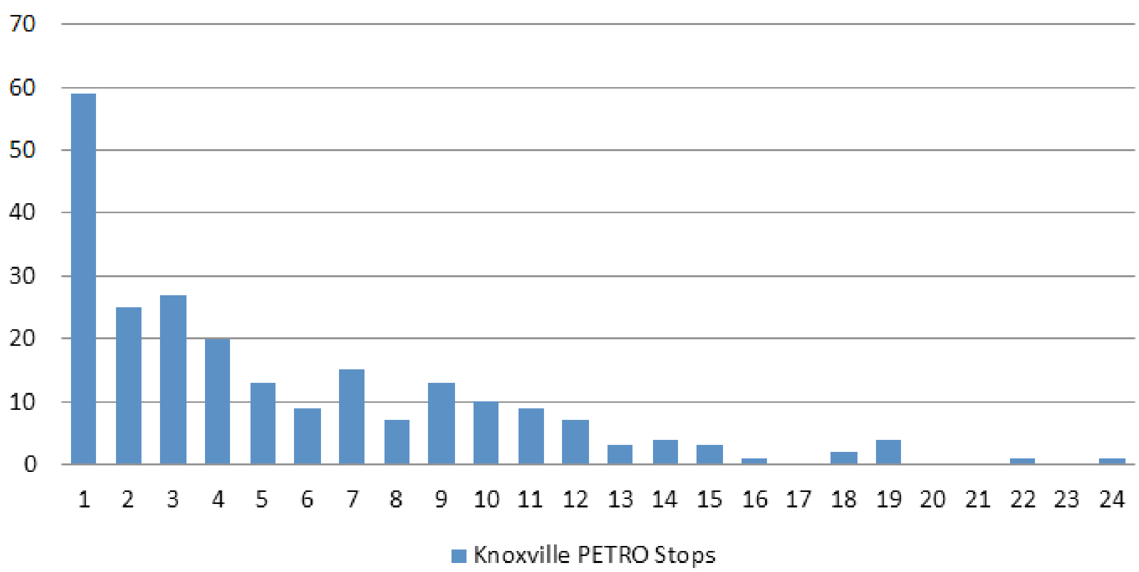

FIGURE 19 Frequency of Truck Stops at Knoxville PETRO Station.

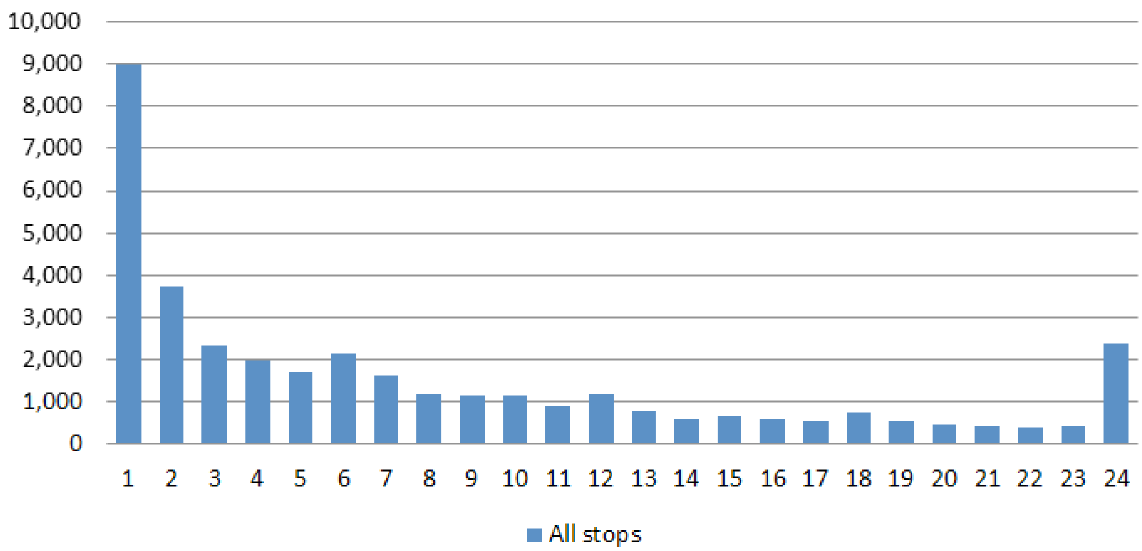

FIGURE 20 Frequency of Truck Stops by Hour (All Stops).

4.3 Results

Once the preceding five steps were completed, it is possible to count the number of stops by rest area and corridor and normalize this demand by the facility area (expressed in acres). The number and relative capacity (expressed in acres) by Interstate route is displayed in Table 2.

It should be noted here that not all trucks are outfitted with transponders that feed into the ATRI FPMWeb system. A rough estimate provided by ATRI indicated that approximately 20% of registered 5-axle trucks report to the FPMWeb system. There may be regional variations as to where these trucks are operating. Therefore, these numbers are relative (not absolute), and a multiplier cannot be applied to all truck stops to determine the actual demand at a truck stop on a given date. Aerial photography images containing truck stops (between 8 and 12 hours) and property outlines of two high-demand truck stops and rest areas are presented in Figures 21 and 22.

Further study of the captured Interstate truck stop events yields useful information about truck stop demand. Figures 23 and 24 show the total number of truck stops for the months of September and October of 2011. Additional research would be necessary to discover reasons more truck stop activity occurred in September and the spikes seen September 20th and October 29th. Note that the Interstate truck stop demand had much less variation and stayed relatively constant during this time period.

TABLE 2 Number and Area (acres) of Truck Stops and Rest Area by Interstate Route.

Interstate Route	Count	Total Acres	Average Acres/Rest Stop
I-40	54	339.8	6.3
I-24	24	113.3	4.7
I-81	13	73.0	5.6
I-65	11	53.2	4.8
I-75	12	43.9	3.7
I-26	1	2.3	2.3

FIGURE 21 Pilot Travel Center (LaVergne, TN: I-24, Exit 64)

FIGURE 22 Ponderosa Truck Stop (Charleston, TN: I-75, exit 33)

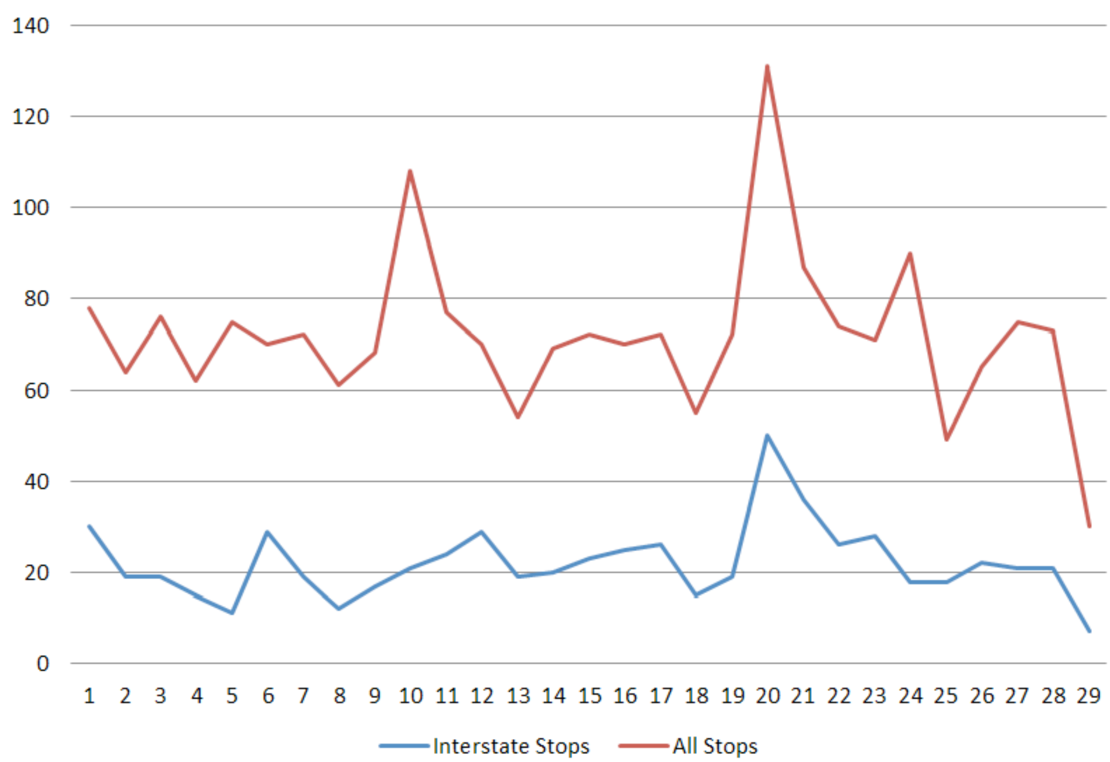

FIGURE 23 Number of Truck Stops by day during September

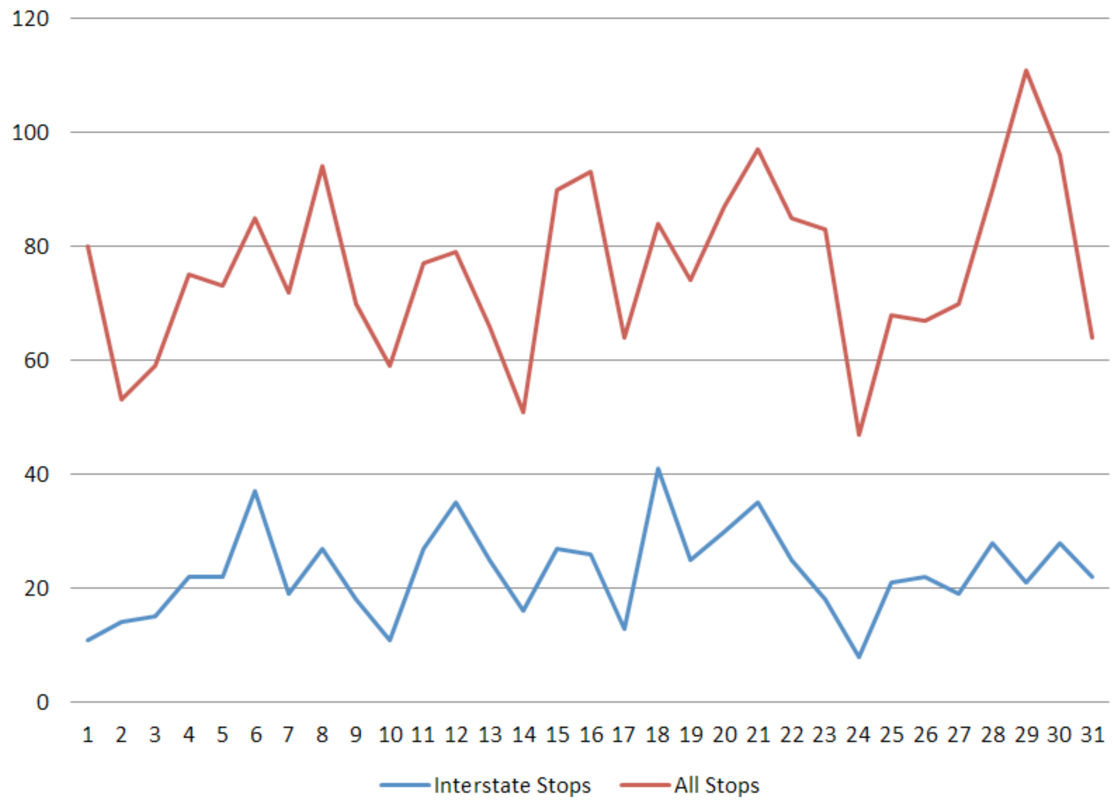

FIGURE 24 Number of Truck Stops by day during October

The data also yields day of week and hour of day demand information as shown in Table 3. The cells are colored from green to red indicating low to high demand, respectively. The morning and afternoon peak hours are shaded in grey. Of note is that there was a lull in the number of truck stop activity on Sundays and Mondays and that the majority of truck stops begin during the first 3 hours of the day (12am – 3am).

Table 4 illustrates the most common resting (stop event) pattern of truckers in Tennessee. Each row denotes the stops' begin time and the column indicates the stops' end time. Conditional formatting is applied to all of the columns (green to red, increasing number of records). For example, there were 59 stops recorded that began during the midnight hour and ended between 9am and 10am. The most common sleep pattern is to rest from between midnight and 2am until between 9am and noon, ostensibly truckers are attempting to avoid the morning rush hour. Interestingly enough, there is no increase in truck stop events before the afternoon peak hour.

TABLE 3 Number of Truck Stops by day of week and hour of day

Hour of Day (Start time)	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Totals
12 am	23	33	31	28	39	33	28	215
1 am	14	10	23	32	25	25	24	153
2 am	13	12	27	18	22	13	16	121
3 am	8	9	20	12	16	11	14	90
4 am	7	3	10	6	11	6	6	49
5 am	5	2	10	7	5	5	4	38
6 am	14	8	7	12	5	10	13	69
7 am	6	1	2	2	3	1	5	20
8 am	4	0	4	8	2	2	6	26
9 am	4	4	2	2	5	2	2	21
10 am	1	4	4	3	4	1	3	20
11 am	3	2	2	1	3	2	3	16
12 pm	2	8	0	4	1	1	5	21
1 pm	3	6	3	3	6	4	3	28
2 pm	2	4	4	3	2	5	7	27
3 pm	4	3	2	3	3	2	3	20
4 pm	2	1	2	3	1	2	4	15
5 pm	2	2	0	1	1	0	1	7
6 pm	6	11	4	6	2	4	7	40
7 pm	4	9	5	5	4	6	5	38
8 pm	8	6	12	17	12	7	9	71
9 pm	8	8	3	16	9	13	6	63
10 pm	9	10	9	20	20	14	17	99
11 pm	16	13	10	13	6	11	11	80
Totals	168	169	196	225	207	180	202	

TABLE 4 Number of truck stops by start and end times (Interstate truck stops, duration 8-12 hours)

End time of truck stop

Start time of truck stop	12a	1a	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	12p	1p	2p	3p	4p	5p	6p	7p	8p	9p	10p	11p
12a									27	59	49	50	30											
1a										29	37	40	39	8										
2a											13	34	46	19	9									
3a												17	38	21	13	1								
4a													19	10	11	5	4							
5a														14	11	7	3	3						
6a															18	25	11	9	6					
7a																5	5	2	5	3				
8a																	5	7	10		4			
9a																		1	10	7	3			
10a																			8	2	6	3	1	
11a																				3	5	4	3	1
12p	3																				8	7	2	1
1p	6	2																				7	8	5
2p	17	1																					3	6
3p	15	1	1																					3
4p	5	3	3	2	2																			
5p		2		2	2	1																		
6p			6	8	5	7	14																	
7p				3	7	9	18	1																
8p					5	9	34	14	9															
9p						13	28	9	9	4														
10p							24	30	12	22	11													
11p								5	23	22	21	9												

4.4 Conclusion

The raw data used in the case study is of very high quality, and can support sophisticated analyses, providing valuable information to the Tennessee Department of Transportation (TDOT) on rest area and truck stop capacity. As mentioned previously, this research effort was exploratory in nature. Additional knowledge discovery could be performed using a longer time period of data (a year or more). Truck events (including truck stops) could be correlated with weather, seasonal, temporal and geographic variations.

5. VALIDATION OF TRUCK-PROHIBITIVE GEOMETRICS IN TENNESSEE

5.1 Introduction

During a previous project, Vanderbilt performed a geographic information system (GIS) analysis of Tennessee roadways and historic incident data (interstate closures) to determine whether truck-specific alternate routes should be developed. The risk-based approach focused on areas with a large number of closures and a relatively high volume of truck traffic. Several criteria were developed during the project that would rule out or diminish the desirability of a roadway segment for routing truck traffic. These included low bridges (vertical clearance), excessive curvature (turning radius), bridge weight limits, high traffic areas, school zones and steep grades. Most easily validated using truck GPS data are the low bridge and excessive curvature segments.

5.2 Methodology

Using the National Bridge Inventory (NBI), 229 bridges in Tennessee with vertical clearances of less than 14 feet were selected and designated as impassable by 18-wheel commercial trucks. The process included verification of the NBI's recorded clearance in the dataset with the bridge using Google Street View. An example of this verification process is displayed in Figure 25. The majority of the low vertical clearance bridges were rail bridges in rural areas.

Using the ATRI/FPMWeb data, researchers were able to validate their selection criteria by selecting bridges under which a significant amount of trucks traveled during the two month period. The spatial selection process included selecting all truck positions within 150 feet of the low vertical clearance location. Truck positions where the truck was not moving (where speed = 0 miles per hour) were eliminated from the selection layer as the dataset included trucks that stopped at the bridge and turned around in some cases, and trucks stopped at warehouses close to the bridge. The next step included turning the selection around and selecting low bridges within 150 feet of the truck position.

5.3 Results

The process resulted in 64 low clearance bridges (out of the initial 229) which had truck positions within 150 feet. By manually zooming into each bridge, it was clear whether or not trucks were routinely going under the bridge or if the selection was a geographic anomaly (e.g., a truck position on a parallel road). At the end of this effort, 26 bridges (out of the 229) should not have been identified as too low for trucks. Thirteen feet, four inches should have been selected as the minimum clearance for trucks in the previous work instead of fourteen feet. Figure 26 shows a bridge which was wrongly selected. The red positions indicate truck positions within 150 feet of the bridge, the yellow positions are all positions. It is clear that trucks are routinely traveling under the bridge. In this example, the bridge clearance, 13.8 feet, should not have been selected and fell into the "invalidated" category. Figure 27 is an example of bridges where no trucks traveled under as all traffic is on the Interstate bridge deck. 203 out of the 229 bridges fell into this “validated” category.

FIGURE 25 Verification of NBI vertical clearances with Marked Clearance.

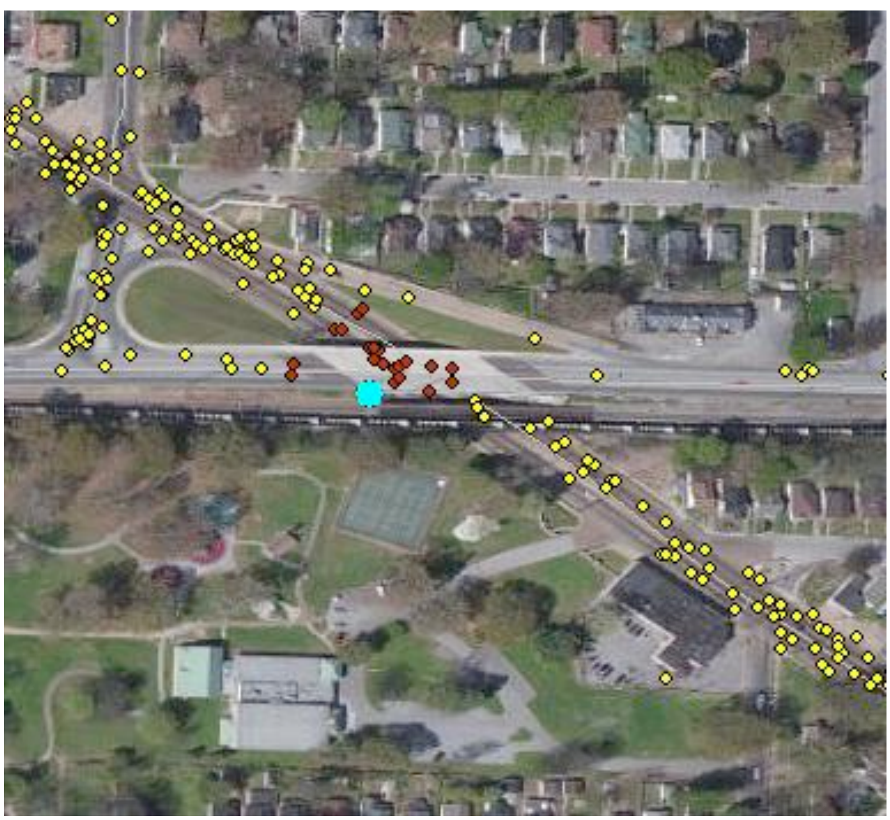
FIGURE 26 Example of an Invalidated Bridge Clearance Restriction

FIGURE 27 Example of a Validated Bridge Vertical Clearance Restriction

Excessive curvature was deemed to exist when the curve was greater than 12.5 degrees. This resulted in 16,671 Tennessee roadway segments being deemed impassable by 18-wheel commercial trucks. These segments were primarily located on local and residential streets. The validation process for excessive curvature segments was simpler than for low vertical clearance bridges, since the segments were polyline features (low clearance bridges were point features). This enabled a finer selection to be performed and statistics on the number of trucks traversing the segment were gathered. Truck positions within 25 feet of these segments were considered to have navigated the curve. Out of the 16,671 segments, only 1,807 (roughly 11%) of them had trucks successfully negotiate the curved segment during the two month time period. By performing a spatial join of unique truck positions to the excessive curvature segments, it is possible to calculate the number of trucks safely navigating each curve. Out of the 1,807 segments (where trucks indeed traveled), 906 were state routes and 901 were local roads. However, the state routes contained 28% of the truck positions, while the local roads were more heavily traveled by trucks (72% of positions). This indicates the largest number of truck trips successfully navigating local roads was trucks making their final deliveries, etc. The results of this research validate the methodology used in the previous research effort.

5.4 Discussion and Conclusion

The tasks completed by Vanderbilt as part of this research were exploratory in nature, and intended to explore the feasibility of using large amounts of truck GPS data for specific research tasks in Tennessee. These tasks included analysis of state line crossing locations, quantification of supply and demand at truck stops/rest areas and validation of previous research into truck-specific geometric limitations. While the state line crossing location study was superseded by the work ATRI performed using data points within and outside Tennessee, the remaining tasks demonstrated the high quality and useful nature of the ATRI/FPMWeb data.

The combination of relational database management systems (RDBMS), geographic information systems (GIS) and data visualization (Tableau Professional) proved very adept at handling the large amount of data. This combination of technologies could also be applied to the large amounts of traffic data that has been compiled by the Regional Transportation Management Centers (RTMCs).

The ATRI/FPMWeb data is useful in determining peak truck stop and rest area demand times, but more research should be conducted into the issue of sufficient parking capacity along Tennessee interstate corridors. The safety issue could be investigated along with additional research into how often truckers are forced to either drive drowsy to the next truck stop or park along an Interstate entrance/exit ramp. The geographic precision and detailed attributes contained in current crash and fatality data could support such research.

Information obtained during this report should be compared with recent research into transportation and fatigue. Establishing times of day when the majority of incidents involving trucks occur could be accomplished using FARS (Fatality Analysis Reporting System) or MCMIS (Motor Carrier Management Information System). This could be mapped with the most common resting patterns of truckers and those determined from this research to determine if there is a relationship between the times of crashes and the average number of hours since the trucker had rested.

The ATRI/FPMWeb data could be used to validate data maintained by TDOT. Such data includes metropolitan speed data, traffic incidents, severe weather events and traffic (vehicle mix data).

References

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2. Beskovnik, B., and Twrdy, E. Productivity simulation model for optimization of maritime container terminals, Transport Problems, Vol. 4 Issue 3 Part 2, 2009, pp. 112-122.
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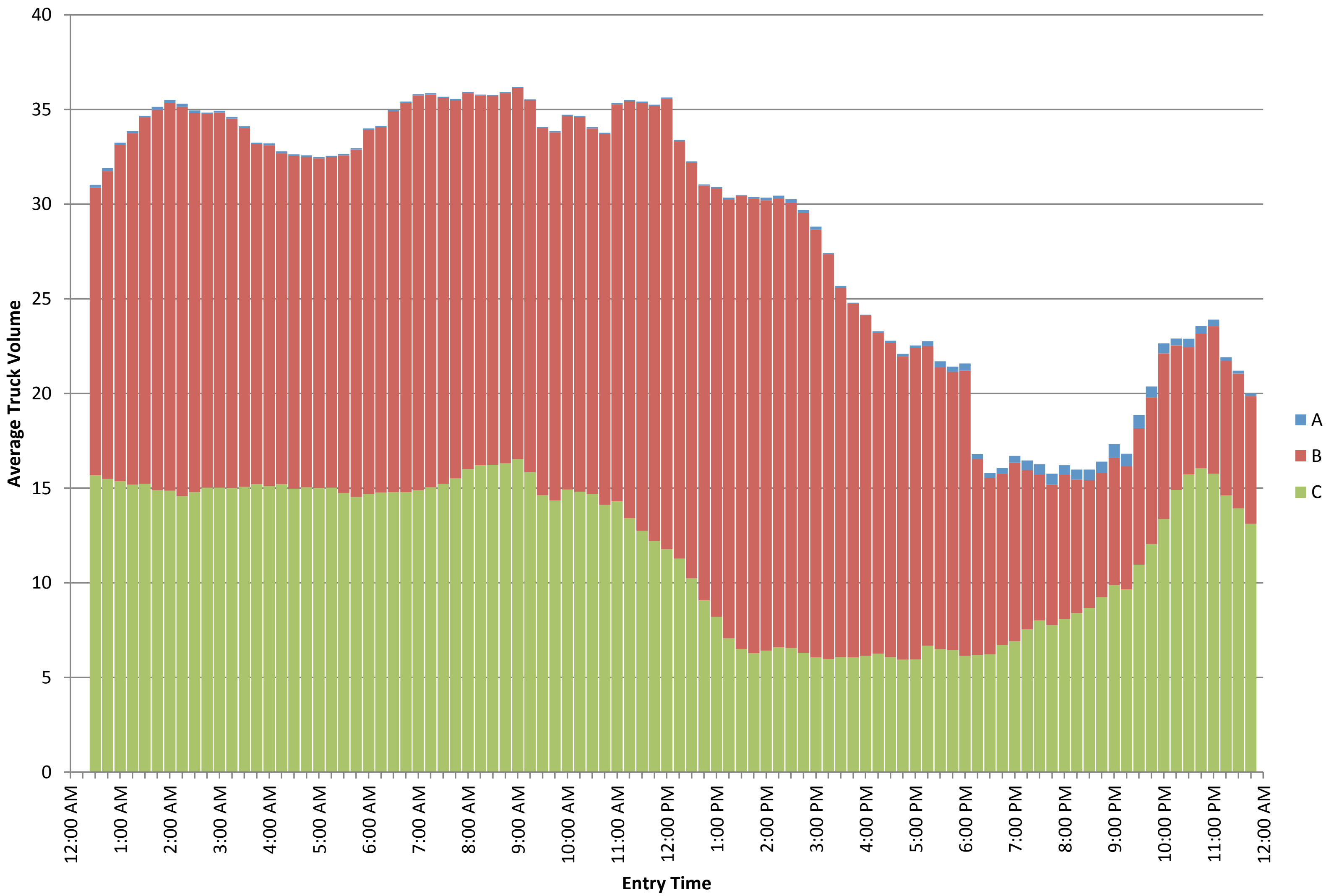
8. Bassok, A., McCormack, E., Outwater, M., and Ta, C., Use of truck GPS data for freight forecasting. Presented at 90th Annual Meeting of the Transportation Research Board, Washington, D.C., 2011.

APPENDIX A. Average Volumes for Each Facility

FIGURE A-1 Weekday Truck Volume for Private Warehouse Facilities



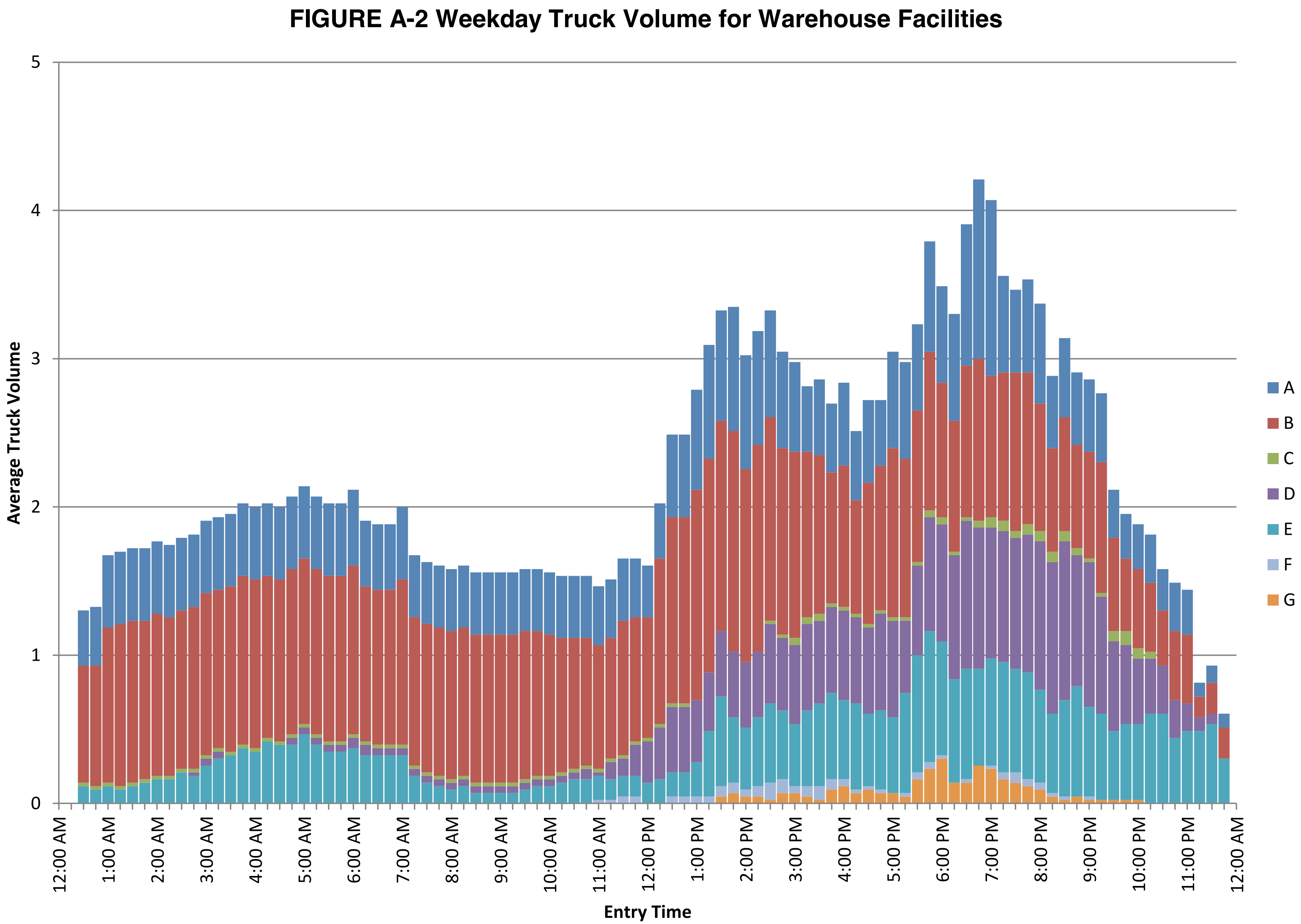


FIGURE A-2 Weekday Truck Volume for Warehouse Facilities
Average Truck Volume
0
1
2
3
4
5
12:00 AM
1:00 AM
2:00 AM
3:00 AM
4:00 AM
5:00 AM
6:00 AM
7:00 AM
8:00 AM
9:00 AM
10:00 AM
11:00 AM
12:00 PM
1:00 PM
2:00 PM
3:00 PM
4:00 PM
5:00 PM
6:00 PM
7:00 PM
8:00 PM
9:00 PM
10:00 PM
11:00 PM
12:00 AM
Entry Time
A
B
C
D
E
F
G

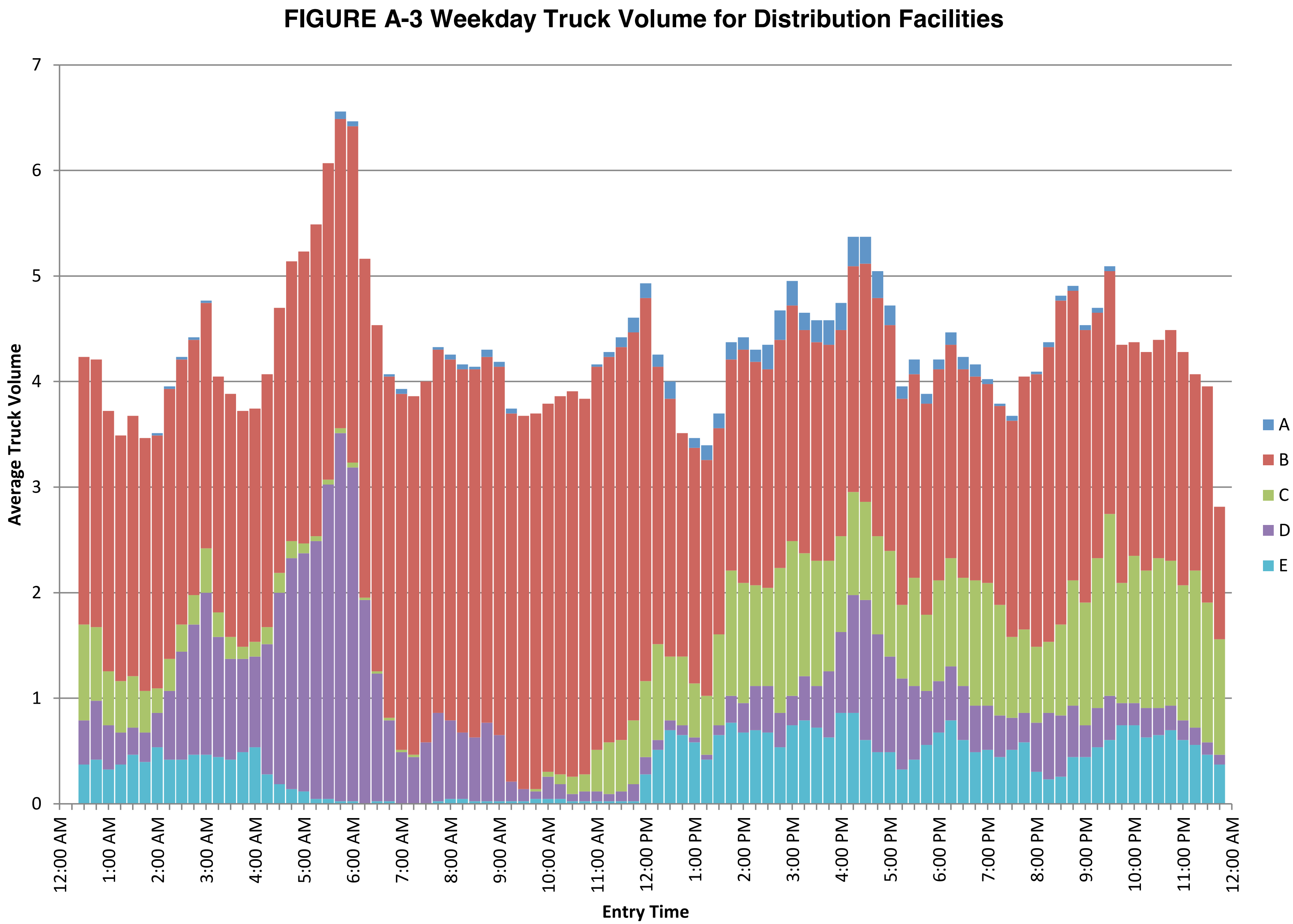


FIGURE A-3 Weekday Truck Volume for Distribution Facilities
Average Truck Volume
0
1
2
3
4
5
6
7
12:00 AM
1:00 AM
2:00 AM
3:00 AM
4:00 AM
5:00 AM
6:00 AM
7:00 AM
8:00 AM
9:00 AM
10:00 AM
11:00 AM
12:00 PM
1:00 PM
2:00 PM
3:00 PM
4:00 PM
5:00 PM
6:00 PM
7:00 PM
8:00 PM
9:00 PM
10:00 PM
11:00 PM
12:00 AM
Entry Time
A
B
C
D
E

FIGURE A-4 Weekday Truck Volume for Intermodal Facilities

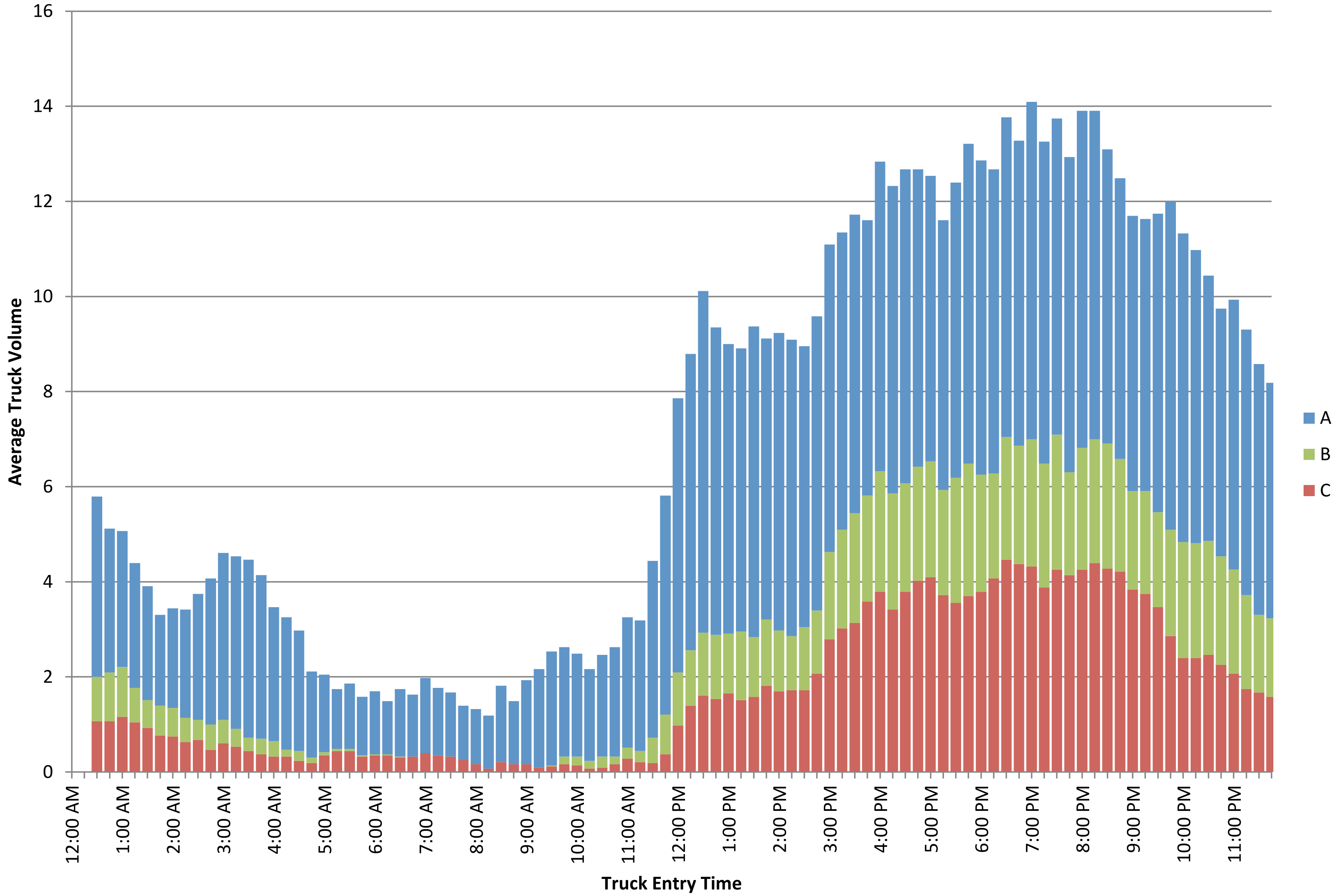
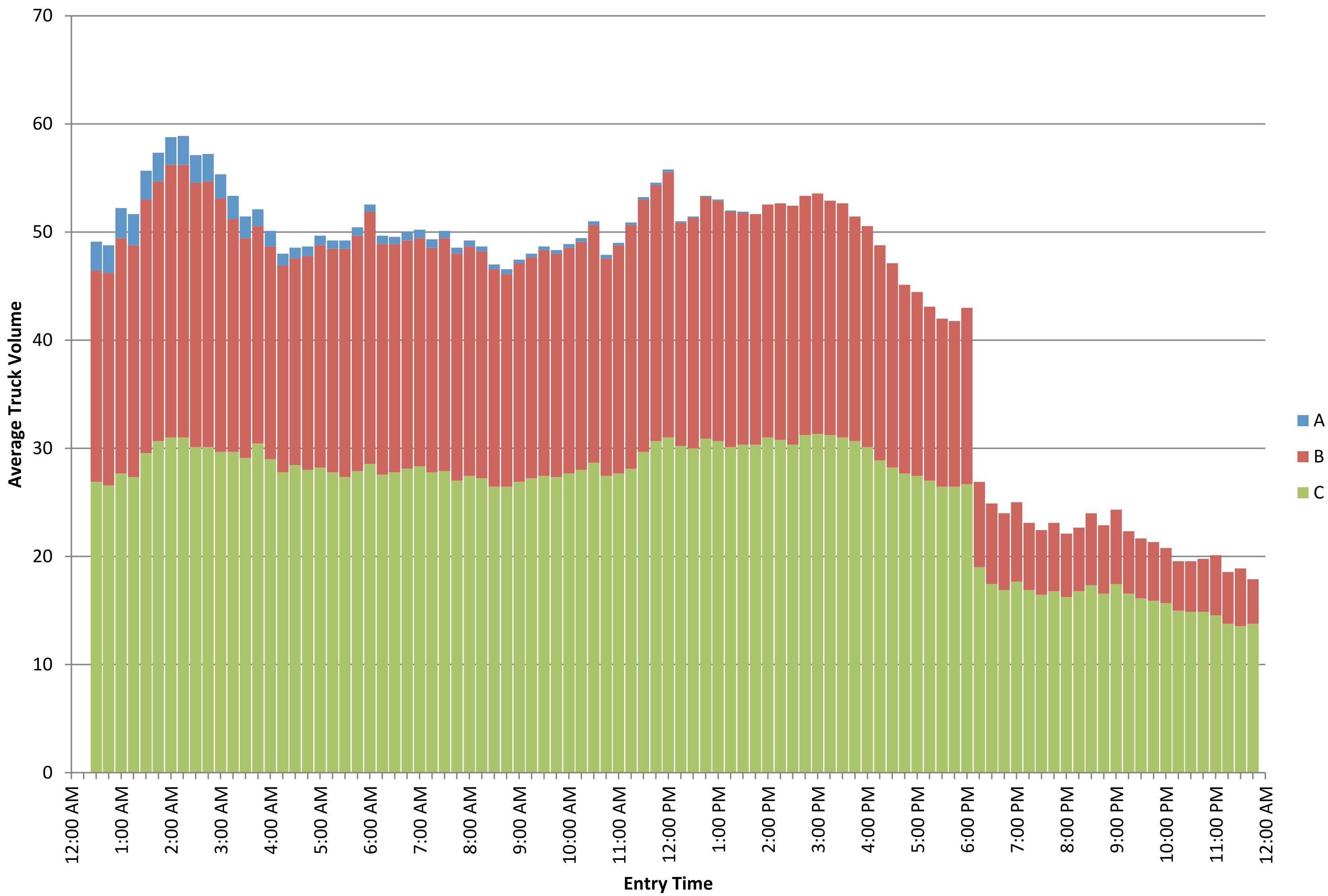


FIGURE A-5 Saturday Truck Volume for Private Warehouse Facilities



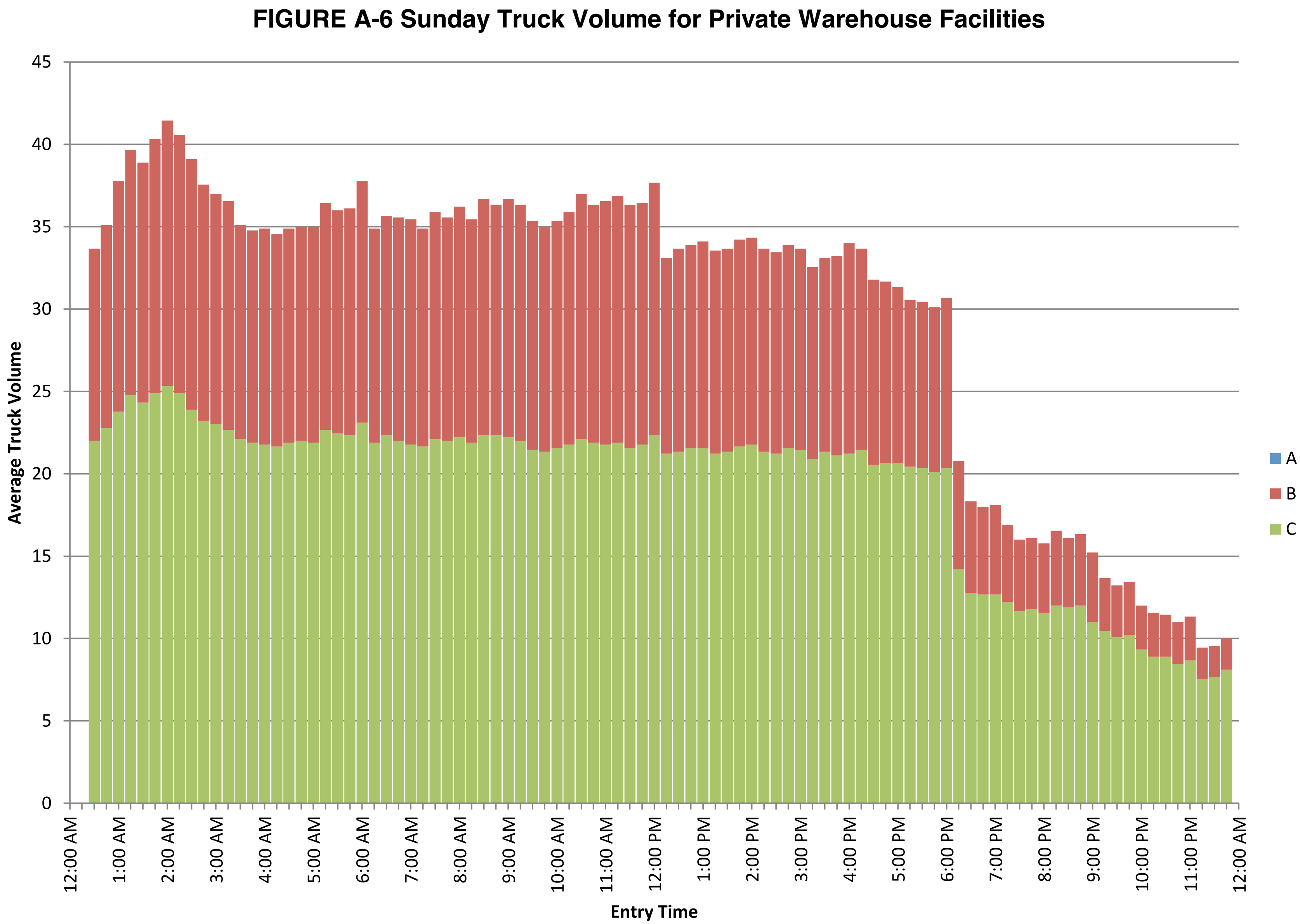


FIGURE A-6 Sunday Truck Volume for Private Warehouse Facilities
Average Truck Volume
45
40
35
30
25
20
15
10
5
0
12:00 AM
1:00 AM
2:00 AM
3:00 AM
4:00 AM
5:00 AM
6:00 AM
7:00 AM
8:00 AM
9:00 AM
10:00 AM
11:00 AM
12:00 PM
1:00 PM
2:00 PM
3:00 PM
4:00 PM
5:00 PM
6:00 PM
7:00 PM
8:00 PM
9:00 PM
10:00 PM
11:00 PM
12:00 AM
Entry Time
A
B
C

FIGURE A-7 Saturday Truck Volume for Warehouse Facilities

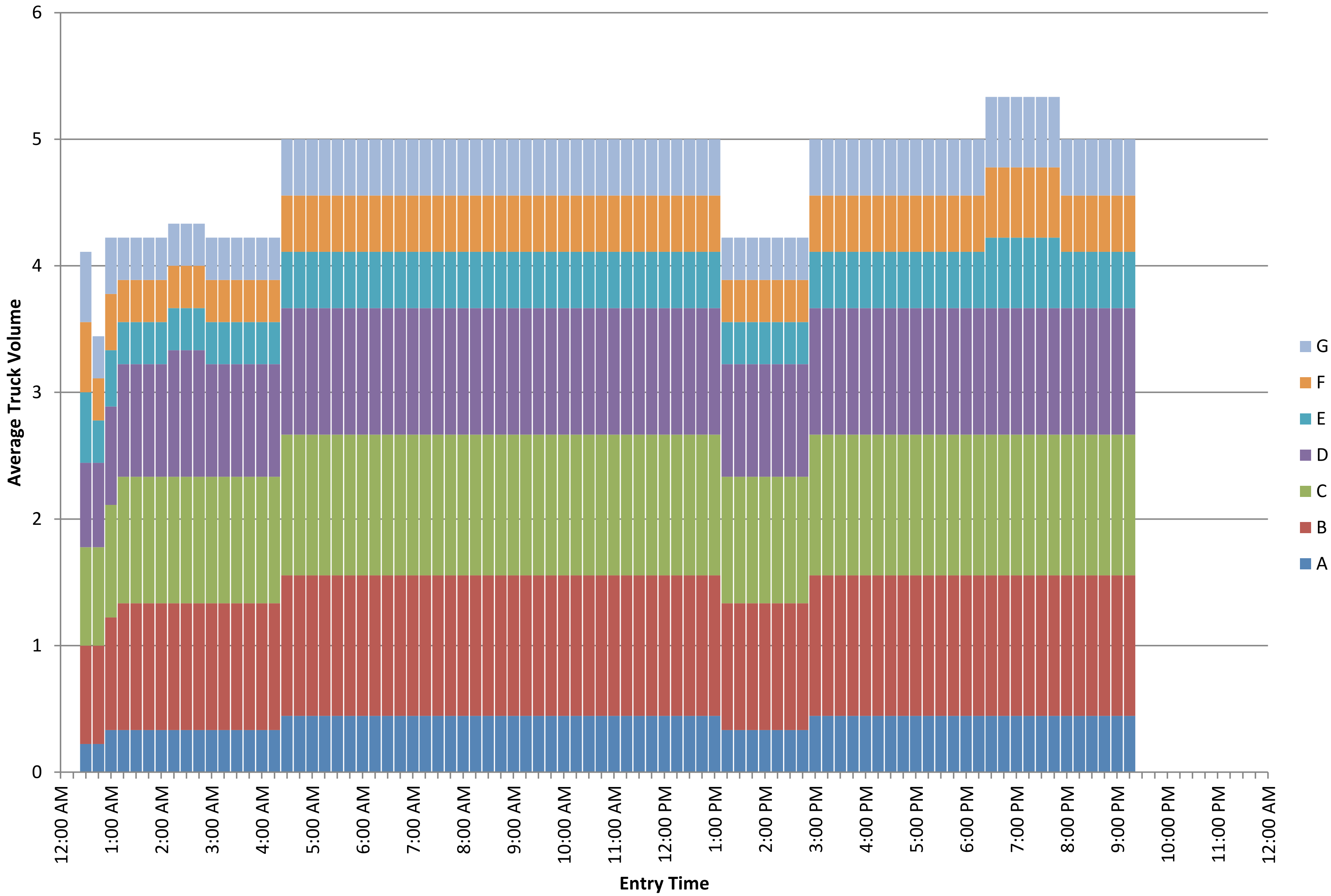
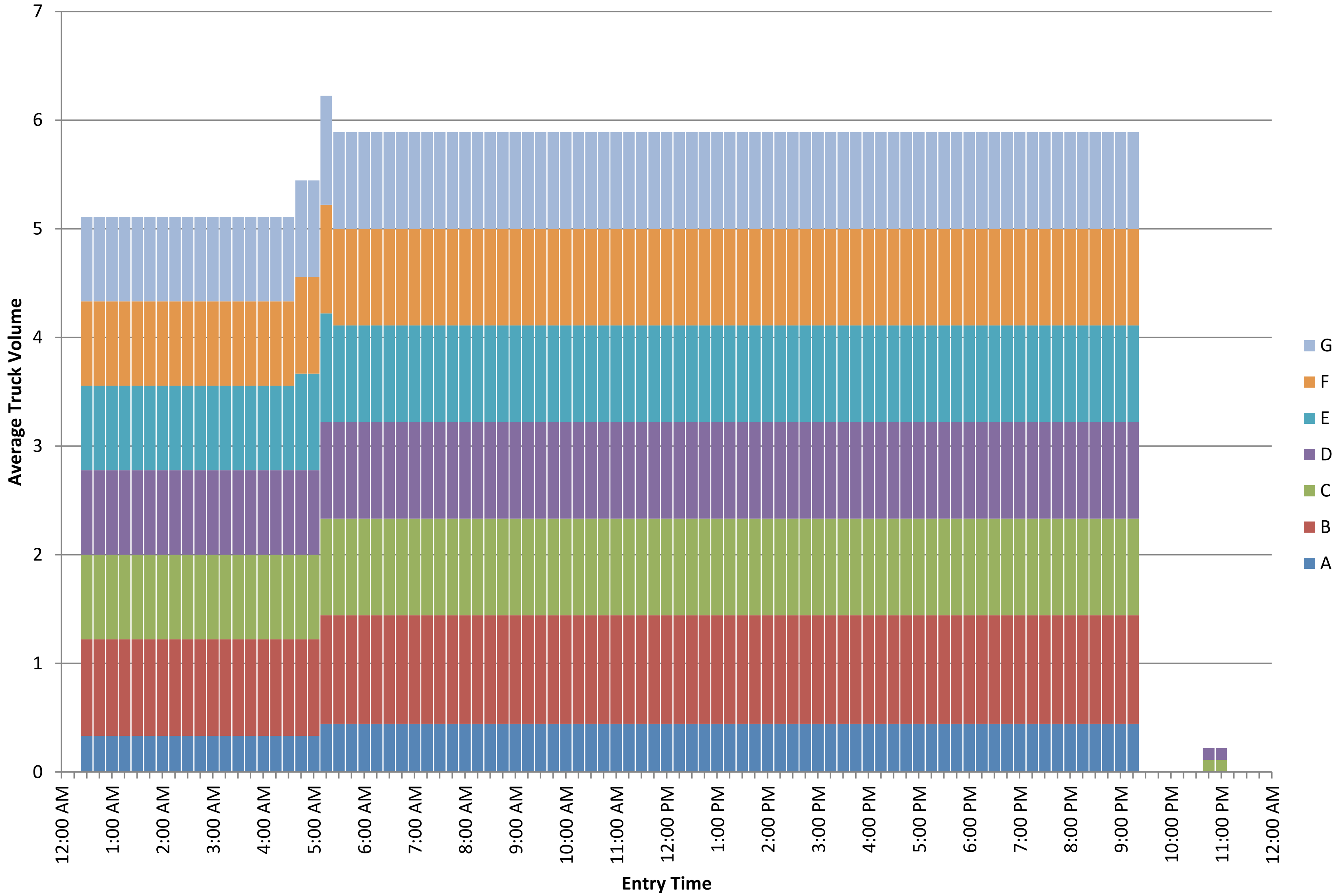


FIGURE A-8 Sunday Truck Volume for Warehouse Facilities



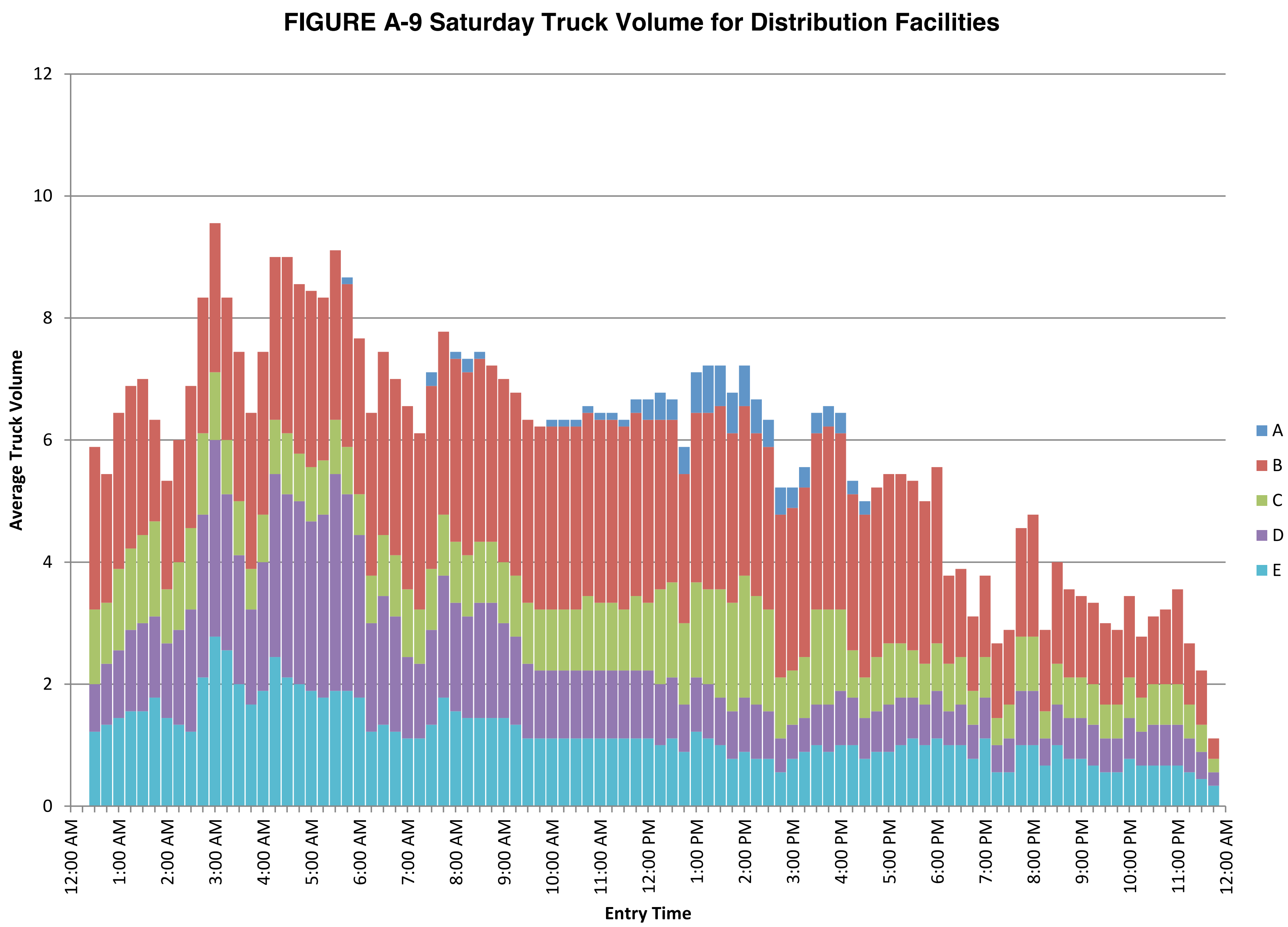


FIGURE A-9 Saturday Truck Volume for Distribution Facilities
Average Truck Volume
12
10
8
6
4
2
0
12:00 AM
1:00 AM
2:00 AM
3:00 AM
4:00 AM
5:00 AM
6:00 AM
7:00 AM
8:00 AM
9:00 AM
10:00 AM
11:00 AM
12:00 PM
1:00 PM
2:00 PM
3:00 PM
4:00 PM
5:00 PM
6:00 PM
7:00 PM
8:00 PM
9:00 PM
10:00 PM
11:00 PM
12:00 AM
Entry Time
A
B
C
D
E

FIGURE A-10 Sunday Truck Volume for Distribution Facilities

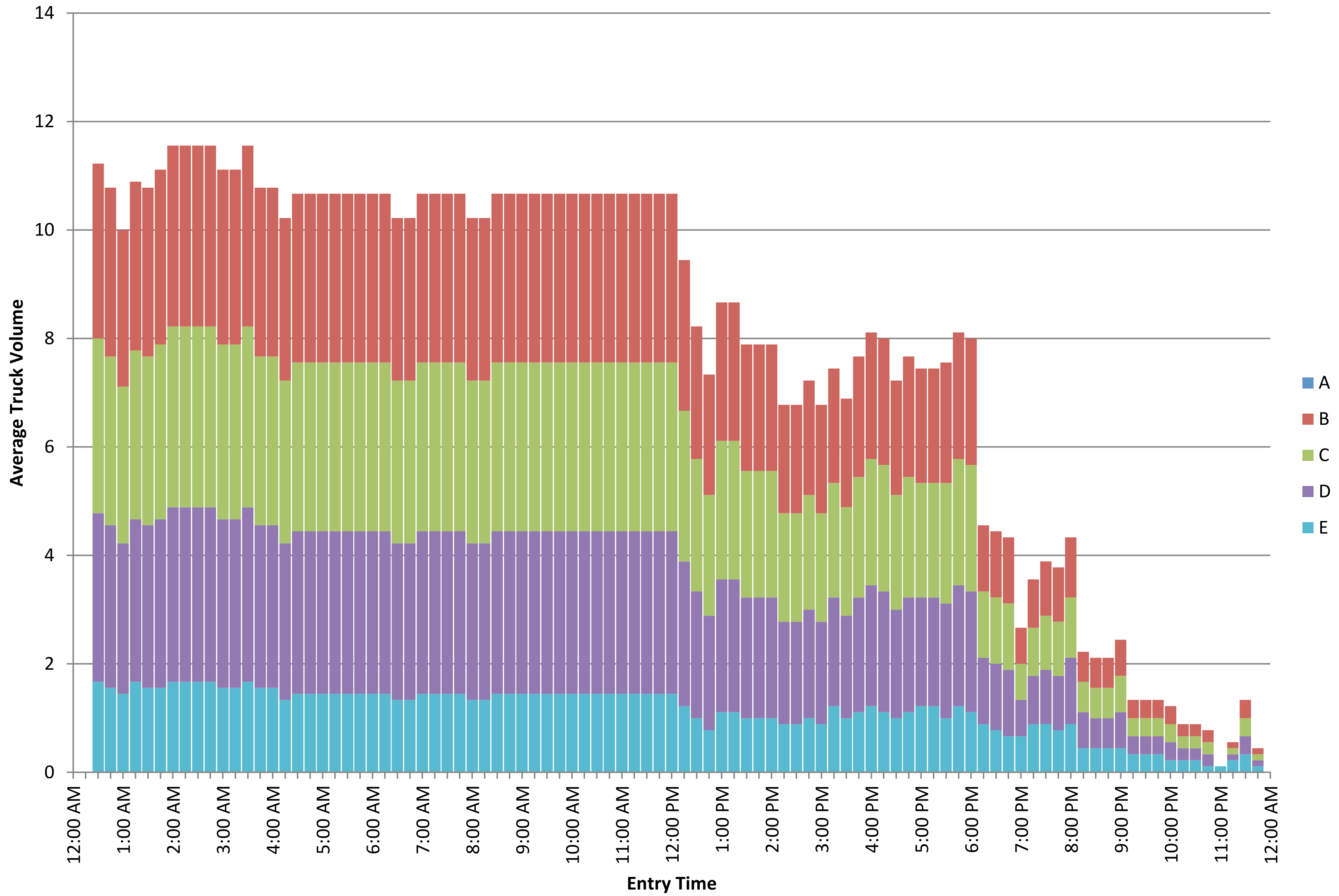


FIGURE A-11 Saturday Truck Volume for Intermodal Facilities

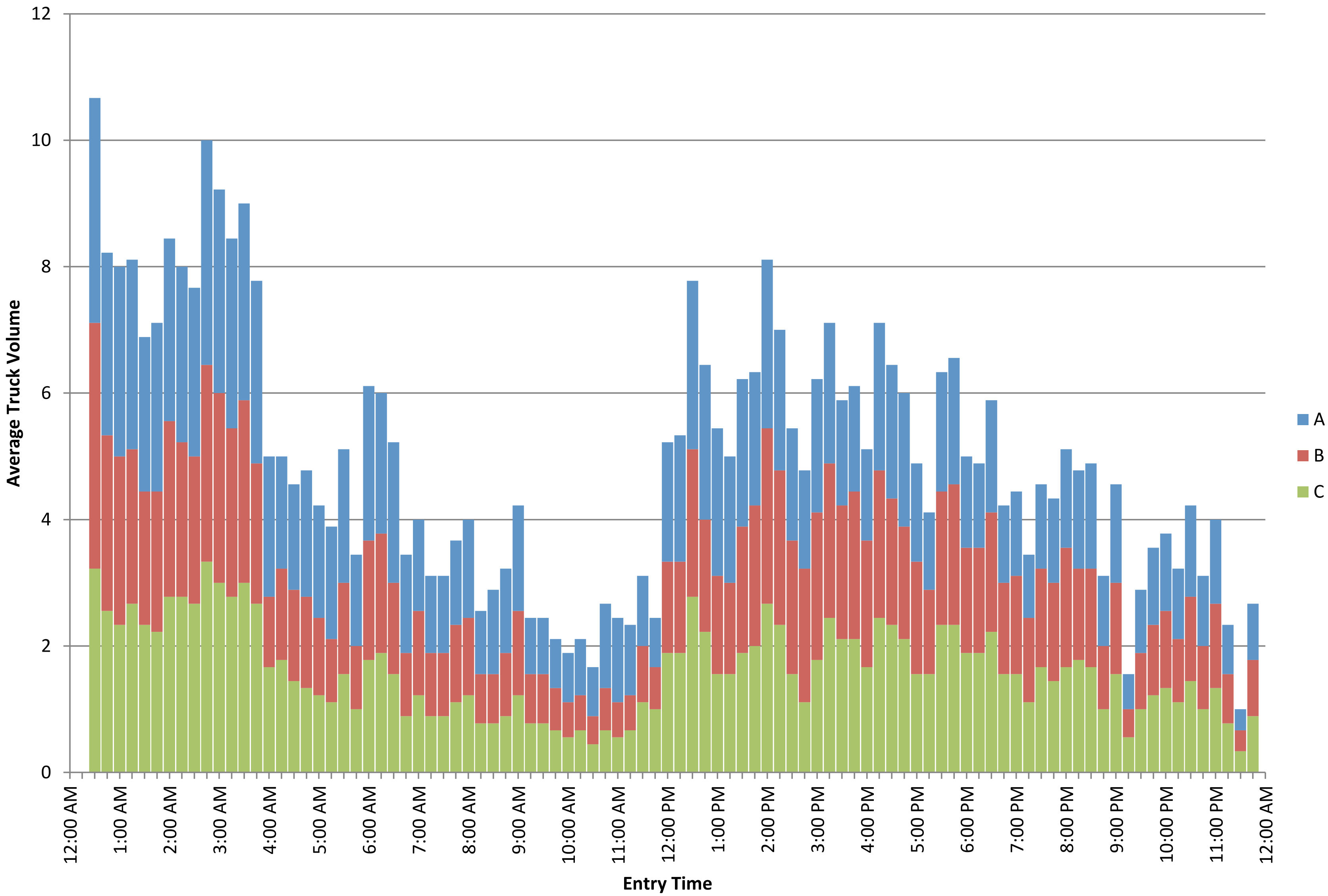
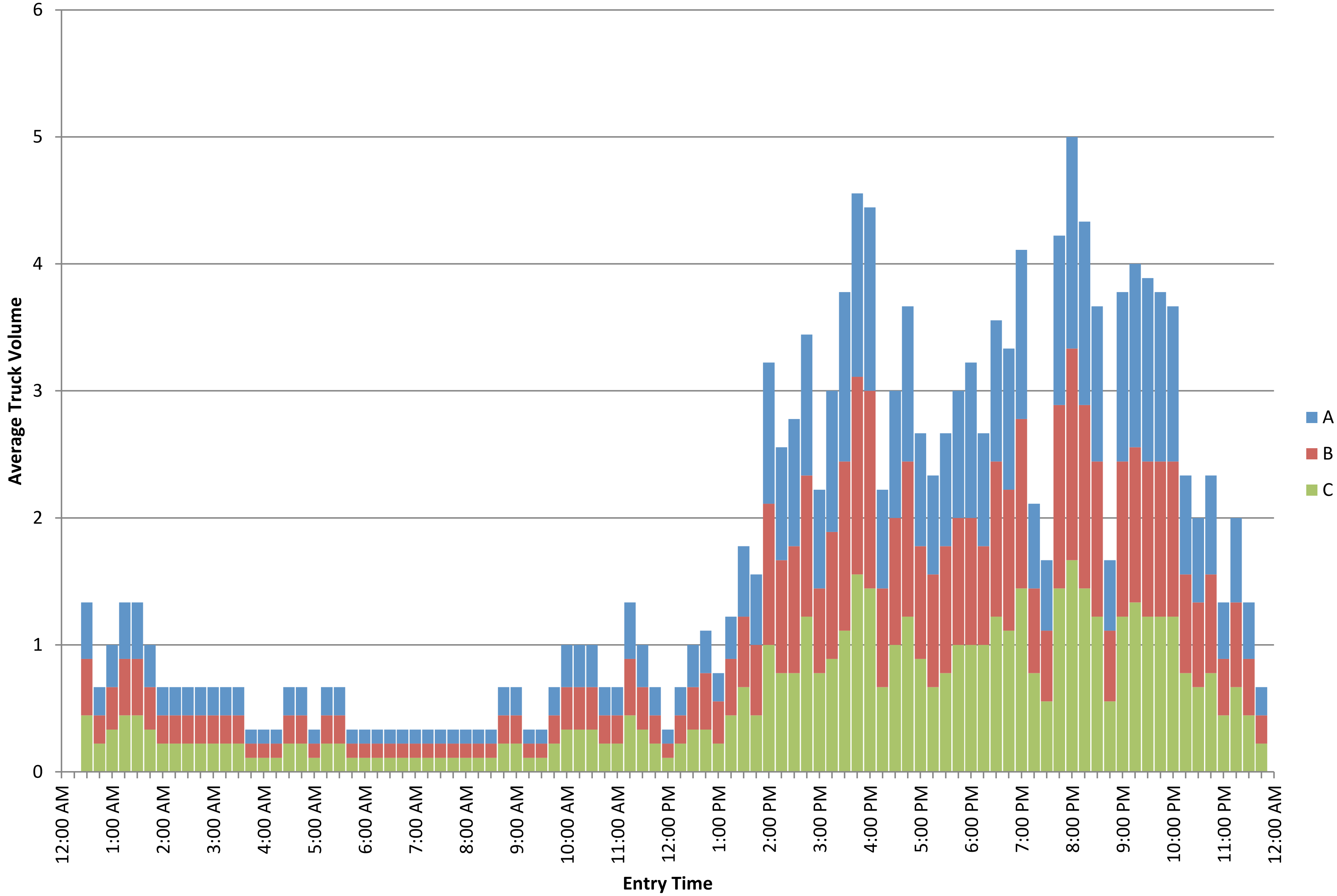


FIGURE A-12 Sunday Truck Volume for Intermodal Facilities



APPENDIX B. Average Entry and Exit Volumes for Each Facility

FIGURE B-1 Weekday Entry/Exit Volumes for Private Warehouse A

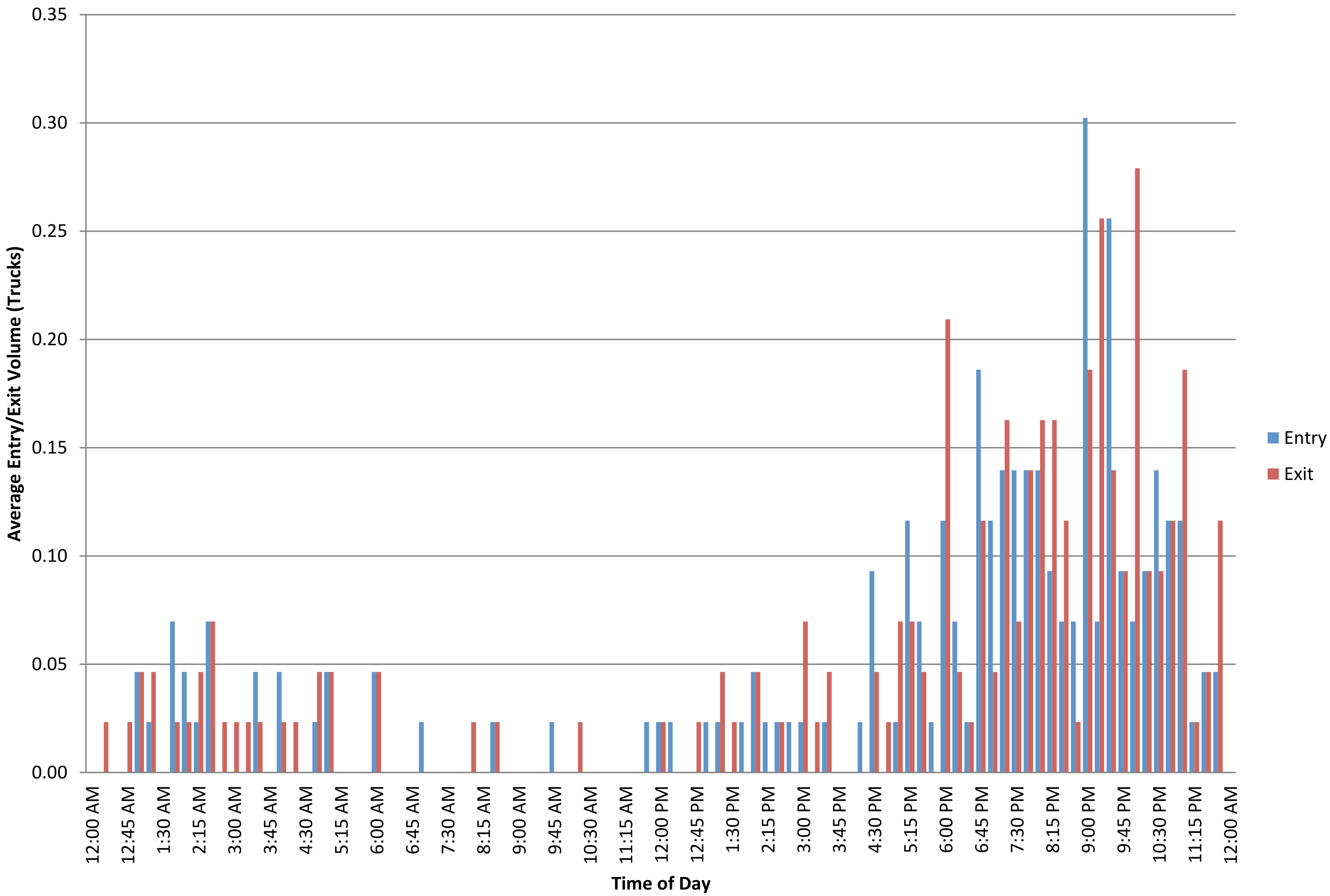
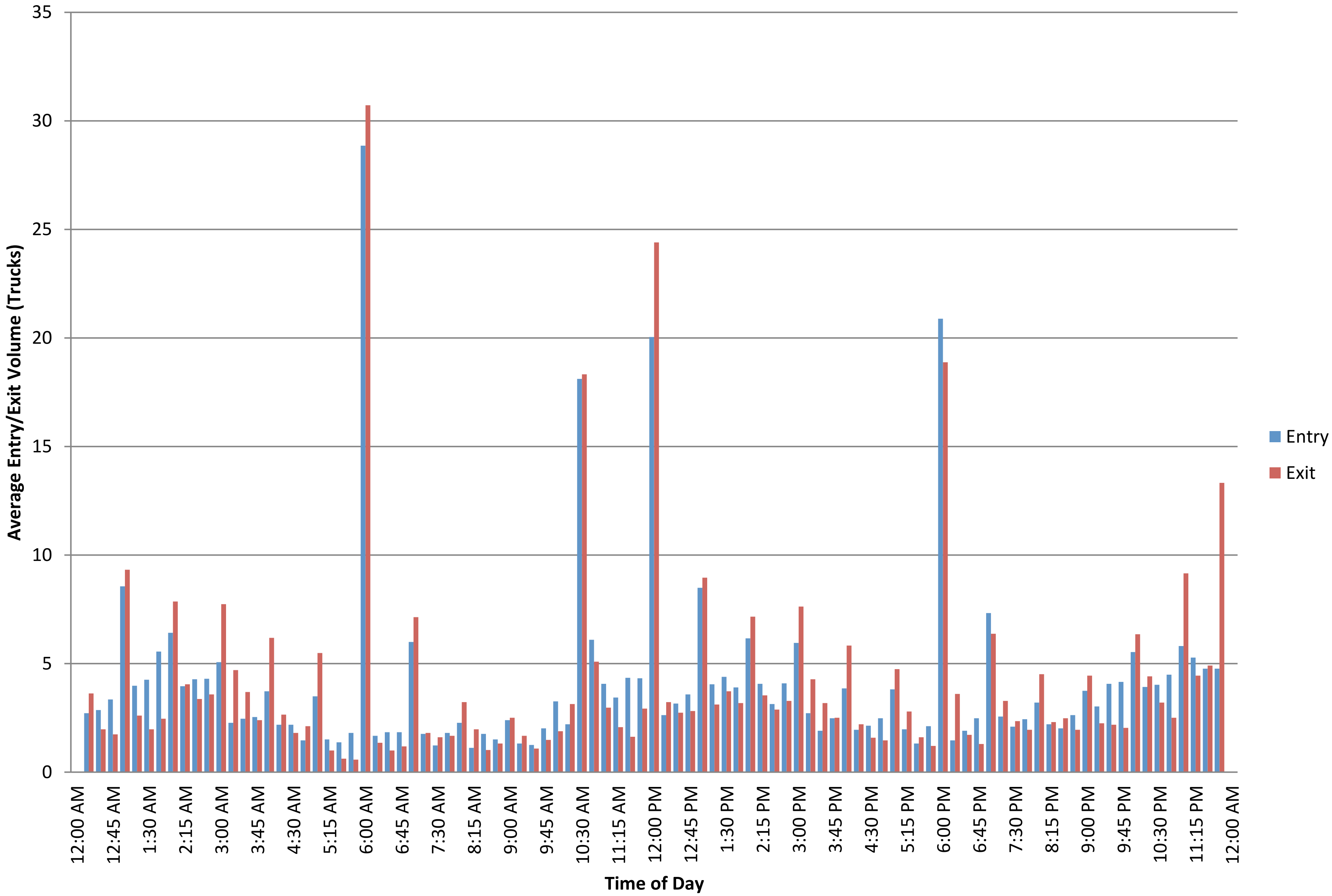


FIGURE B-2 Weekday Entry/Exit Volumes for Private Warehouse B



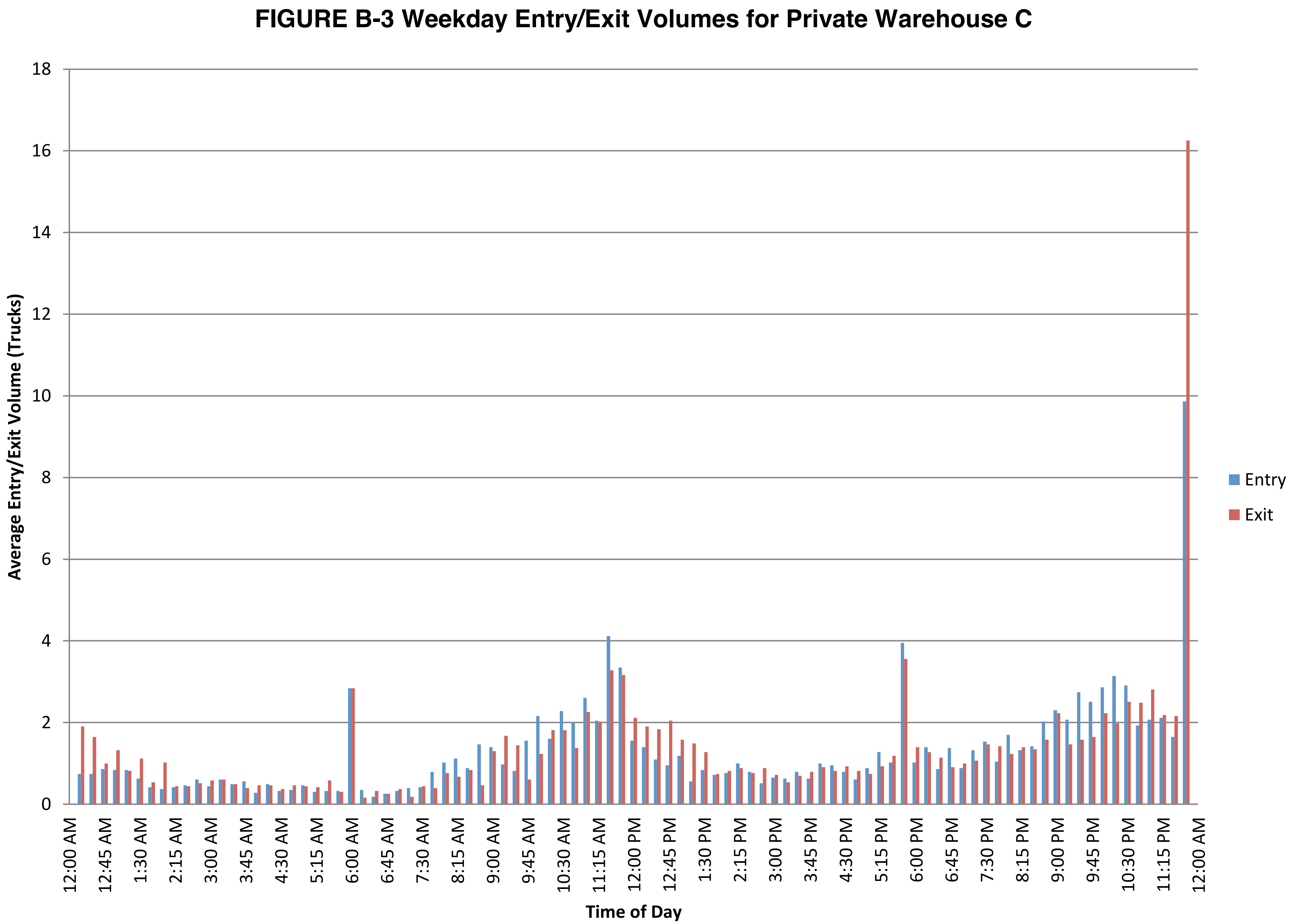


FIGURE B-3 Weekday Entry/Exit Volumes for Private Warehouse C
Average Entry/Exit Volume (Trucks)
0
2
4
6
8
10
12
14
16
18
12:00 AM
12:45 AM
1:30 AM
2:15 AM
3:00 AM
3:45 AM
4:30 AM
5:15 AM
6:00 AM
6:45 AM
7:30 AM
8:15 AM
9:00 AM
9:45 AM
10:30 AM
11:15 AM
12:00 PM
12:45 PM
1:30 PM
2:15 PM
3:00 PM
3:45 PM
4:30 PM
5:15 PM
6:00 PM
6:45 PM
7:30 PM
8:15 PM
9:00 PM
9:45 PM
10:30 PM
11:15 PM
12:00 AM
Time of Day
Entry
Exit

FIGURE B-4 Weekday Entry/Exit Volumes for Warehouse Facility A

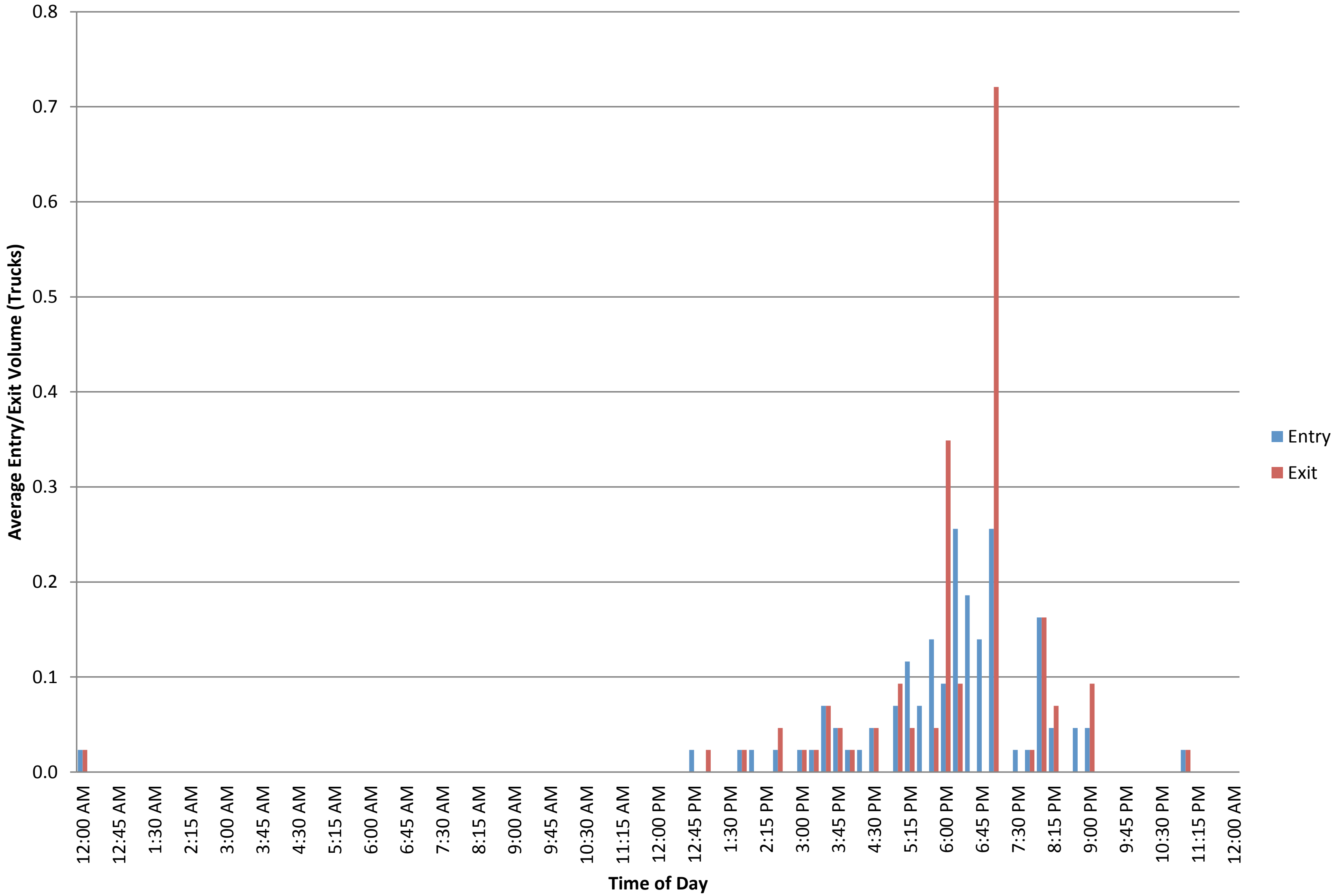


FIGURE B-5 Weekday Entry/Exit Volumes for Warehouse Facility B

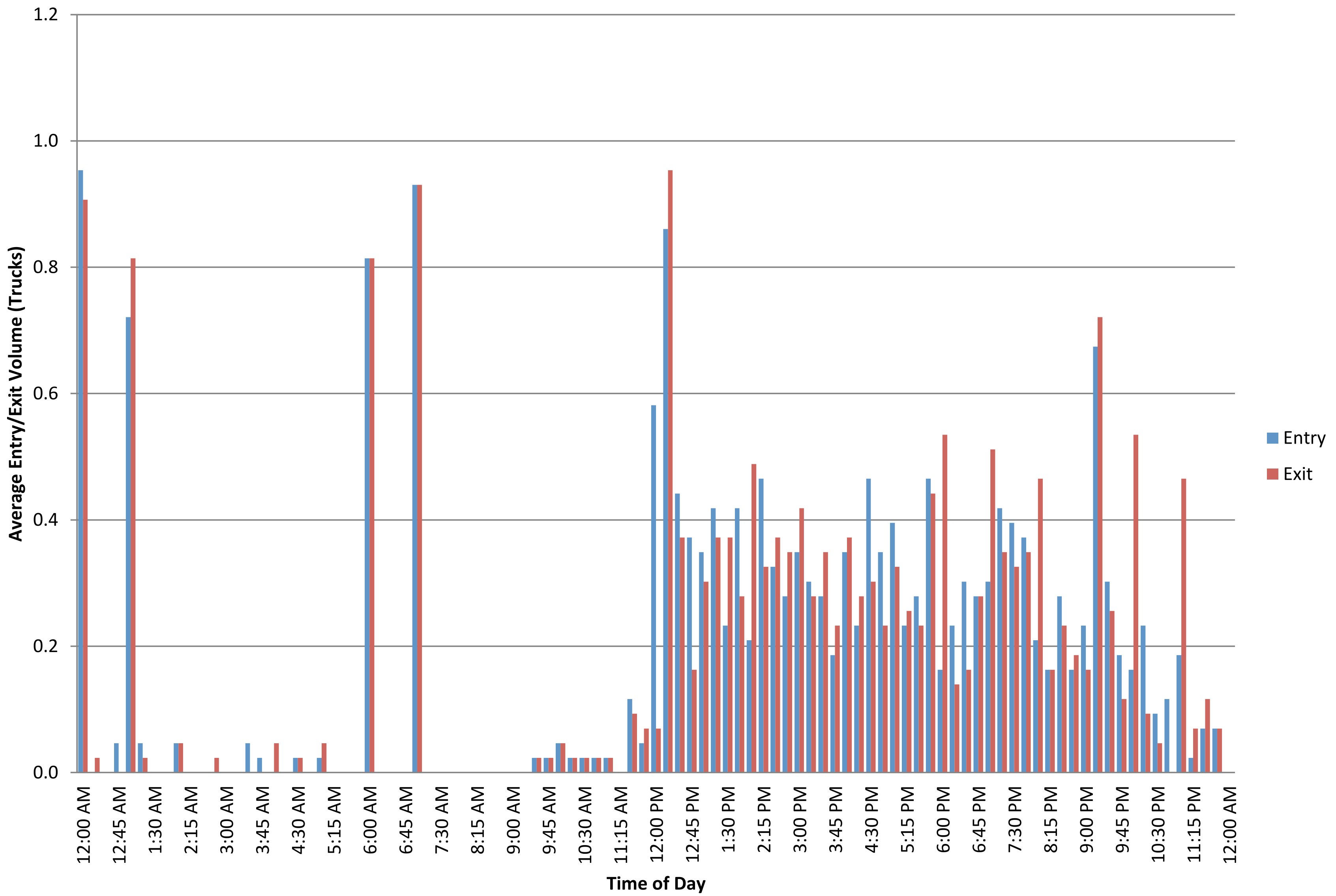


FIGURE B-6 Weekday Entry/Exit Volumes for Warehouse Facility C

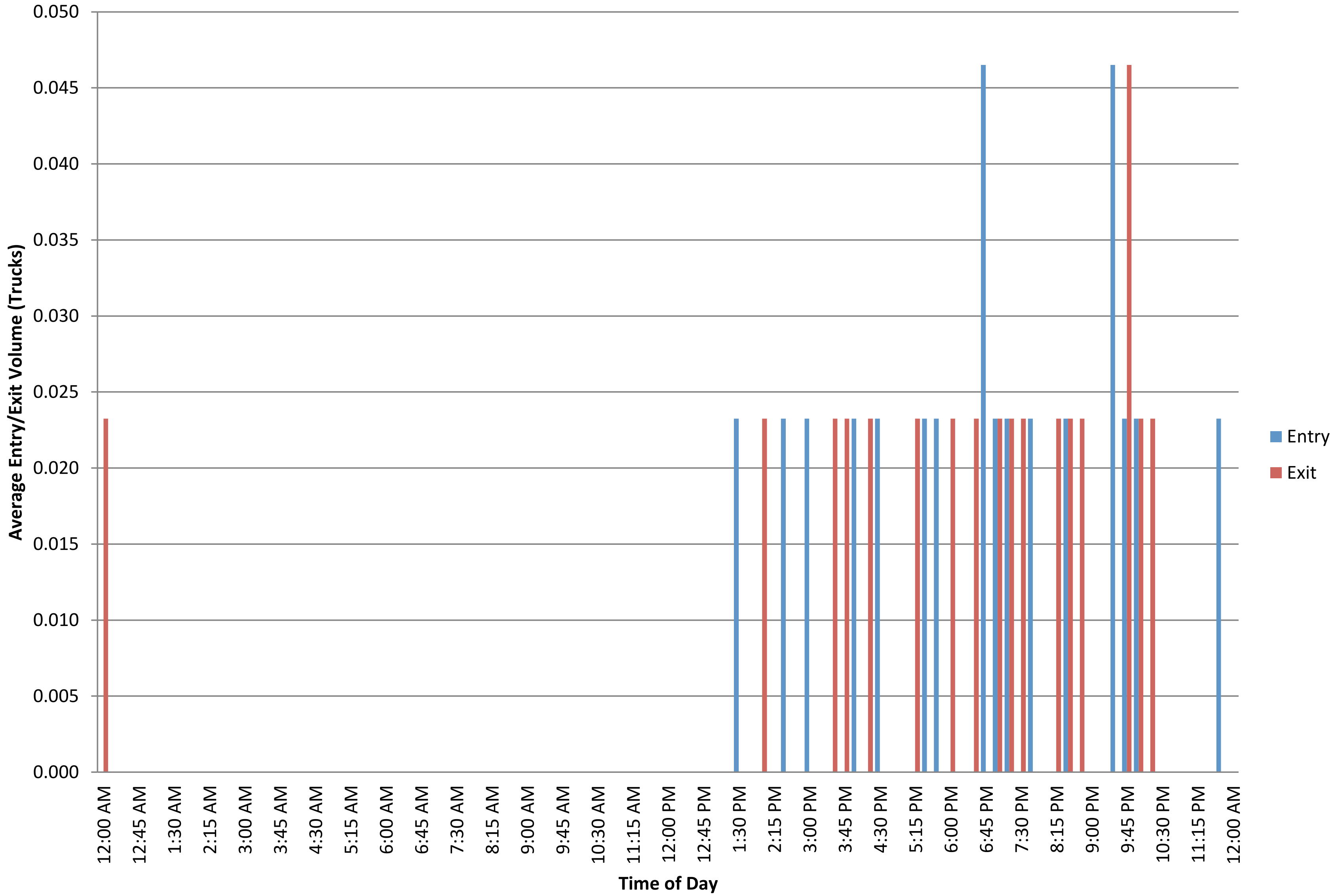


FIGURE B-7 Weekday Entry/Exit Volumes for Warehouse Facility D

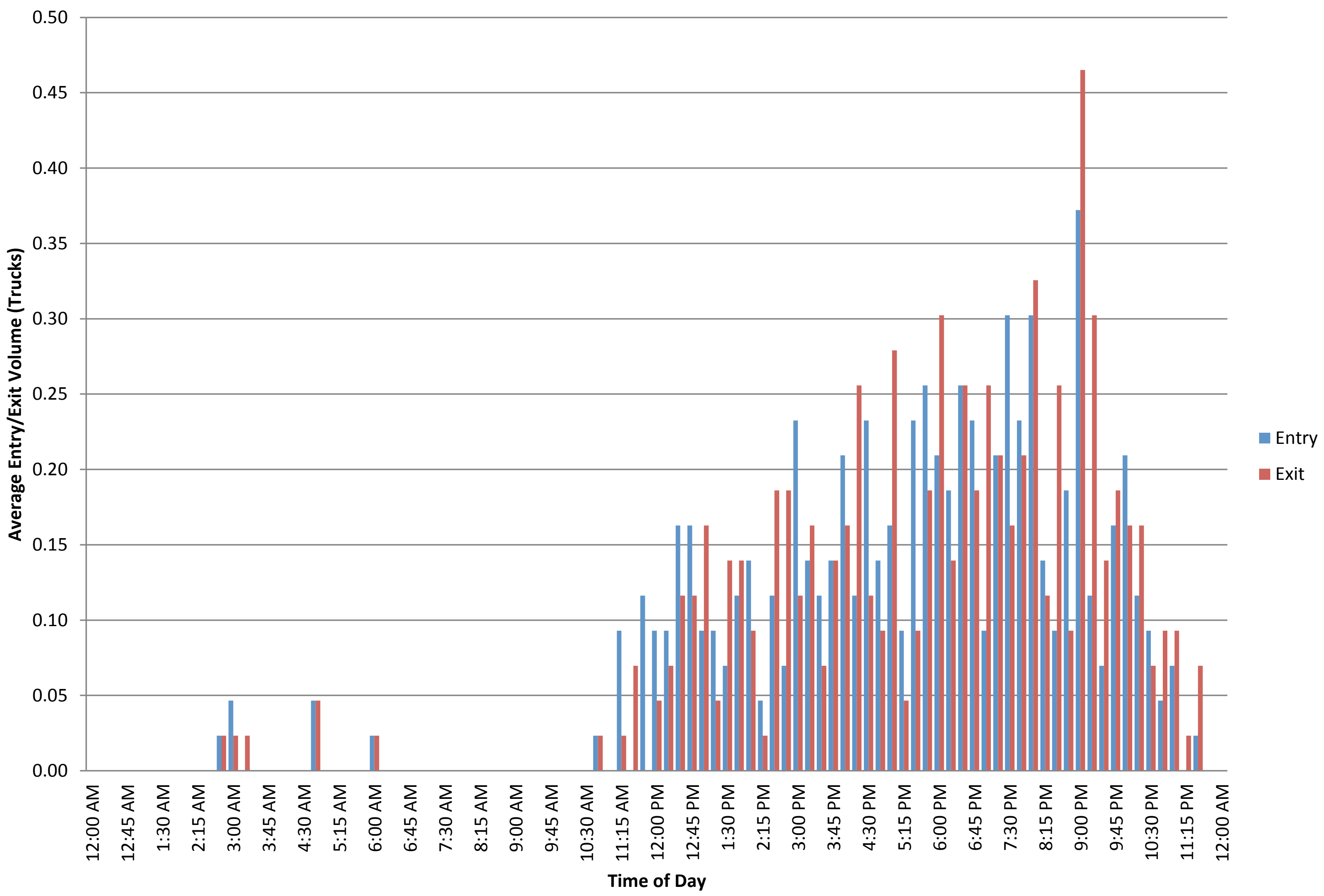
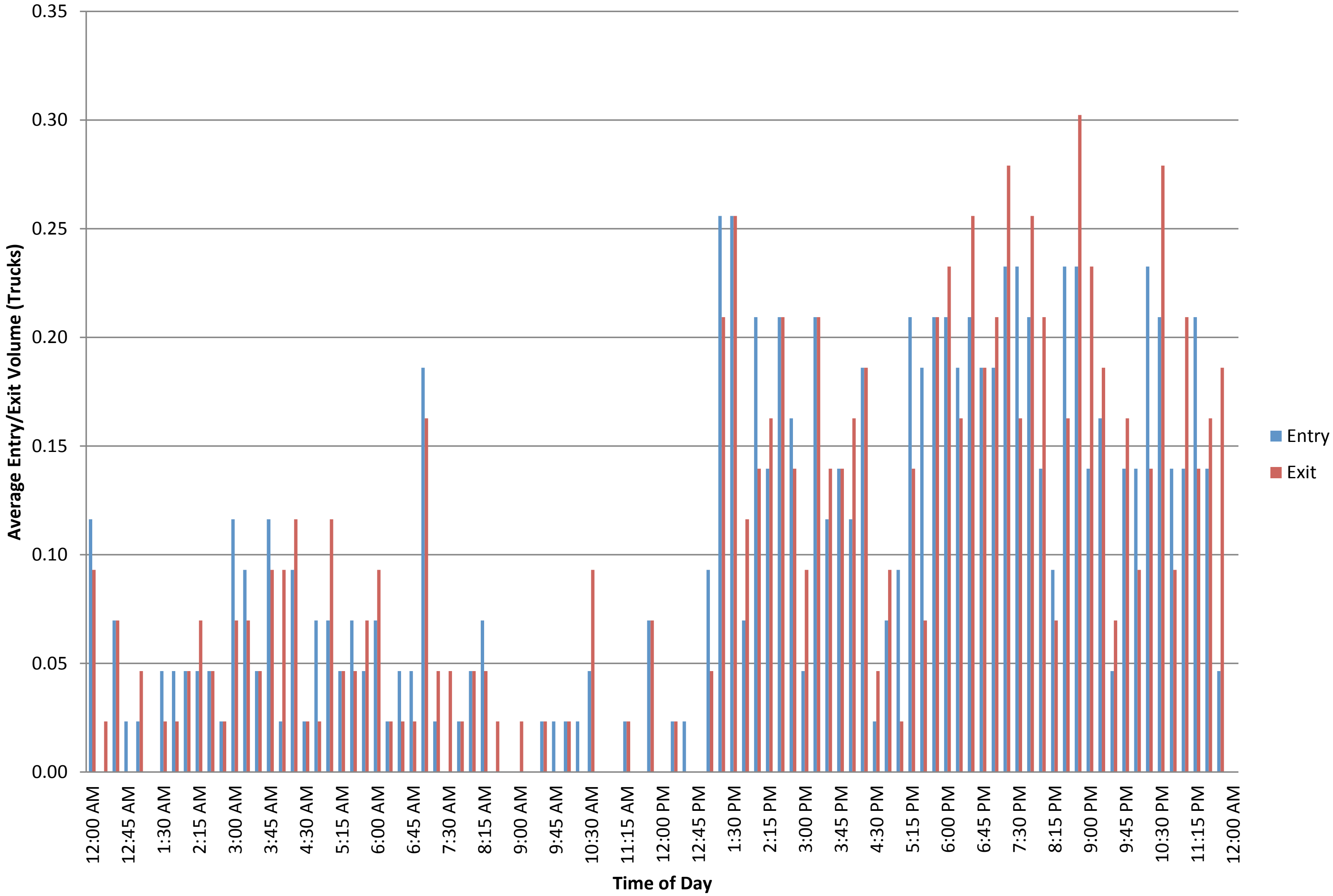


FIGURE B-8 Weekday Entry/Exit Volumes for Warehouse Facility E



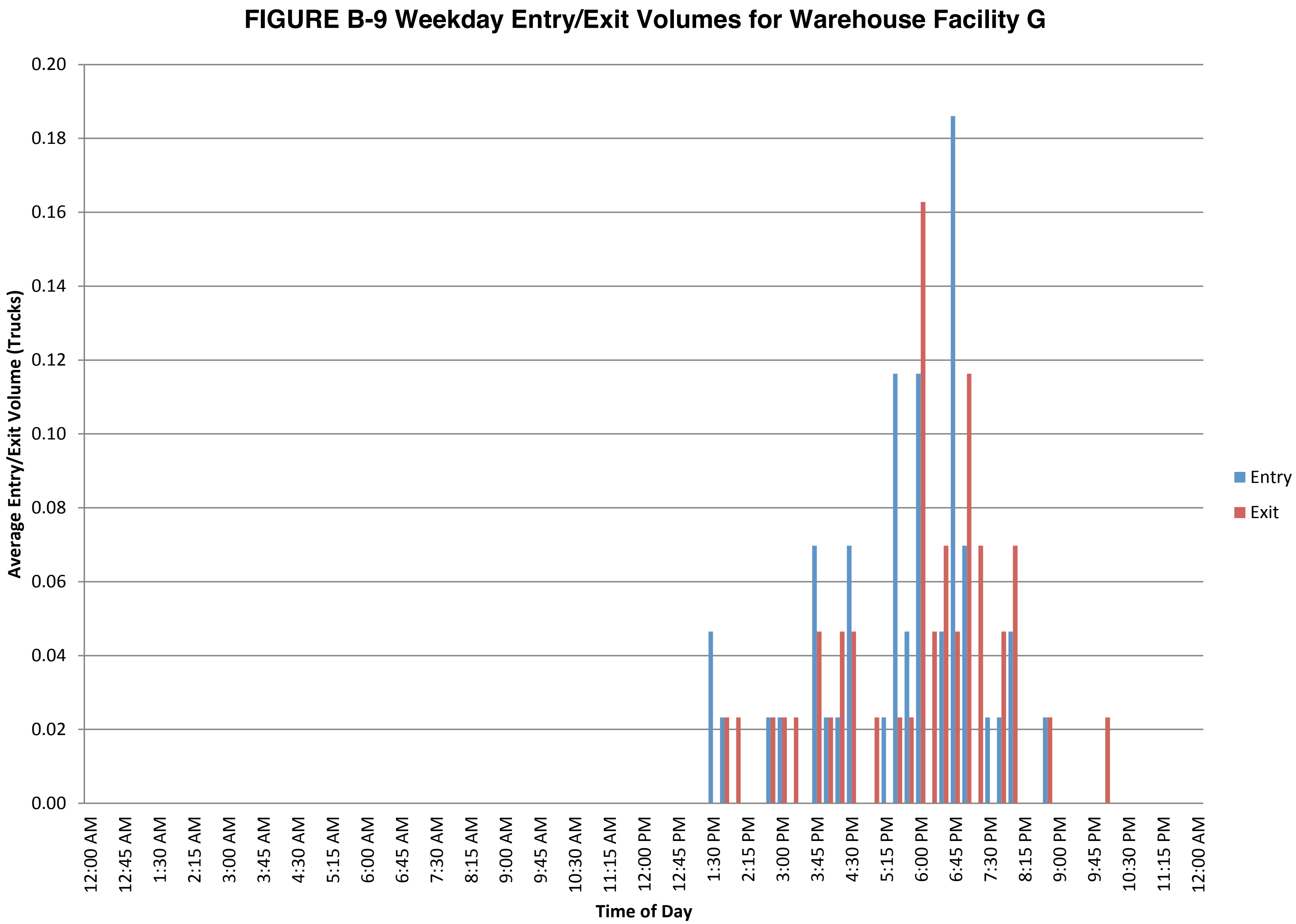


FIGURE B-9 Weekday Entry/Exit Volumes for Warehouse Facility G
Average Entry/Exit Volume (Trucks)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
12:00 AM
12:45 AM
1:30 AM
2:15 AM
3:00 AM
3:45 AM
4:30 AM
5:15 AM
6:00 AM
6:45 AM
7:30 AM
8:15 AM
9:00 AM
9:45 AM
10:30 AM
11:15 AM
12:00 PM
12:45 PM
1:30 PM
2:15 PM
3:00 PM
3:45 PM
4:30 PM
5:15 PM
6:00 PM
6:45 PM
7:30 PM
8:15 PM
9:00 PM
9:45 PM
10:30 PM
11:15 PM
12:00 AM
Time of Day
Entry
Exit

FIGURE B-10 Weekday Entry/Exit Volumes for Warehouse Facility F

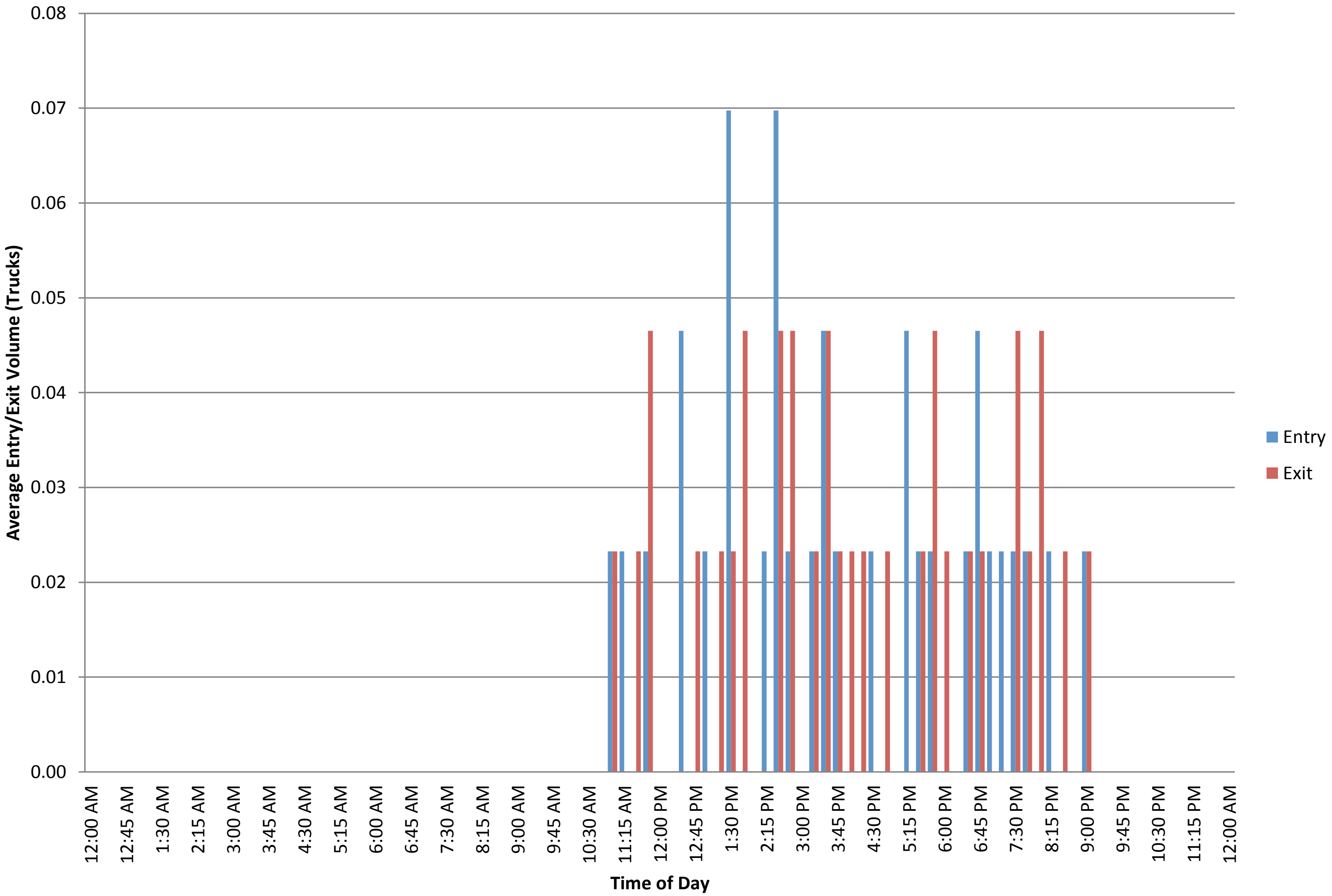


FIGURE B-11 Weekday Entry/Exit Volume for Distribution Facility A

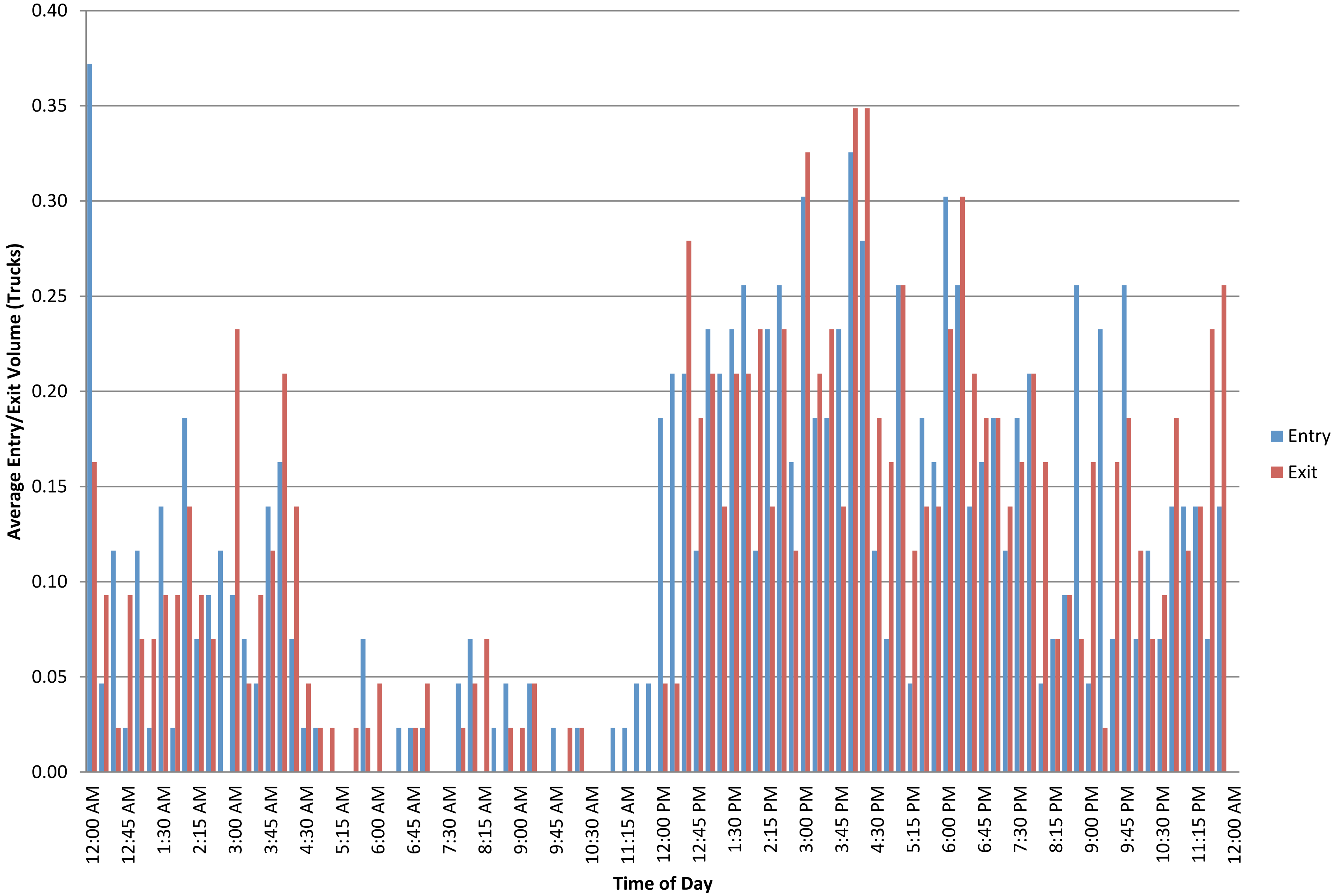


FIGURE B-12 Weekday Entry/Exit Volume for Distribution Facility B

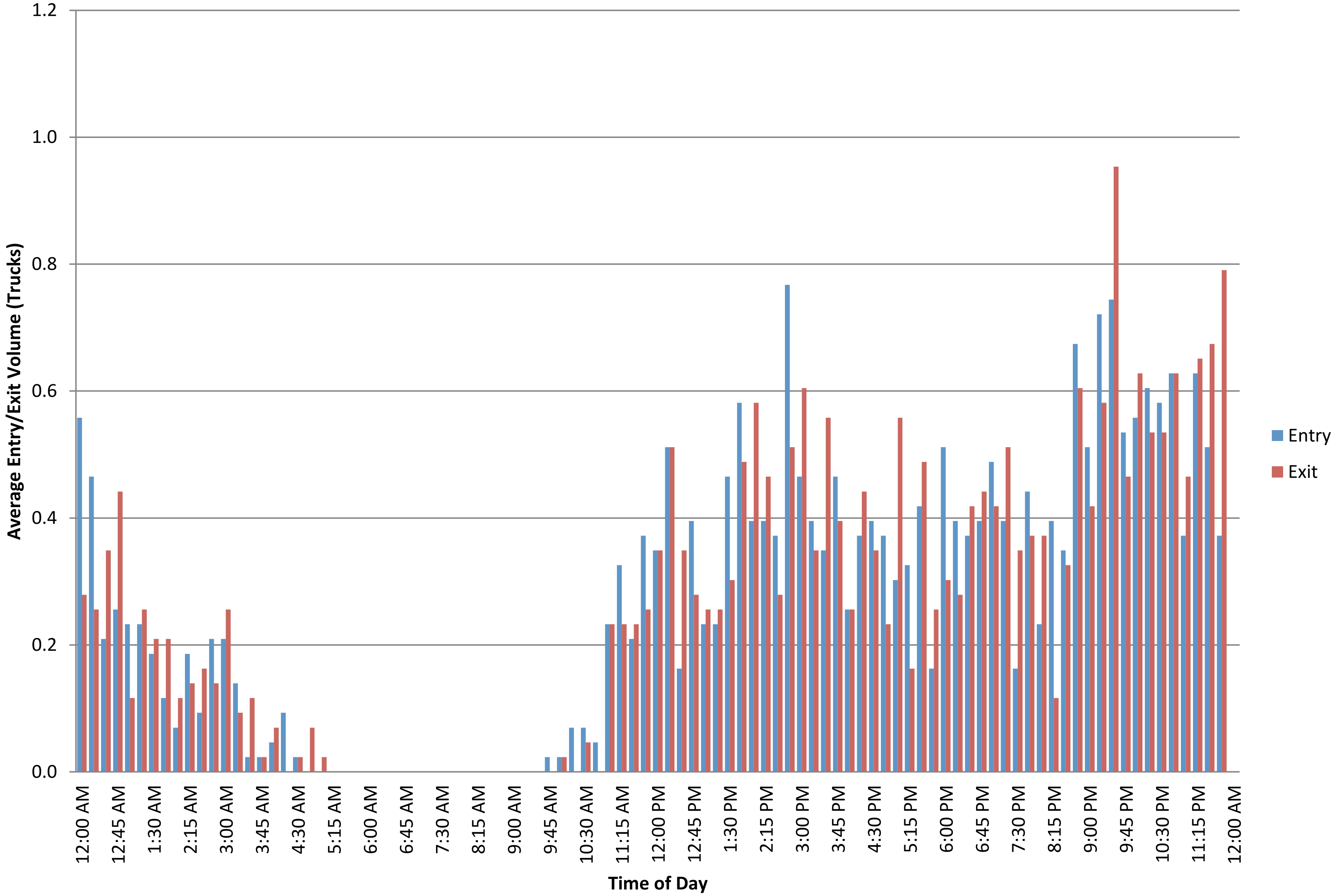


FIGURE B-13 Weekday Entry/Exit Volume for Distribution Facility C

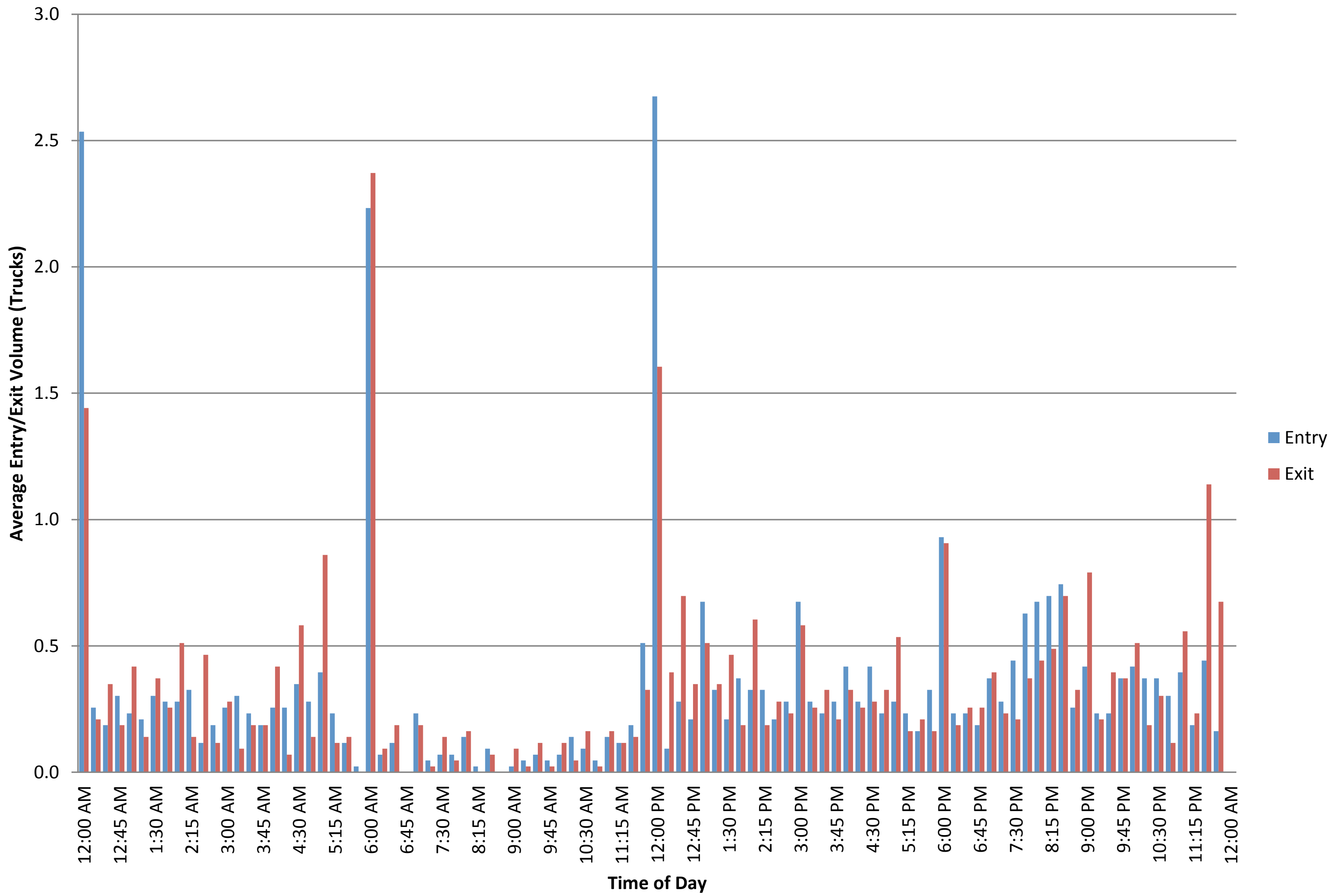
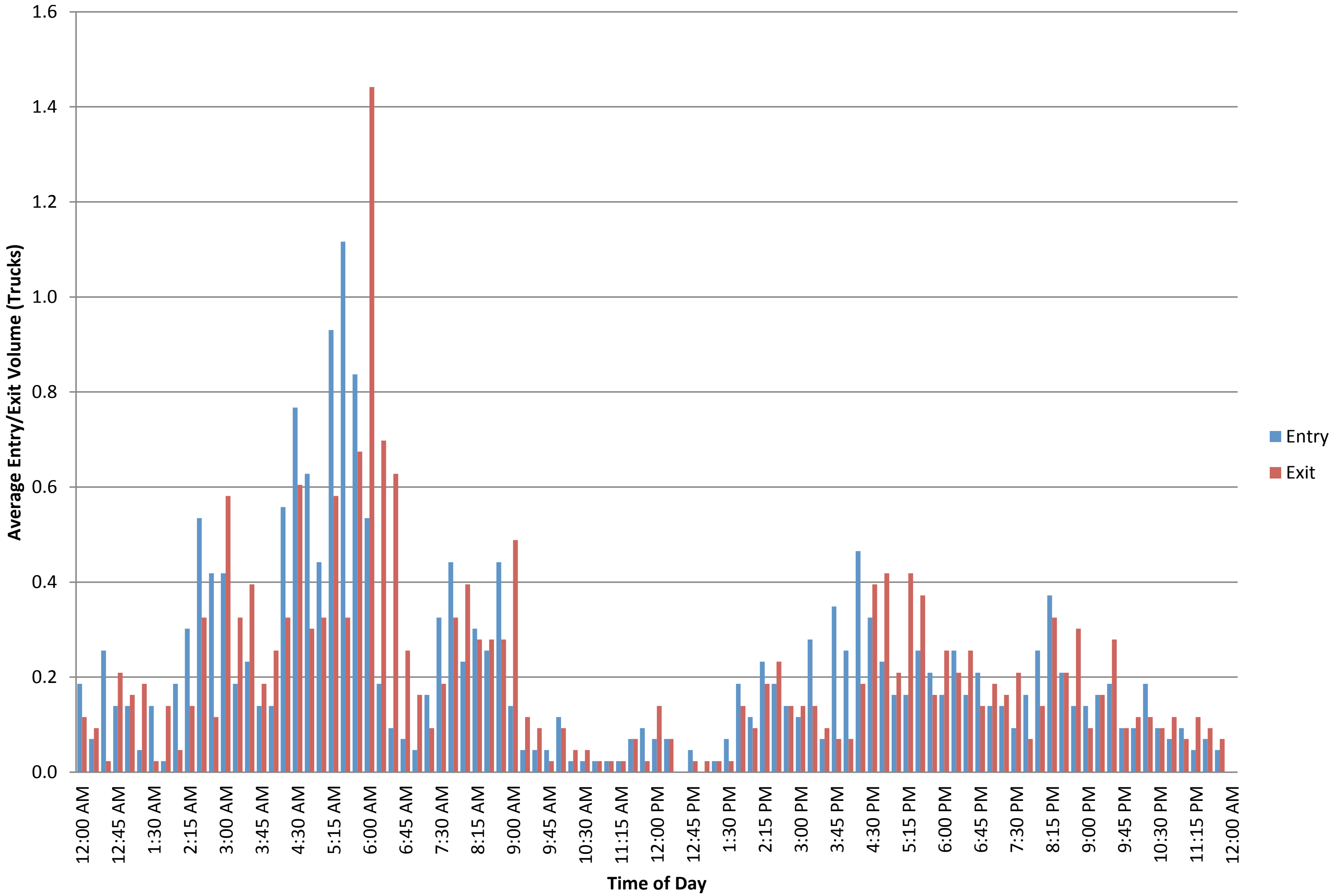


FIGURE B-14 Weekday Entry/Exit Volume for Distribution Facility D



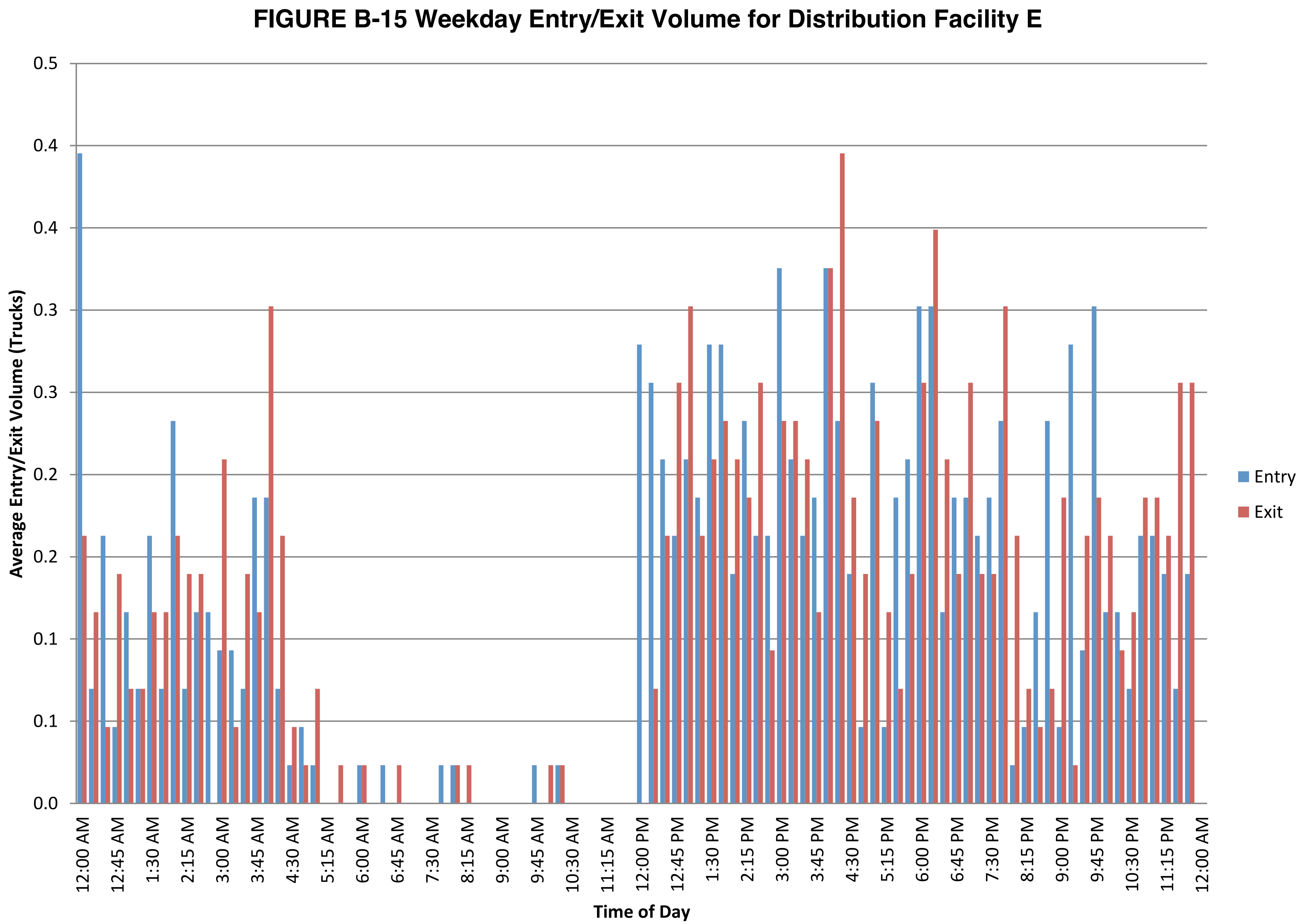


FIGURE B-15 Weekday Entry/Exit Volume for Distribution Facility E
Average Entry/Exit Volume (Trucks)
0.0
0.1
0.1
0.2
0.2
0.3
0.3
0.4
0.4
0.5
12:00 AM
12:45 AM
1:30 AM
2:15 AM
3:00 AM
3:45 AM
4:30 AM
5:15 AM
6:00 AM
6:45 AM
7:30 AM
8:15 AM
9:00 AM
9:45 AM
10:30 AM
11:15 AM
12:00 PM
12:45 PM
1:30 PM
2:15 PM
3:00 PM
3:45 PM
4:30 PM
5:15 PM
6:00 PM
6:45 PM
7:30 PM
8:15 PM
9:00 PM
9:45 PM
10:30 PM
11:15 PM
12:00 AM
Time of Day
Entry
Exit

FIGURE B-16 Weekday Entry/Exit Volumes for Intermodal Facility A

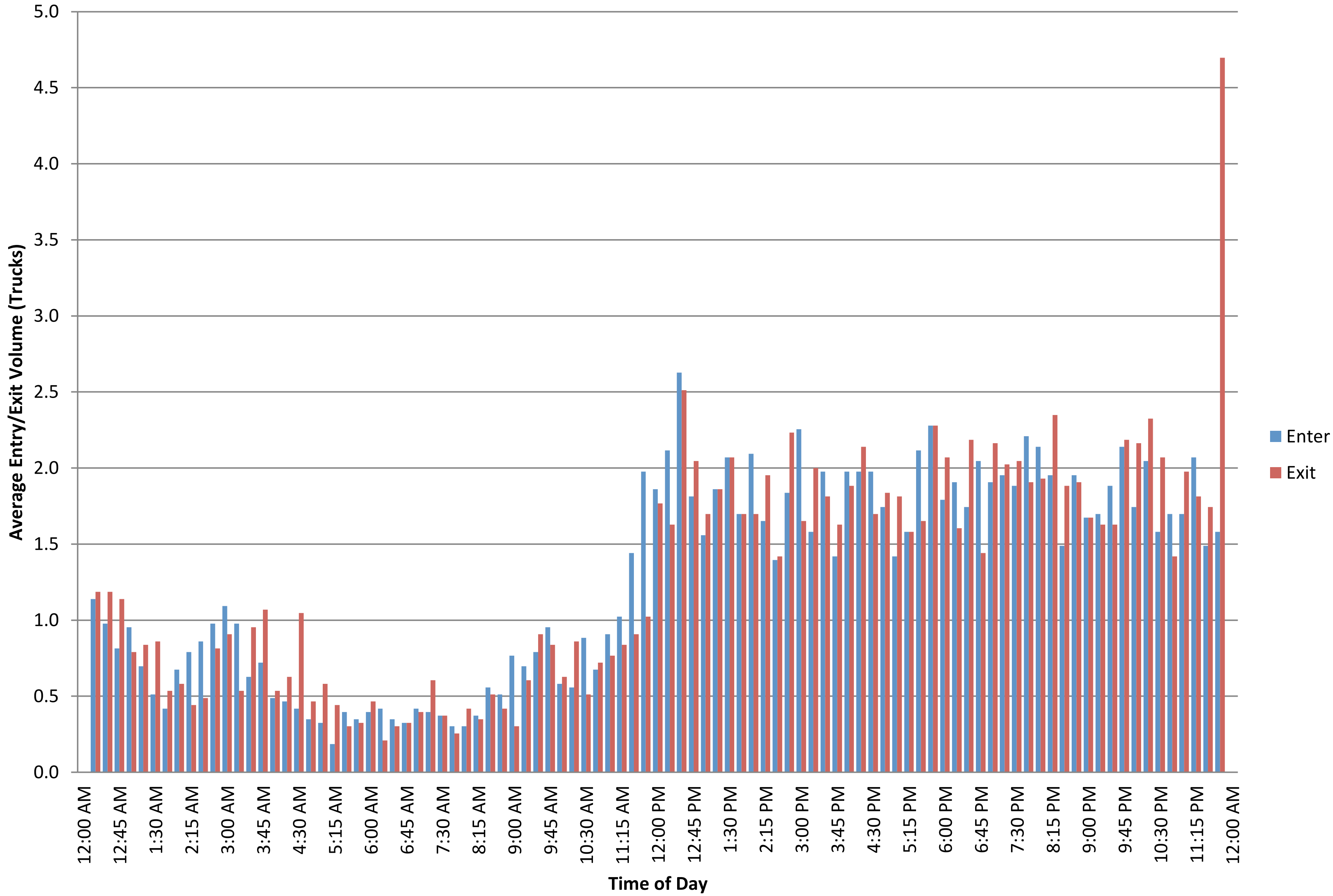


FIGURE B-17 Weekday Entry/Exit Volumes for Intermodal Facility B

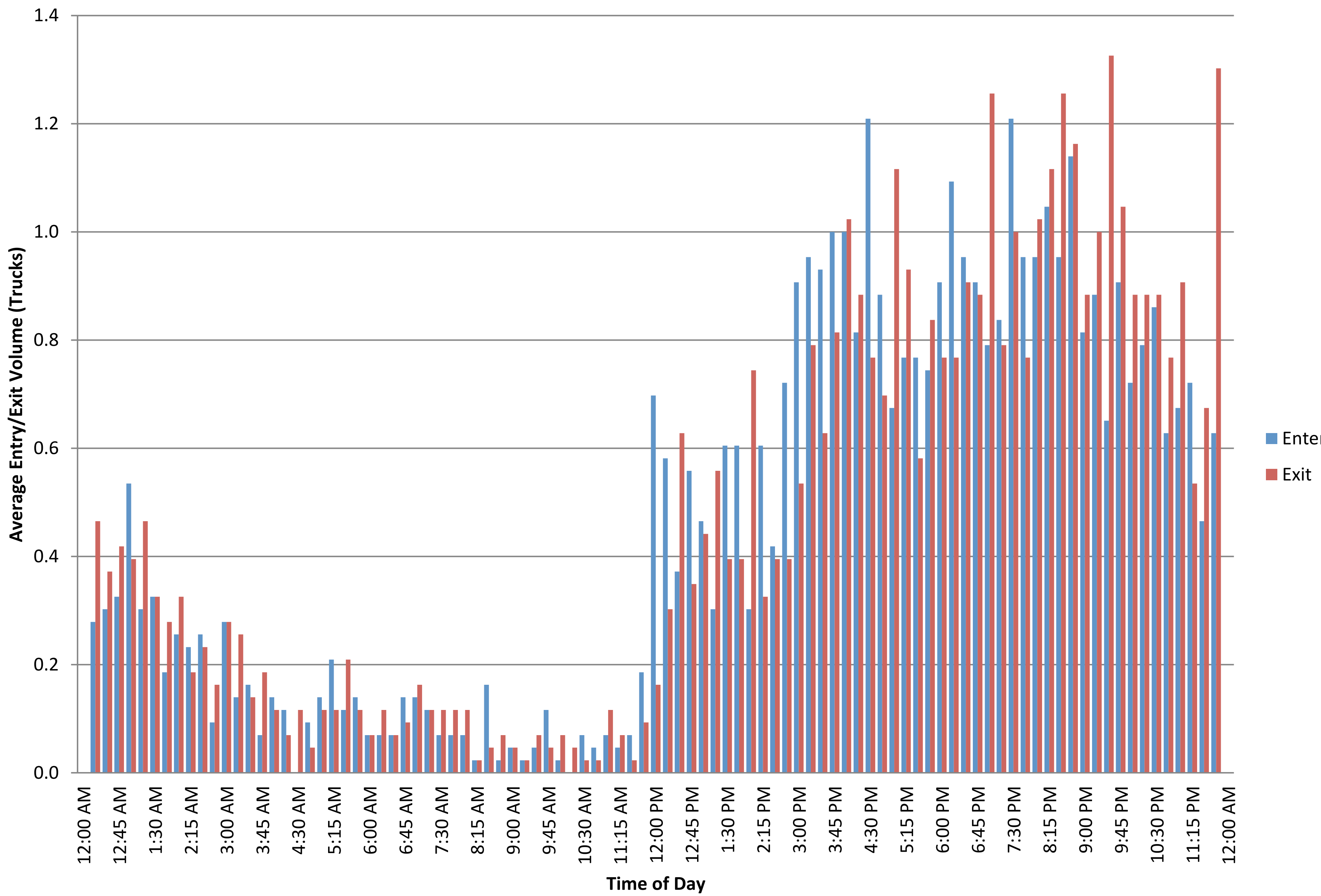


FIGURE B-18 Weekday Entry/Exit Volumes for Intermodal Facility C

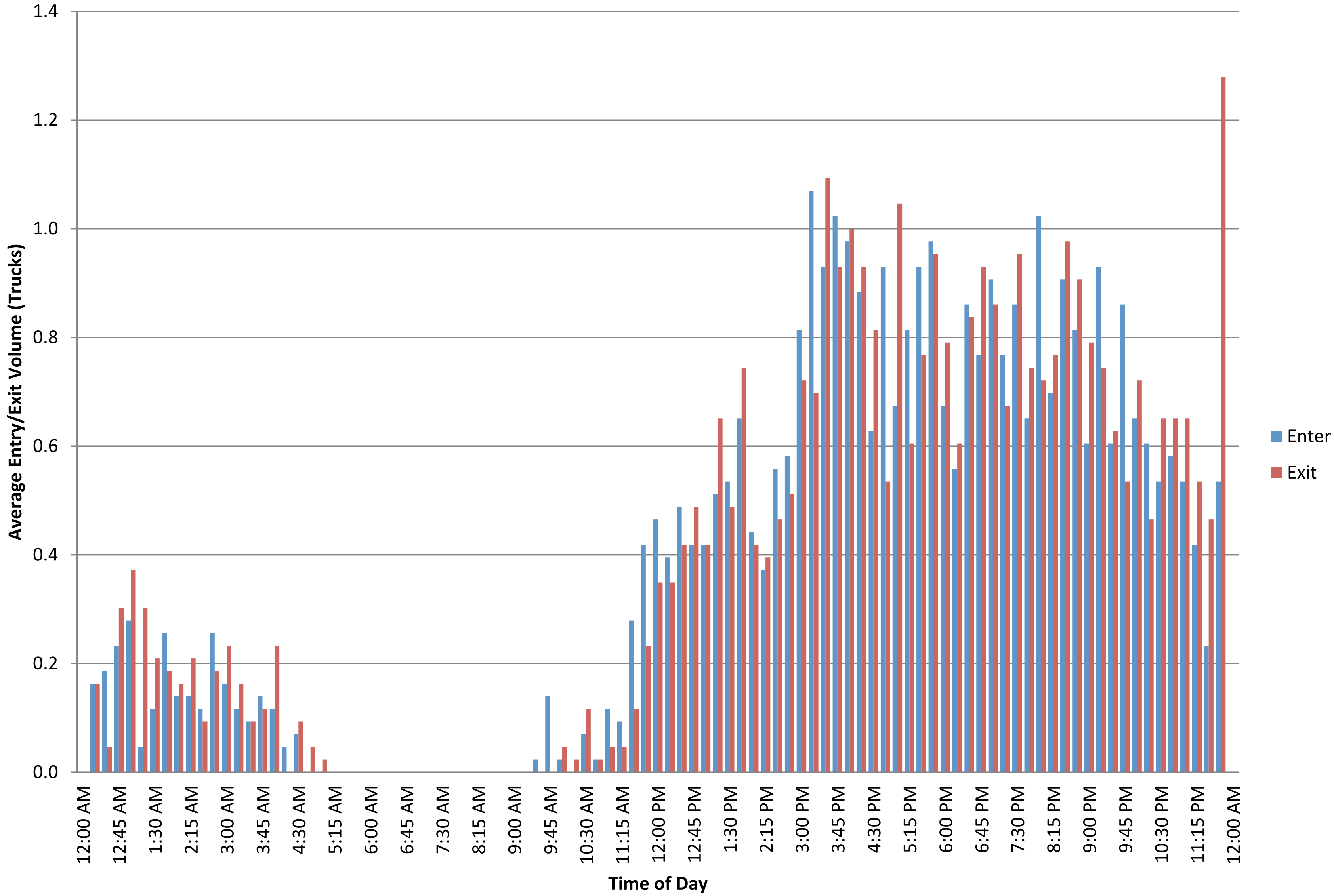


FIGURE B-19 Saturday Entry Volume for Private Warehouse Facilities

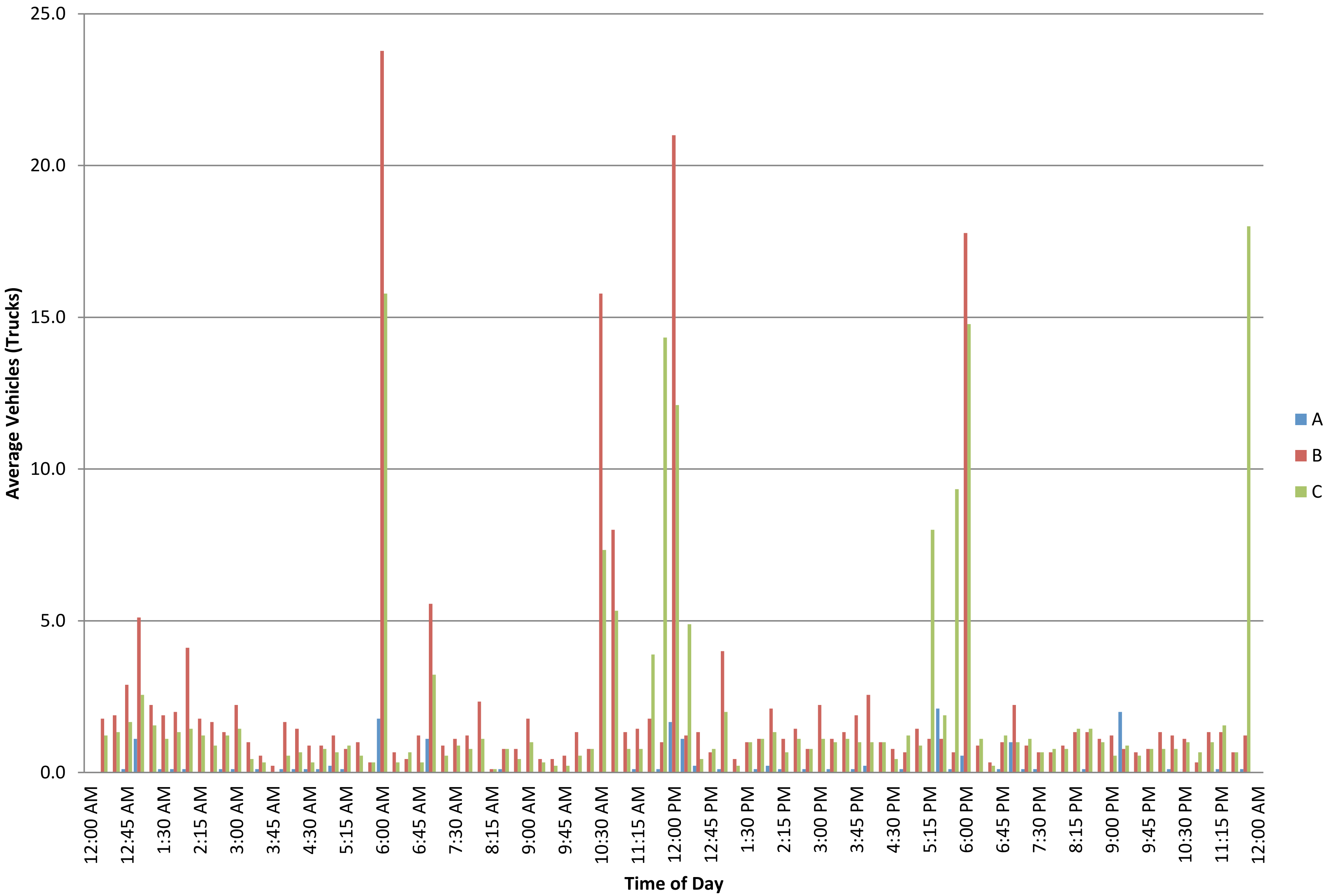


FIGURE B-20 Saturday Exit Volume for Private Warehouse Facilities

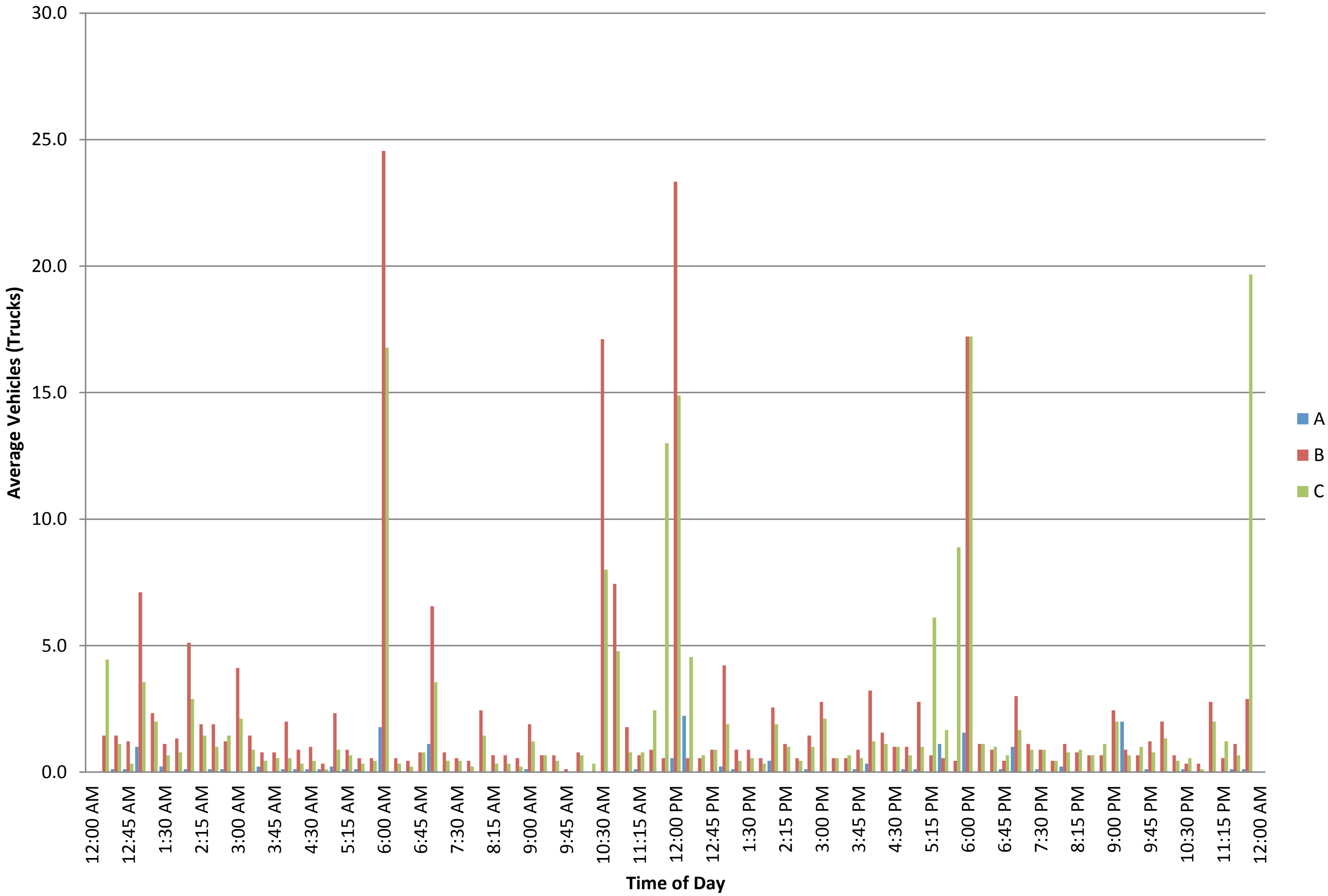


FIGURE B-21 Sunday Entry Volume for Private Warehouse Facilities

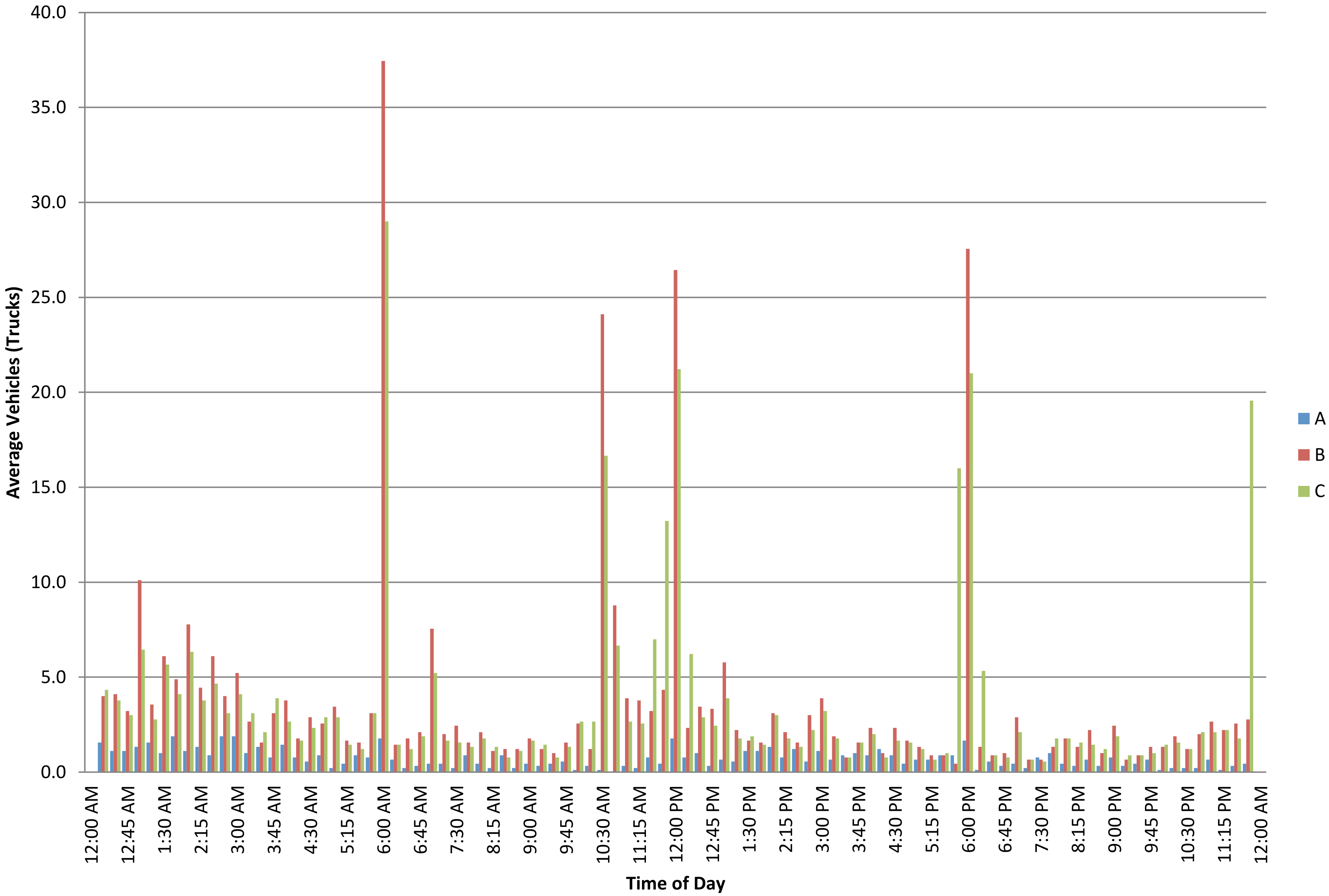


FIGURE B-22 Sunday Exit Volume for Private Warehouse Facilities

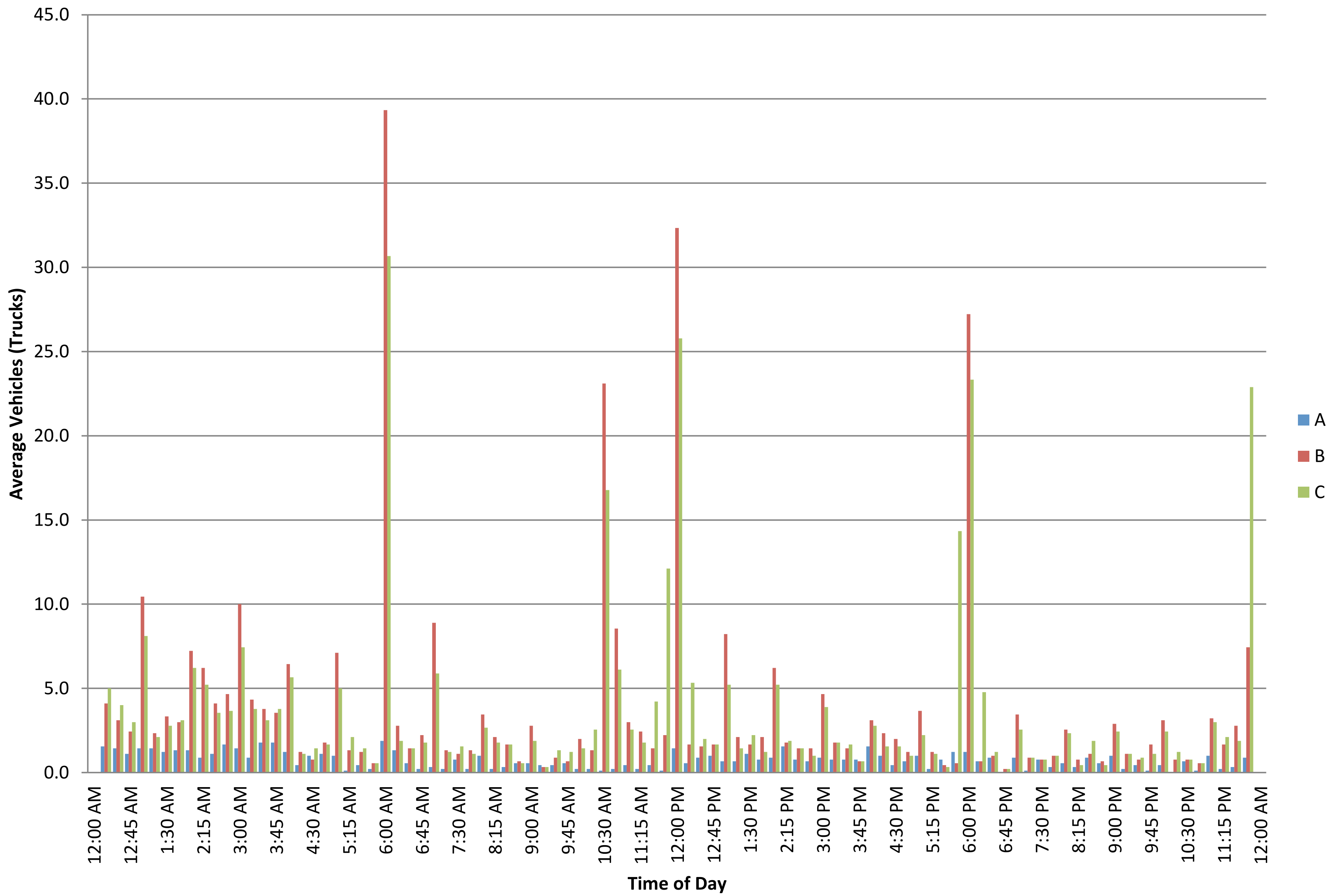


FIGURE B-23 Saturday Entry Volume for Warehouse Facilities

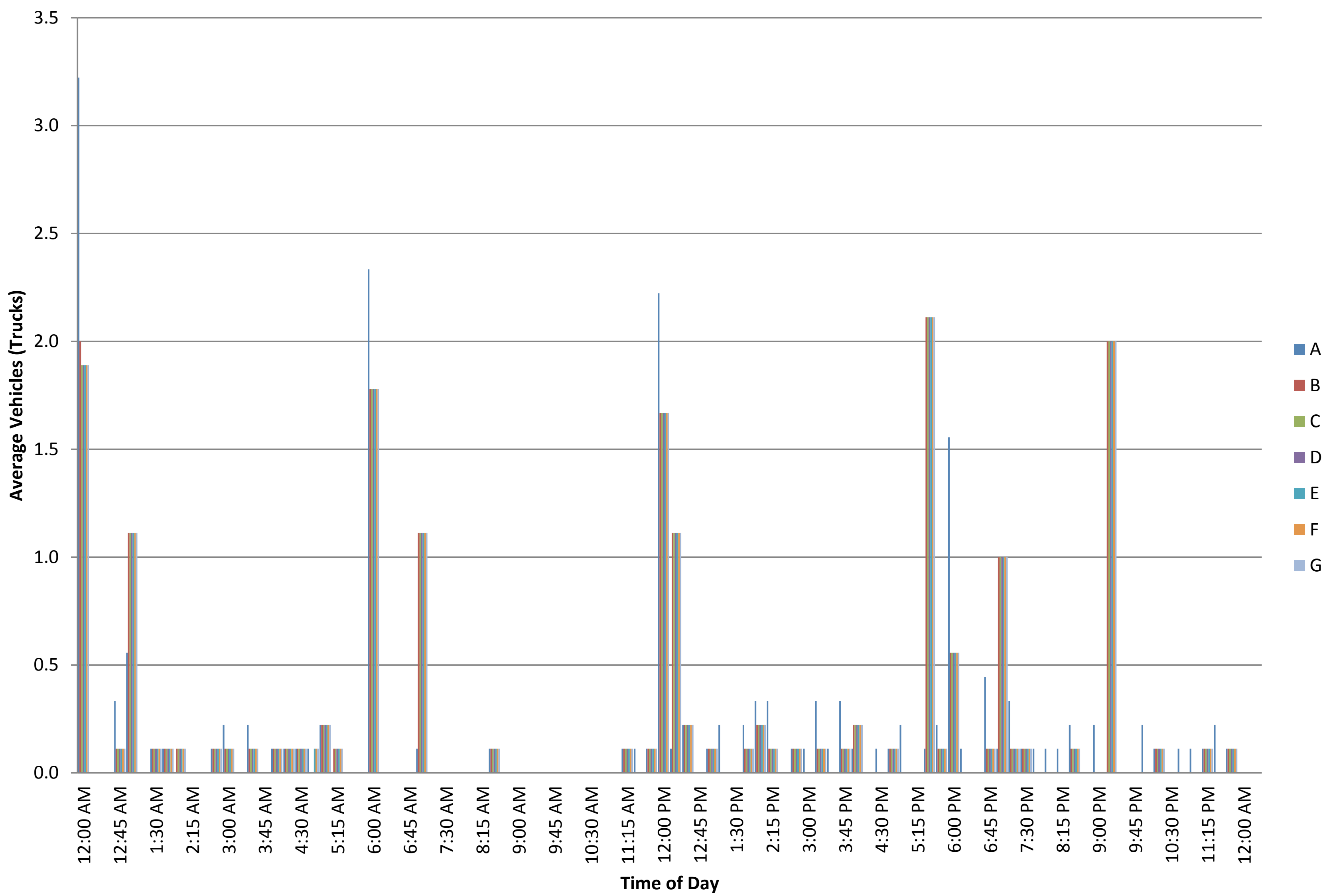


FIGURE B-24 Saturday Exit Volume for Warehouse Facilities

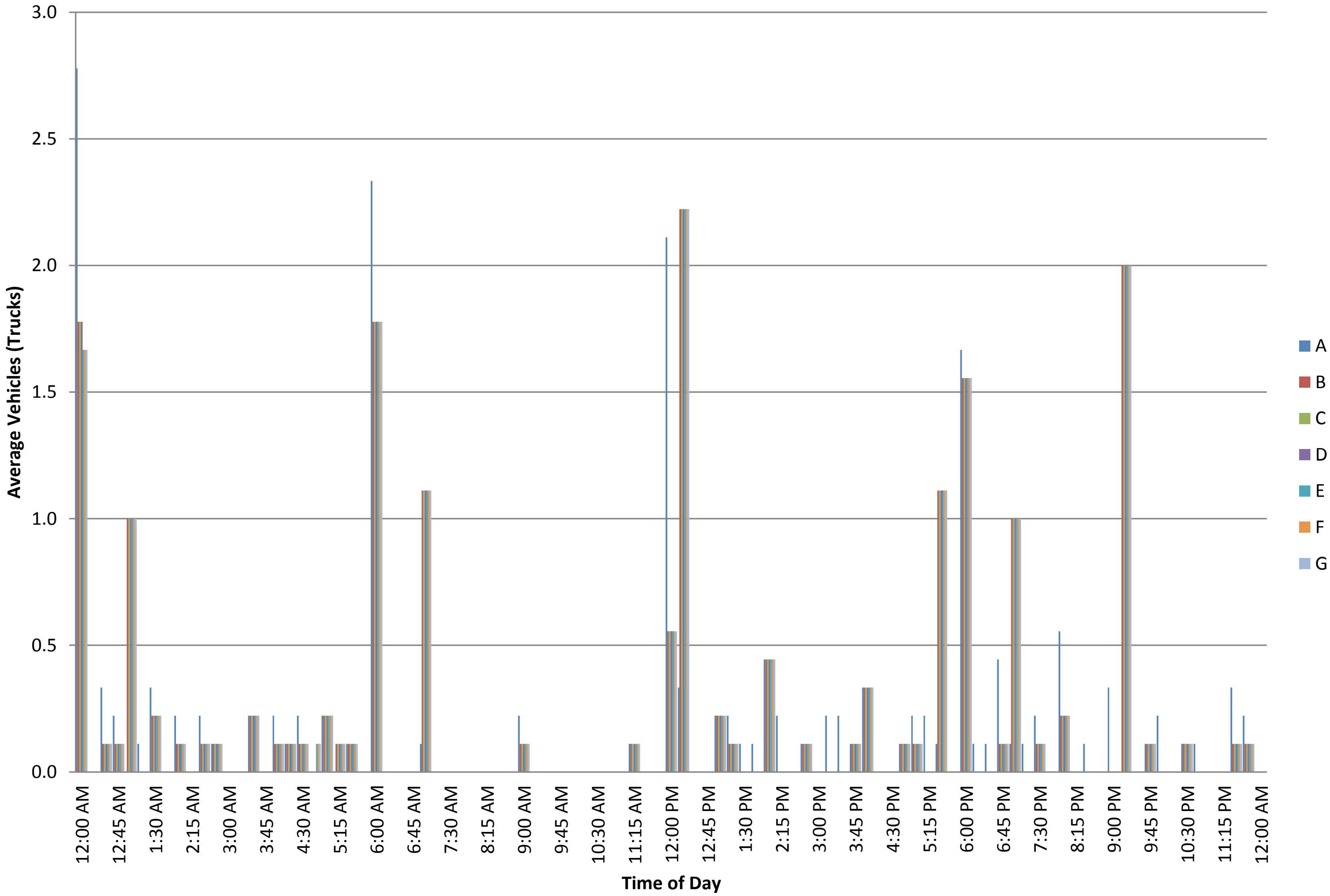


FIGURE B-25 Sunday Entry Volume for Warehouse Facilities

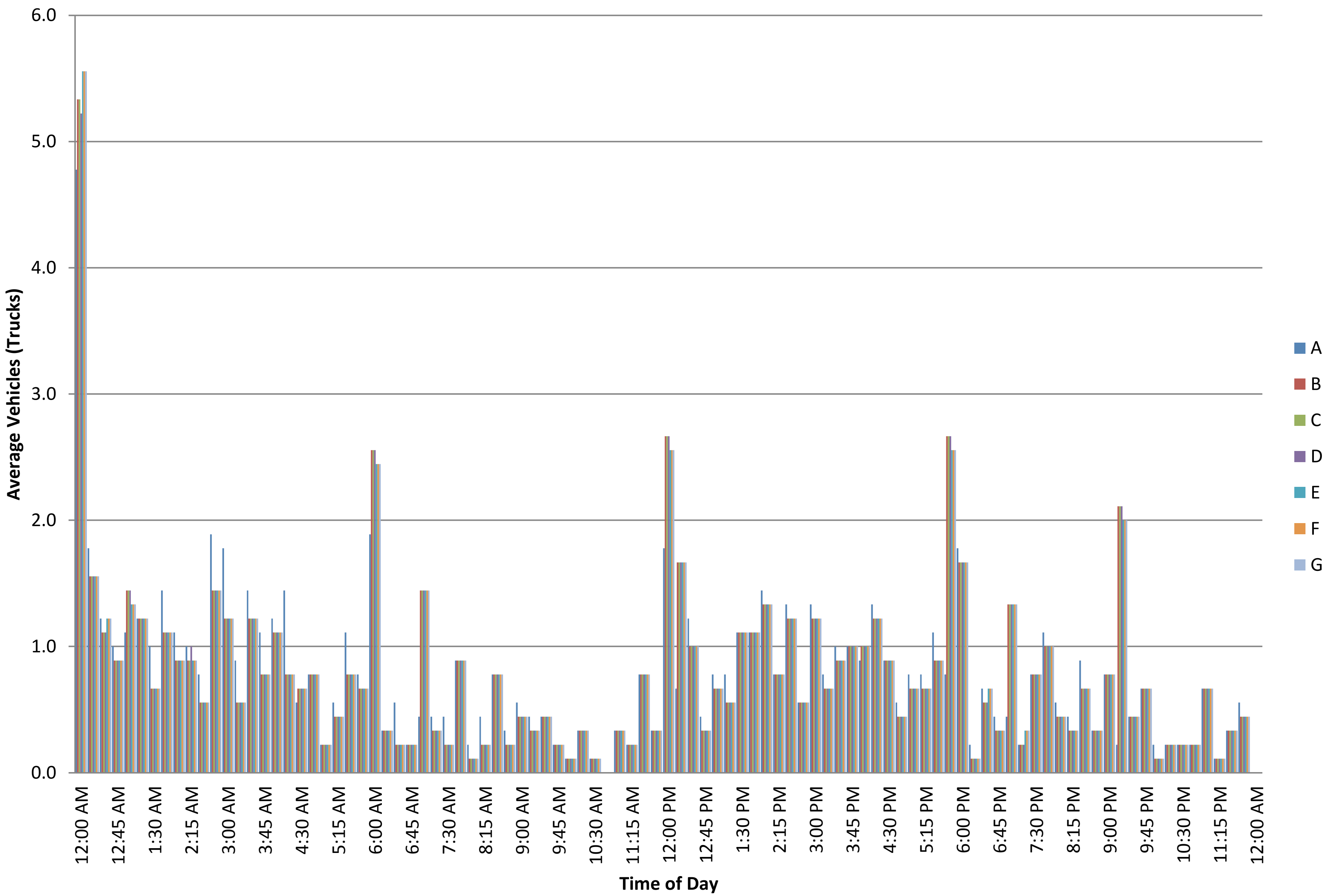


FIGURE B-26 Sunday Exit Volume for Warehouse Facilities

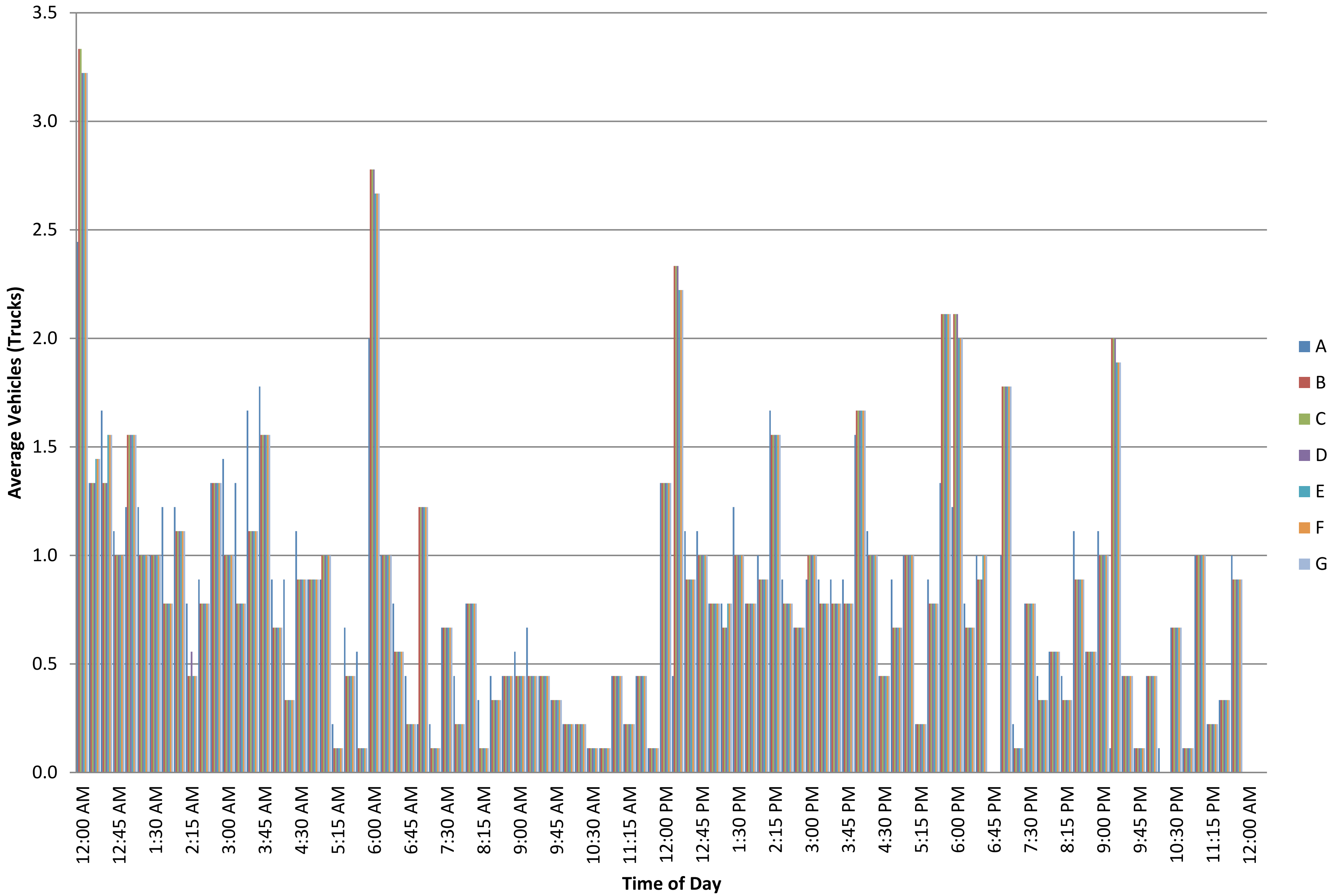


FIGURE B-27 Saturday Entry Volume for Distribution Facilities

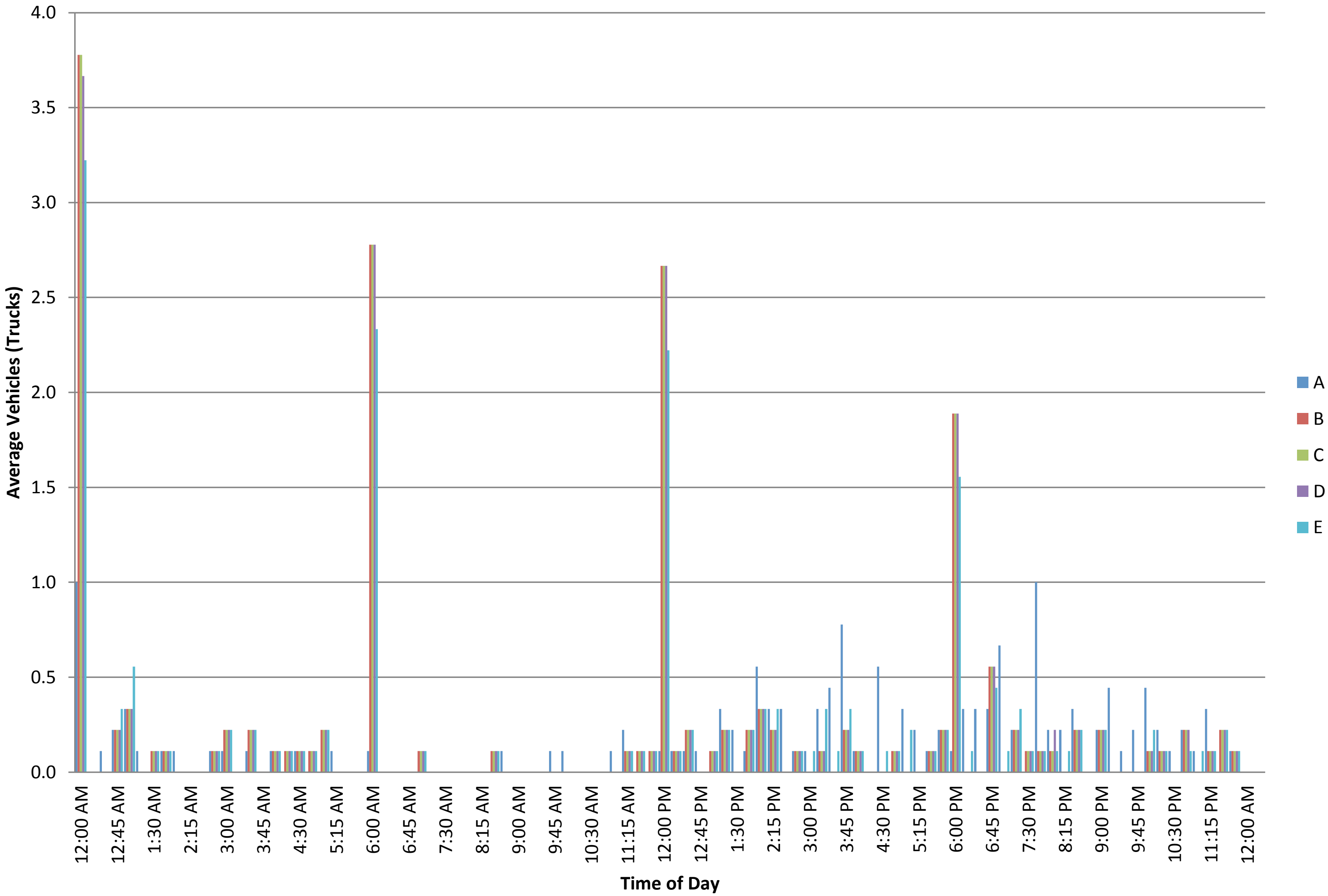


FIGURE B-28 Saturday Exit Volume for Distribution Facilities

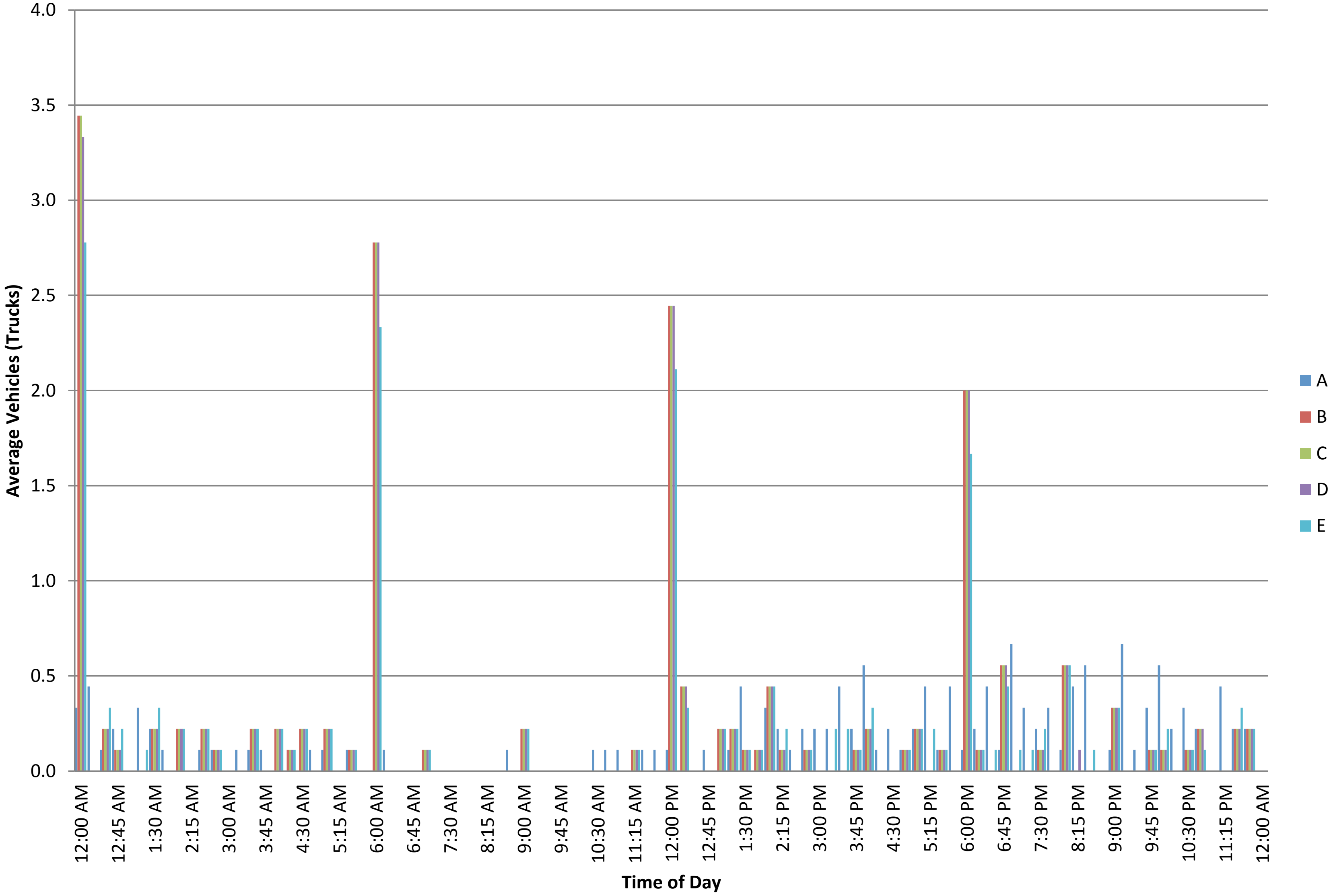
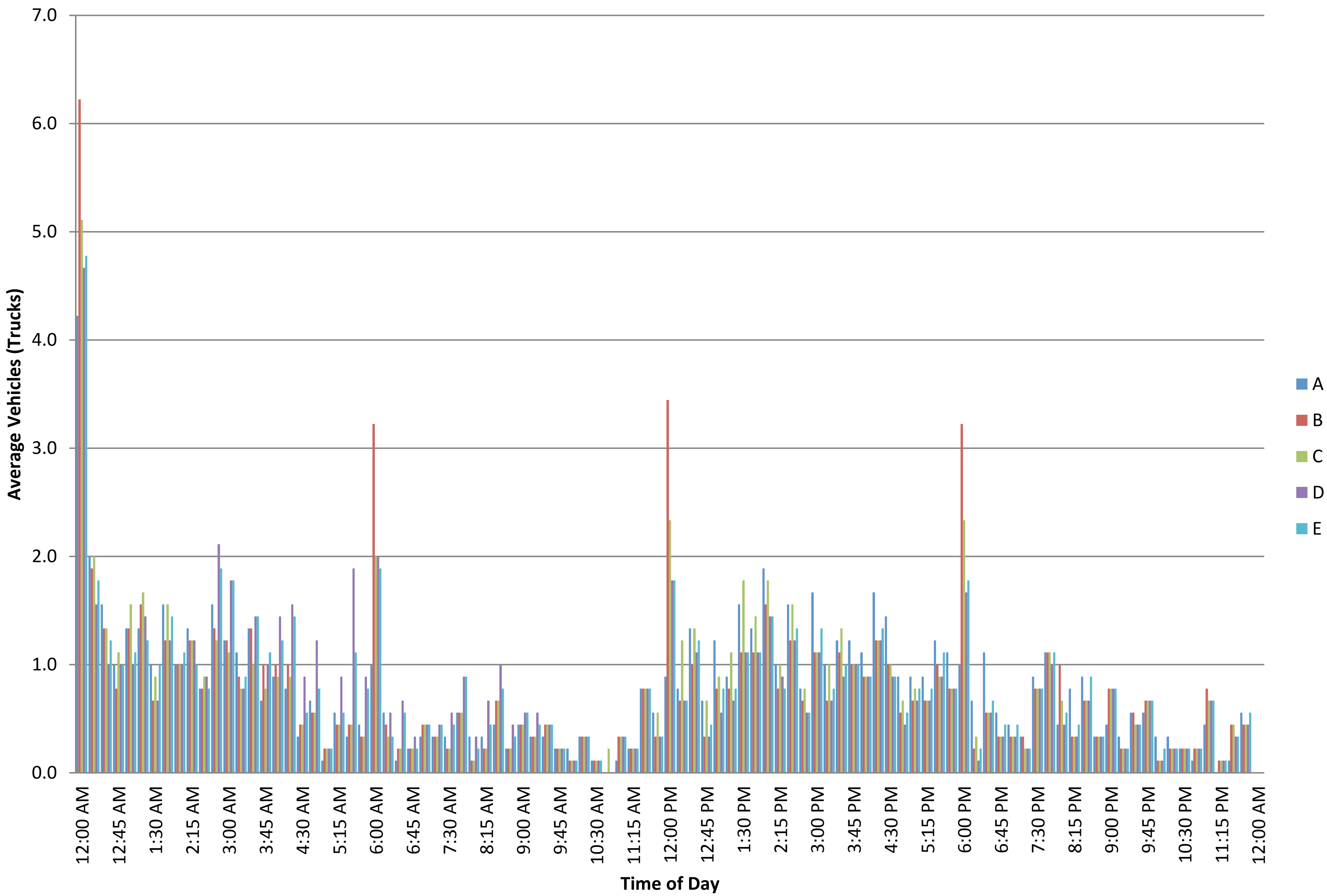


FIGURE B-29 Sunday Entry Volume for Distribution Facilities



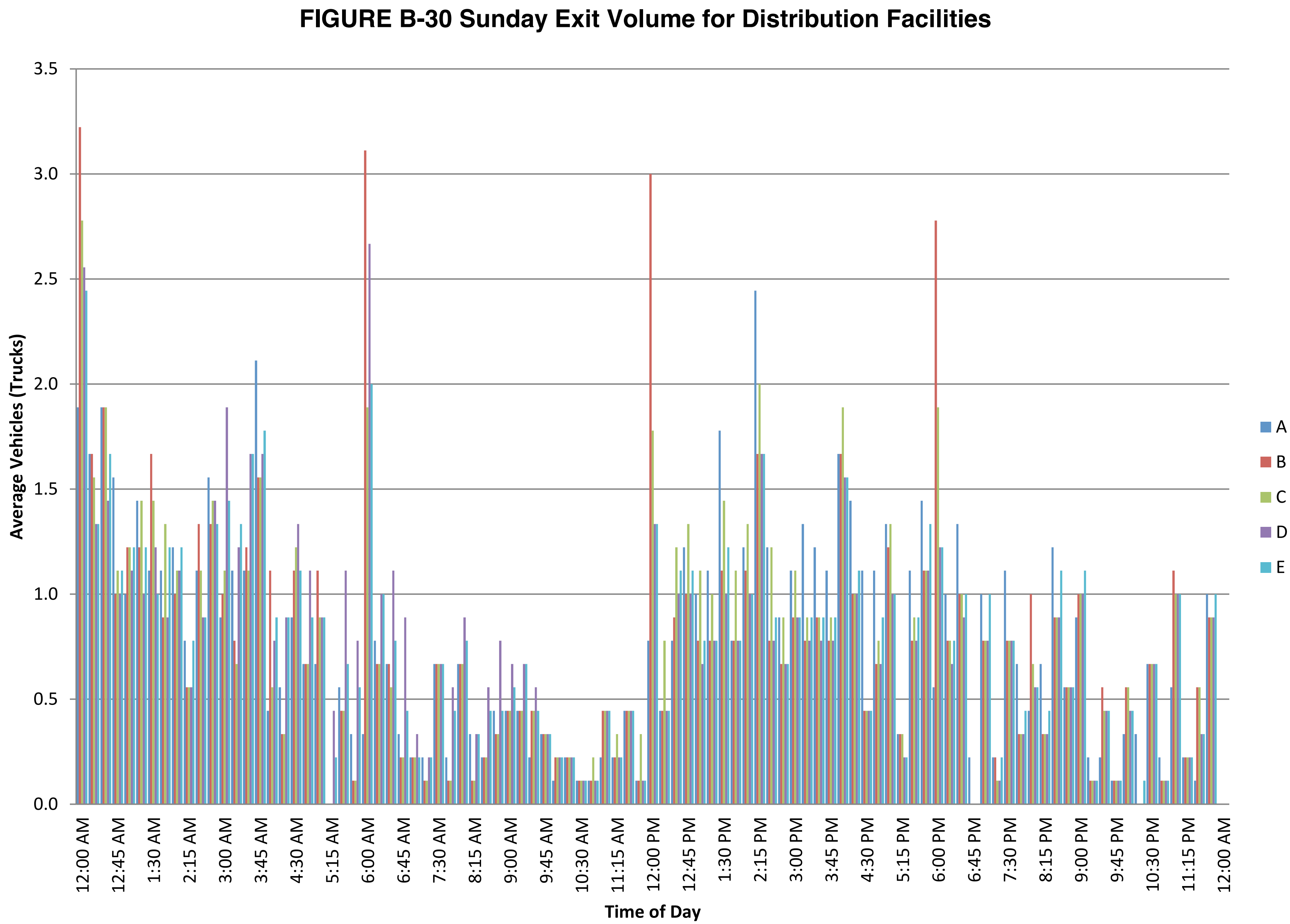


FIGURE B-30 Sunday Exit Volume for Distribution Facilities
Average Vehicles (Trucks)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
12:00 AM
12:45 AM
1:30 AM
2:15 AM
3:00 AM
3:45 AM
4:30 AM
5:15 AM
6:00 AM
6:45 AM
7:30 AM
8:15 AM
9:00 AM
9:45 AM
10:30 AM
11:15 AM
12:00 PM
12:45 PM
1:30 PM
2:15 PM
3:00 PM
3:45 PM
4:30 PM
5:15 PM
6:00 PM
6:45 PM
7:30 PM
8:15 PM
9:00 PM
9:45 PM
10:30 PM
11:15 PM
12:00 AM
Time of Day
A
B
C
D
E

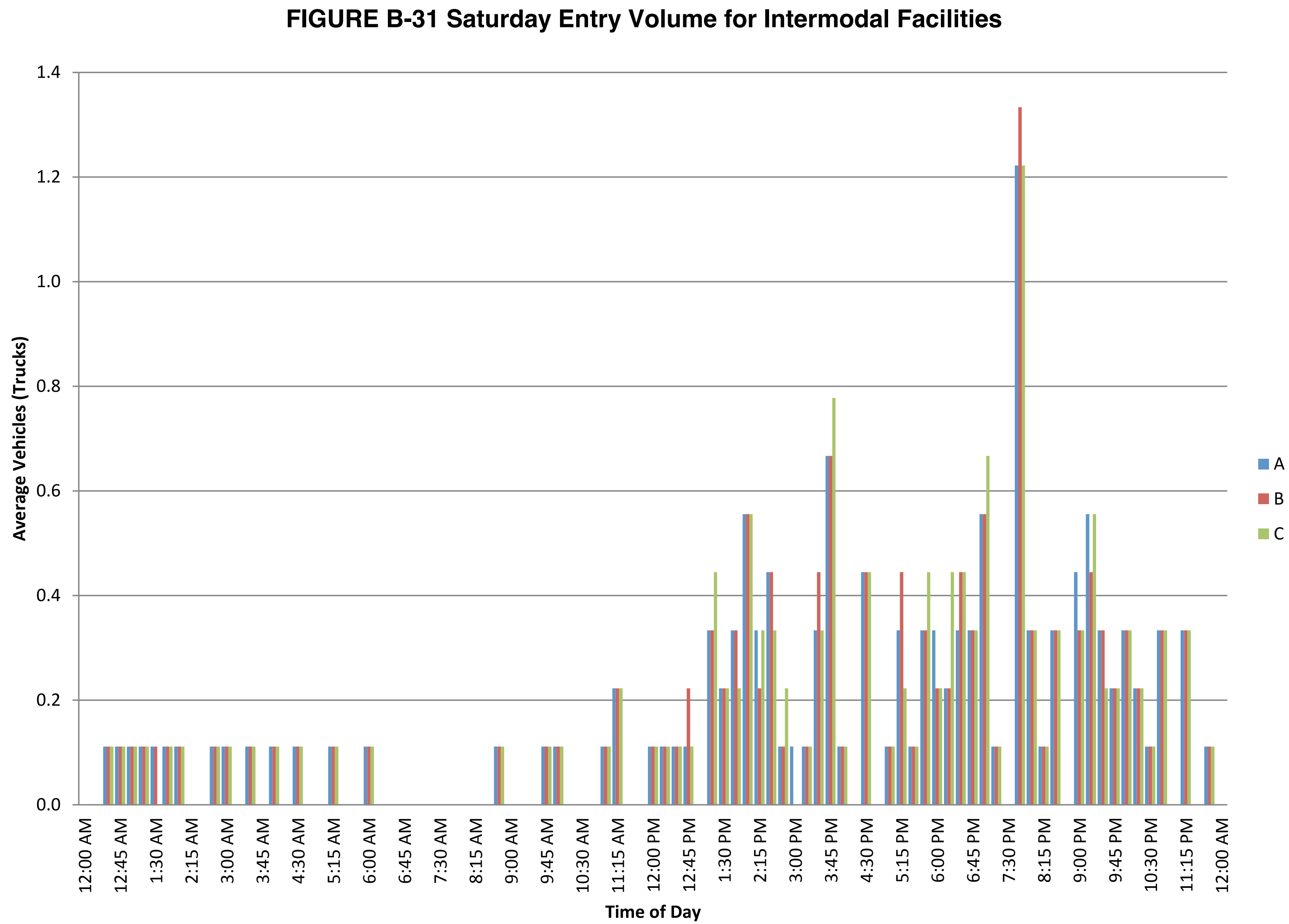


FIGURE B-31 Saturday Entry Volume for Intermodal Facilities
Average Vehicles (Trucks)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
12:00 AM
12:45 AM
1:30 AM
2:15 AM
3:00 AM
3:45 AM
4:30 AM
5:15 AM
6:00 AM
6:45 AM
7:30 AM
8:15 AM
9:00 AM
9:45 AM
10:30 AM
11:15 AM
12:00 PM
12:45 PM
1:30 PM
2:15 PM
3:00 PM
3:45 PM
4:30 PM
5:15 PM
6:00 PM
6:45 PM
7:30 PM
8:15 PM
9:00 PM
9:45 PM
10:30 PM
11:15 PM
12:00 AM
Time of Day
A
B
C

FIGURE B-32 Saturday Exit Volume for Intermodal Facilities

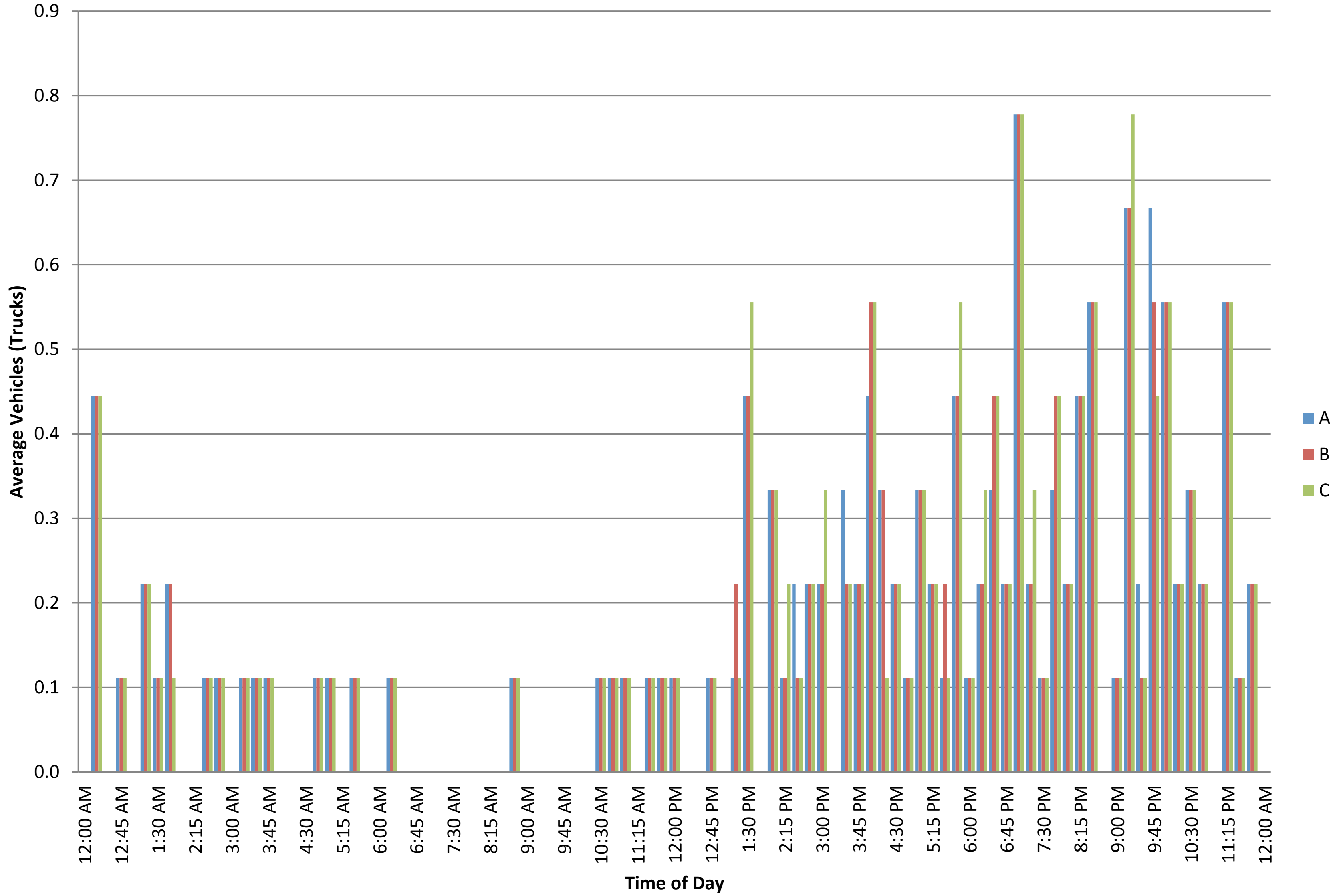


FIGURE B-33 Sunday Entry Volume for Intermodal Facilities

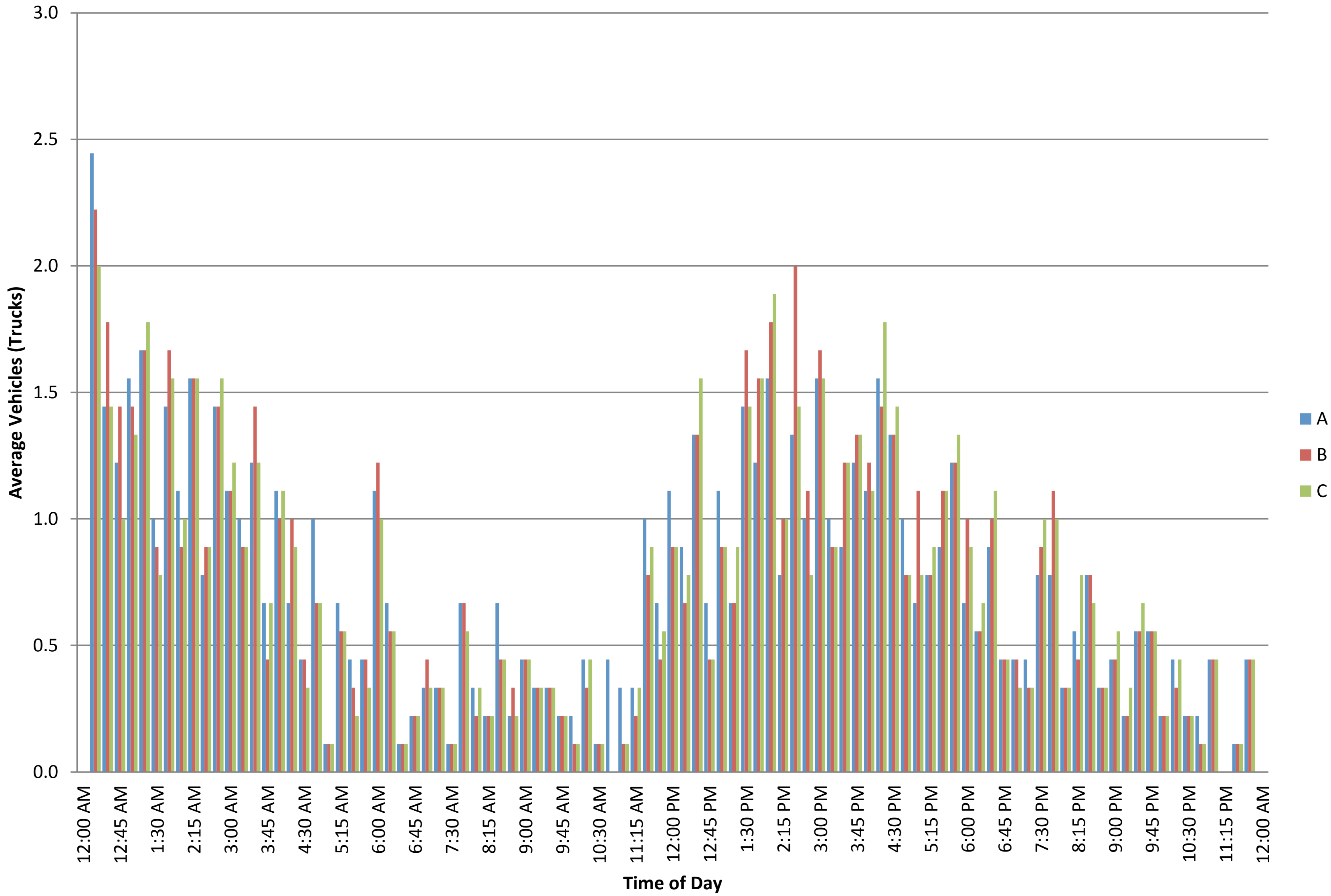
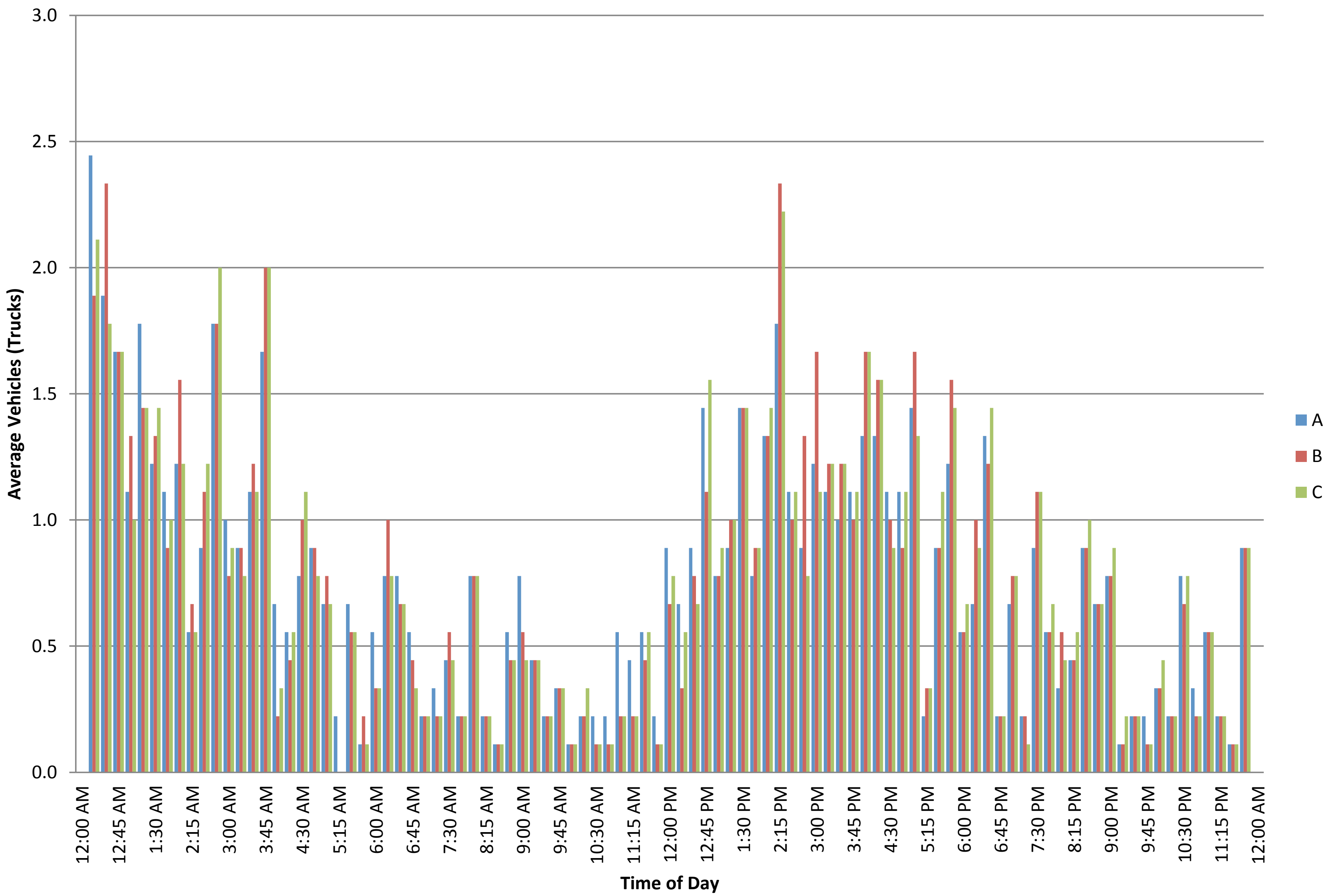


FIGURE B-34 Sunday Exit Volume for Intermodal Facilities



APPENDIX C. Comparison of Average Turn Times to Average Volumes for Each Facility

FIGURE C-1 Comparison of Weekday Volume and Average Turn Time for Intermodal Facility A

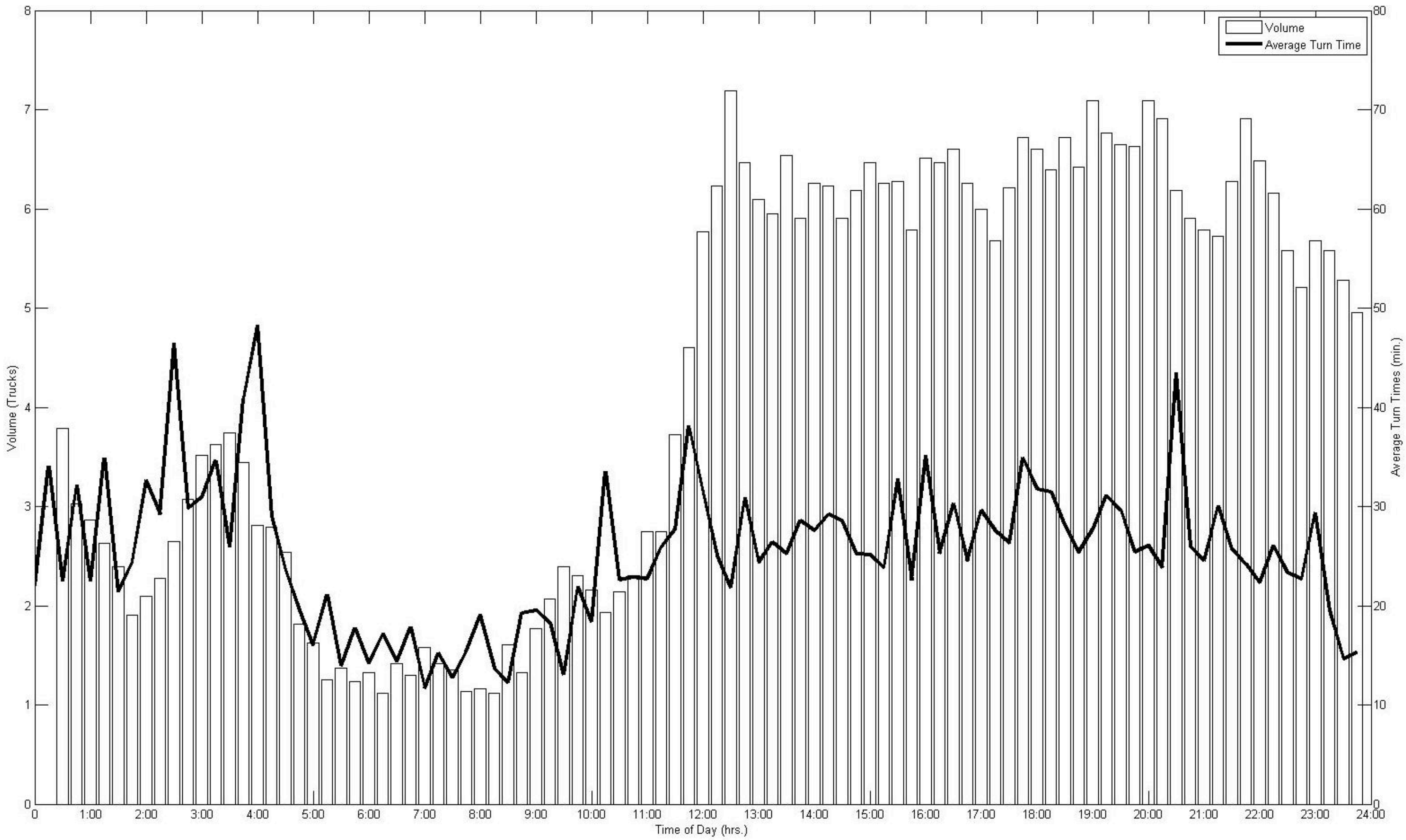


FIGURE C-2 Comparison of Saturday Volume and Average Turn Time for Intermodal Facility A

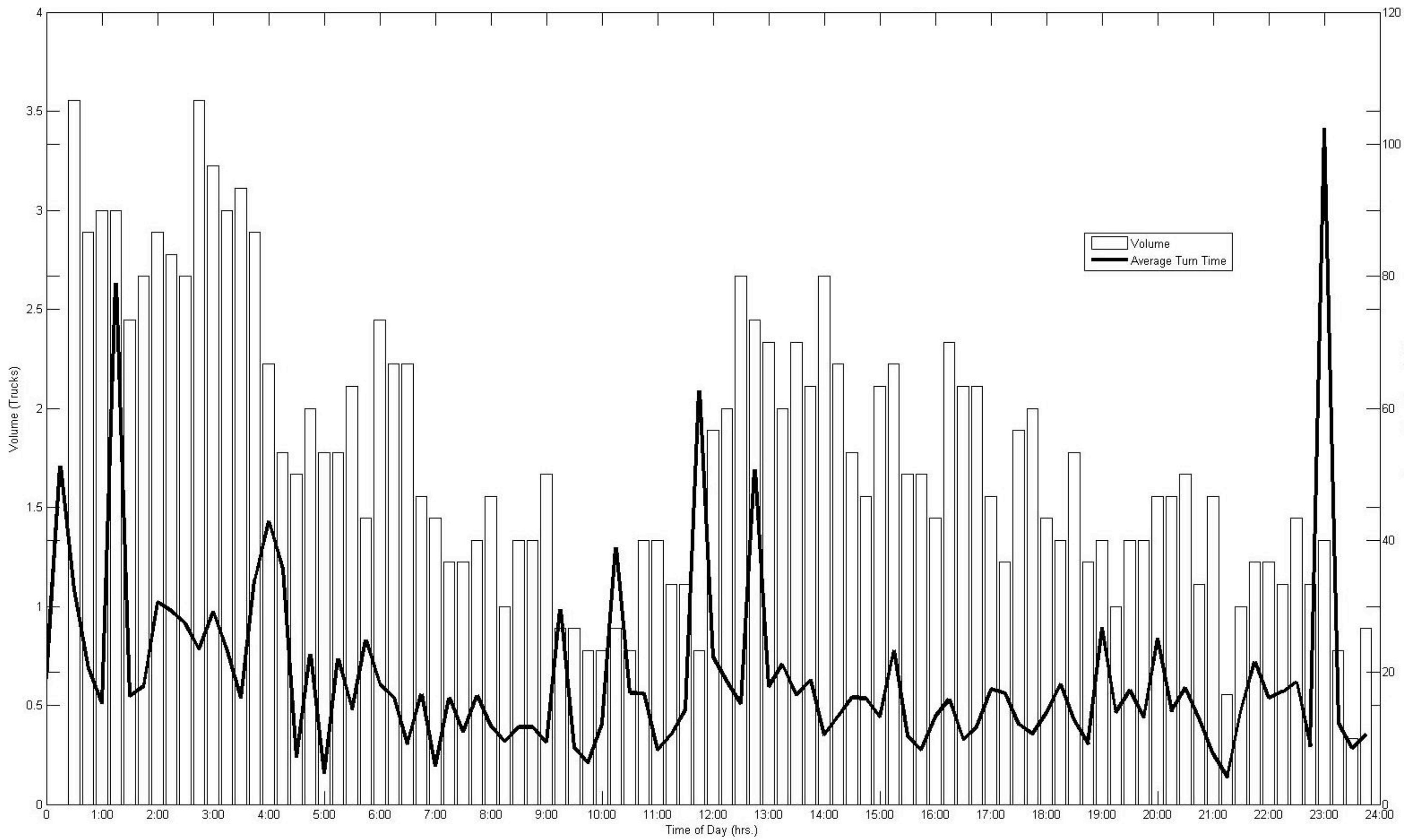


FIGURE C-3 Comparison of Sunday Volume and Average Turn Time for Intermodal Facility A

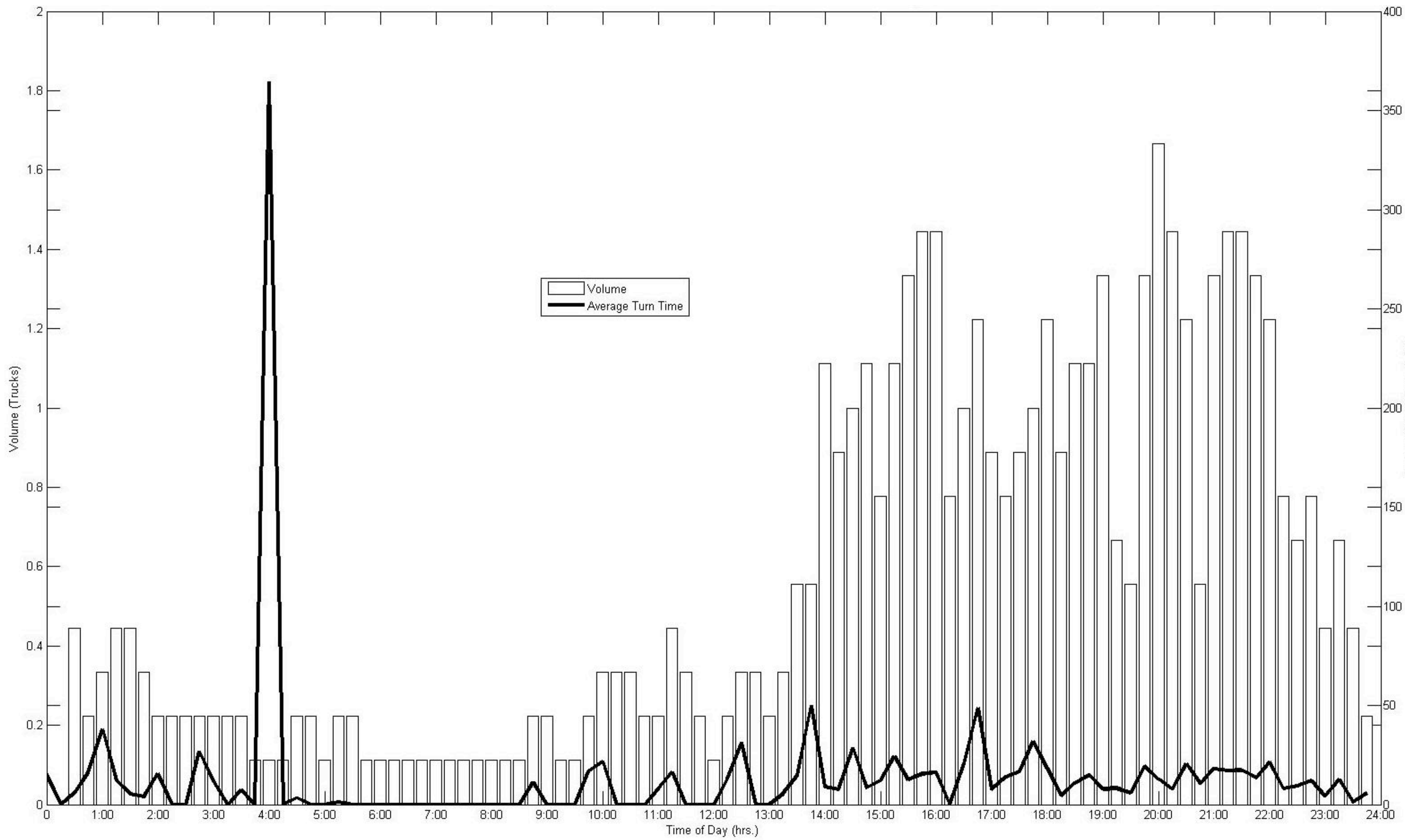


FIGURE C-4 Comparison of Weekday Volume and Average Turn Time for Intermodal Facility B

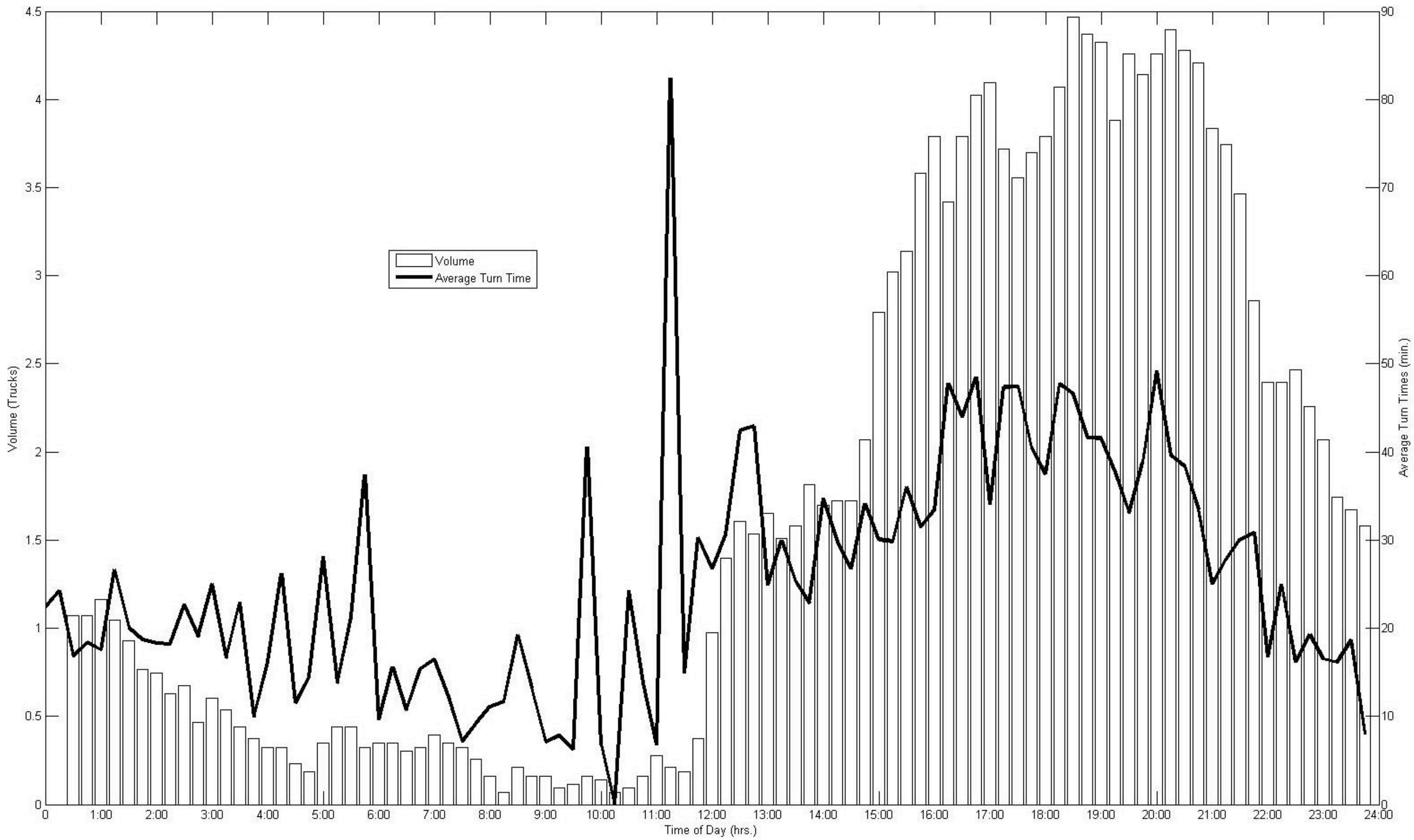


FIGURE C-5 Comparison of Saturday Volume and Average Turn Time for Intermodal Facility B

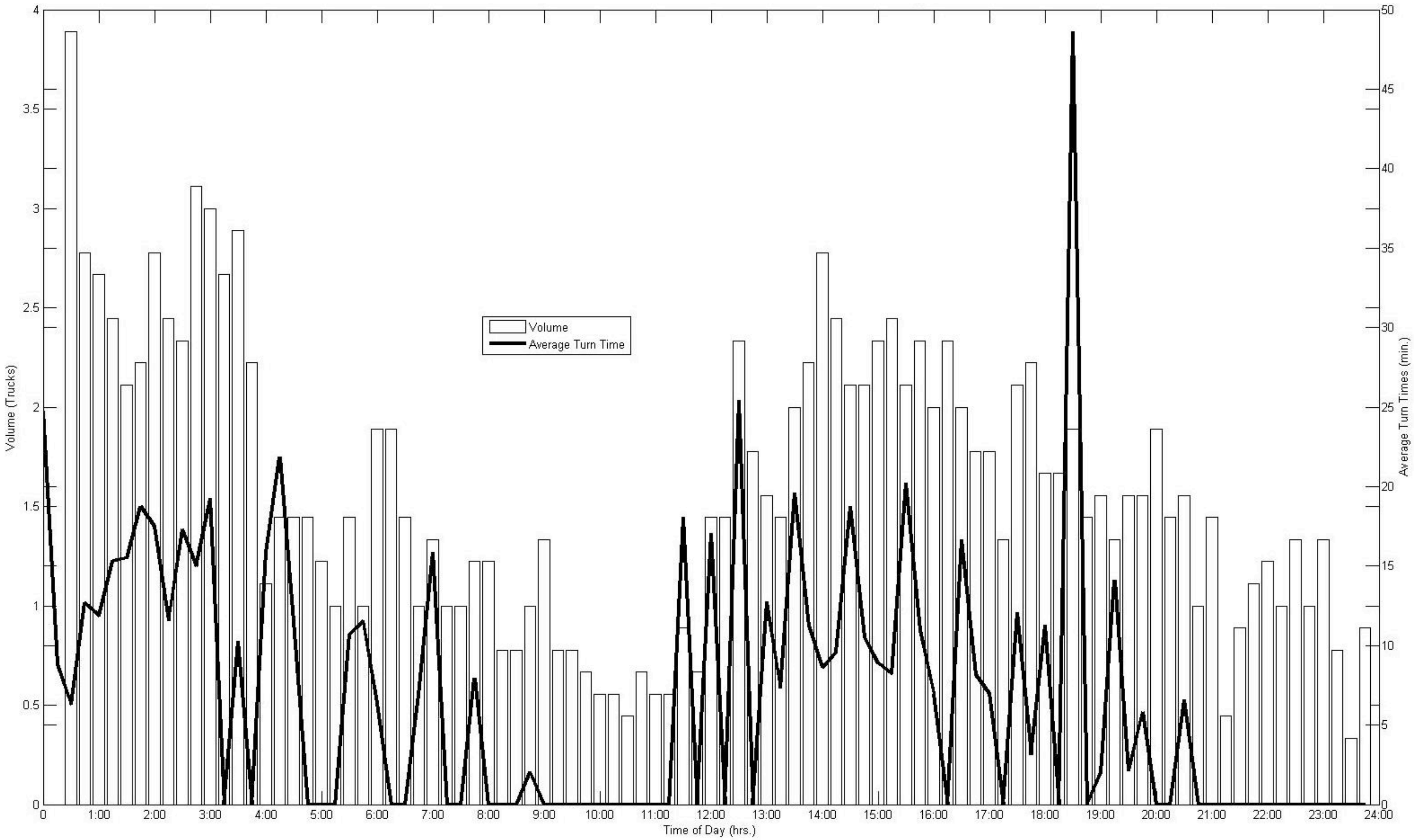


FIGURE C-6 Comparison of Sunday Volume and Average Turn Time for Intermodal Facility B

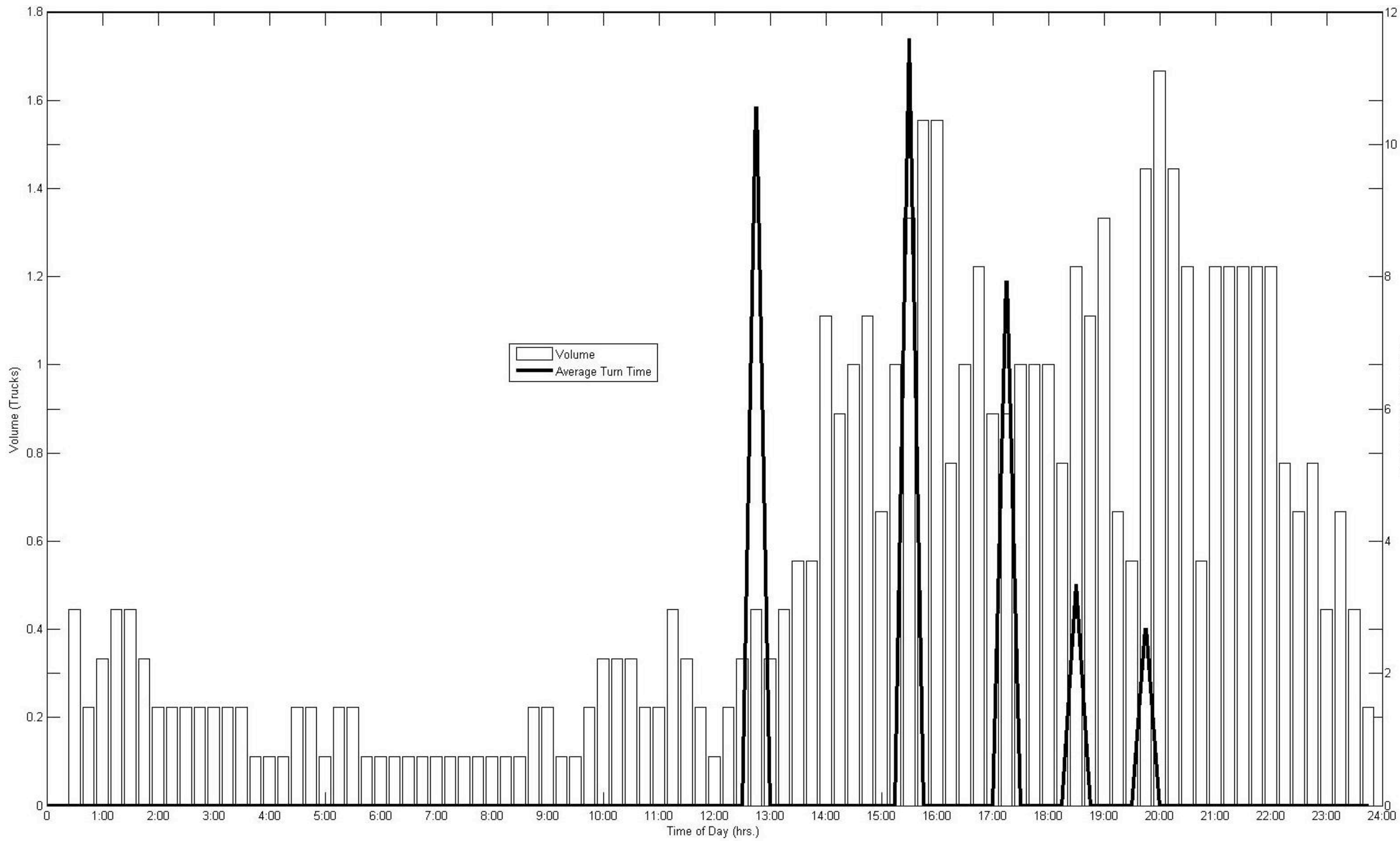


FIGURE C-7 Comparison of Weekday Volume and Average Turn Time for Intermodal Facility C

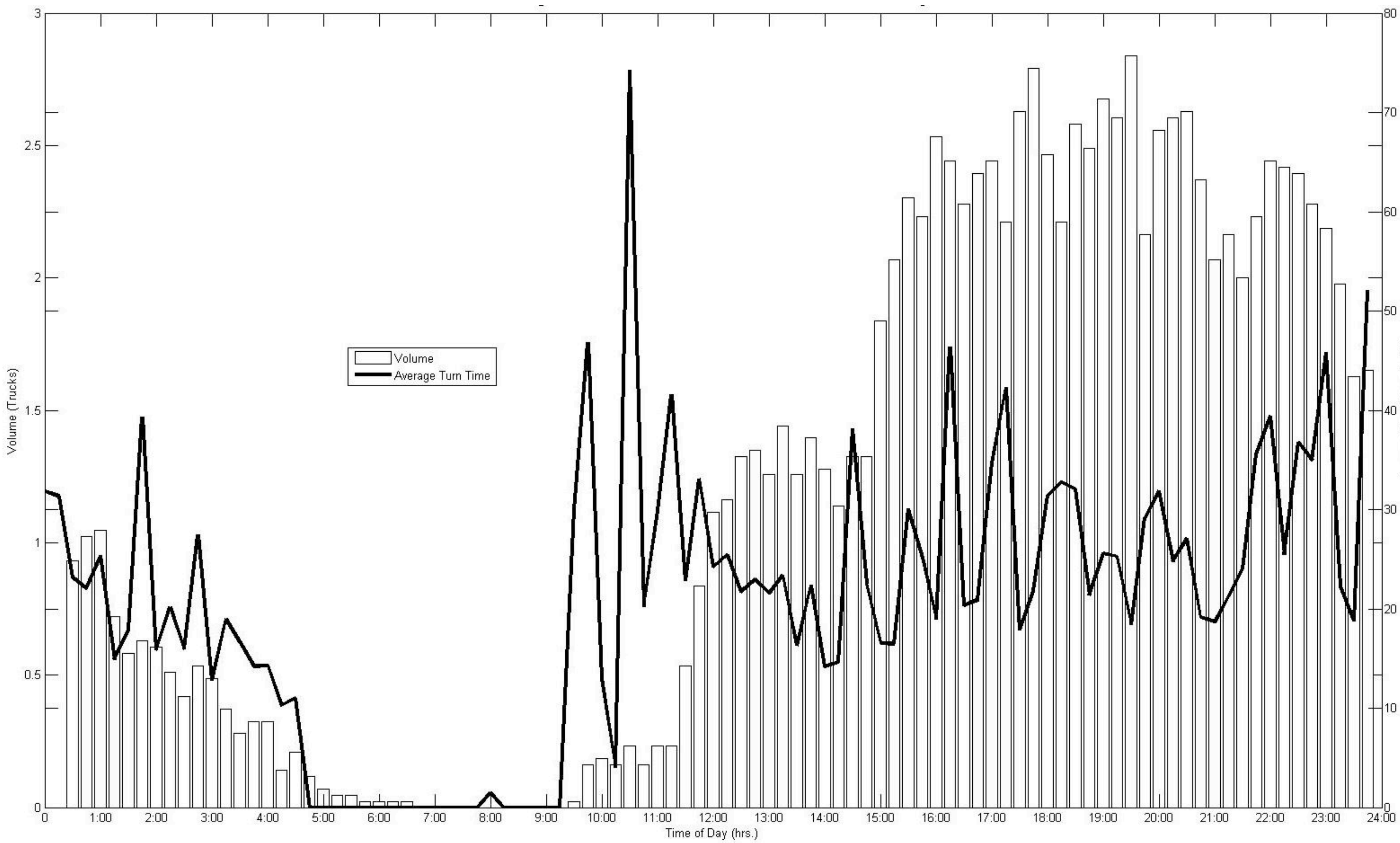


FIGURE C-8 Comparison of Saturday Volume and Average Turn Time for Intermodal Facility C

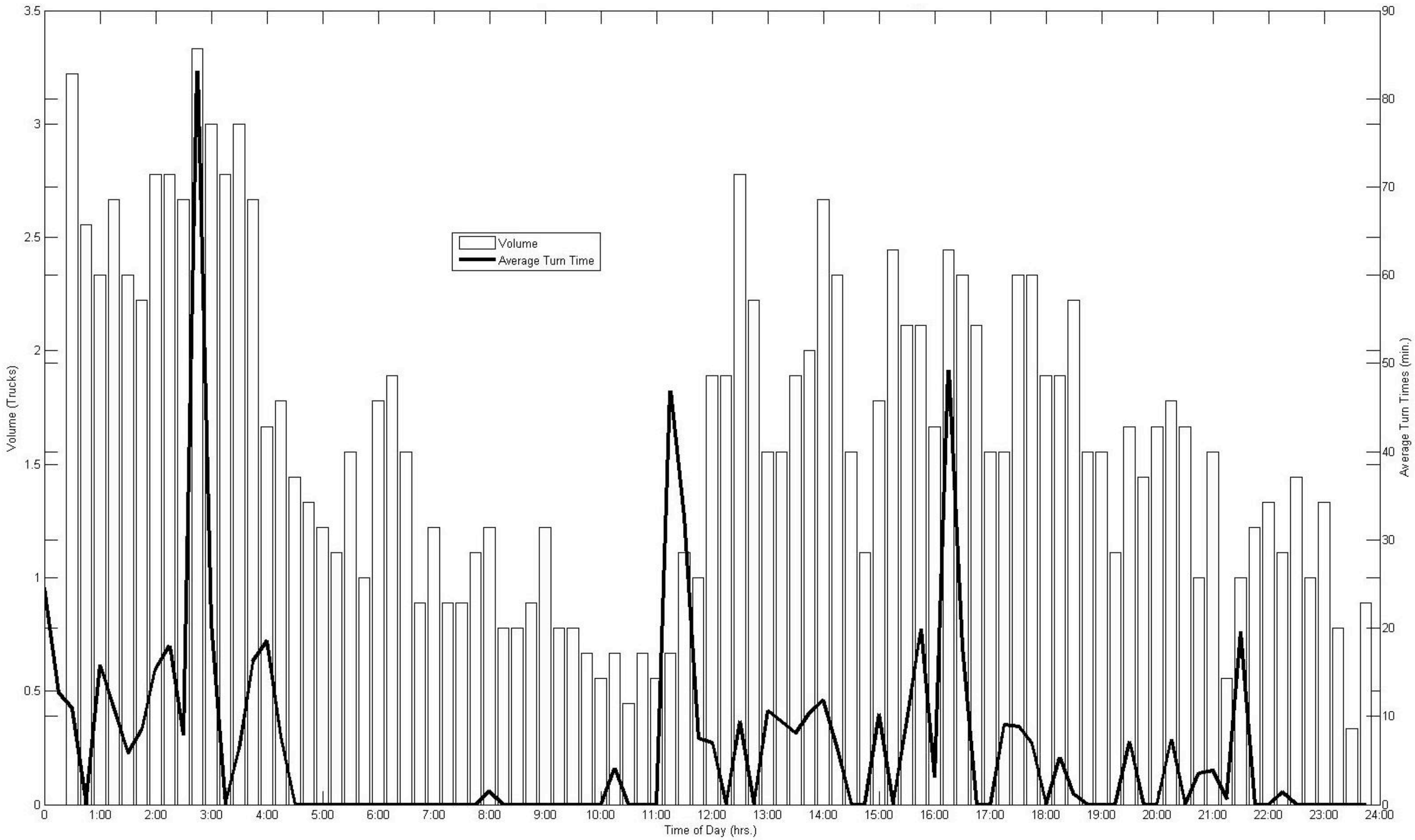


FIGURE C-9 Comparison of Sunday Volume and Average Turn Time for Intermodal Facility C

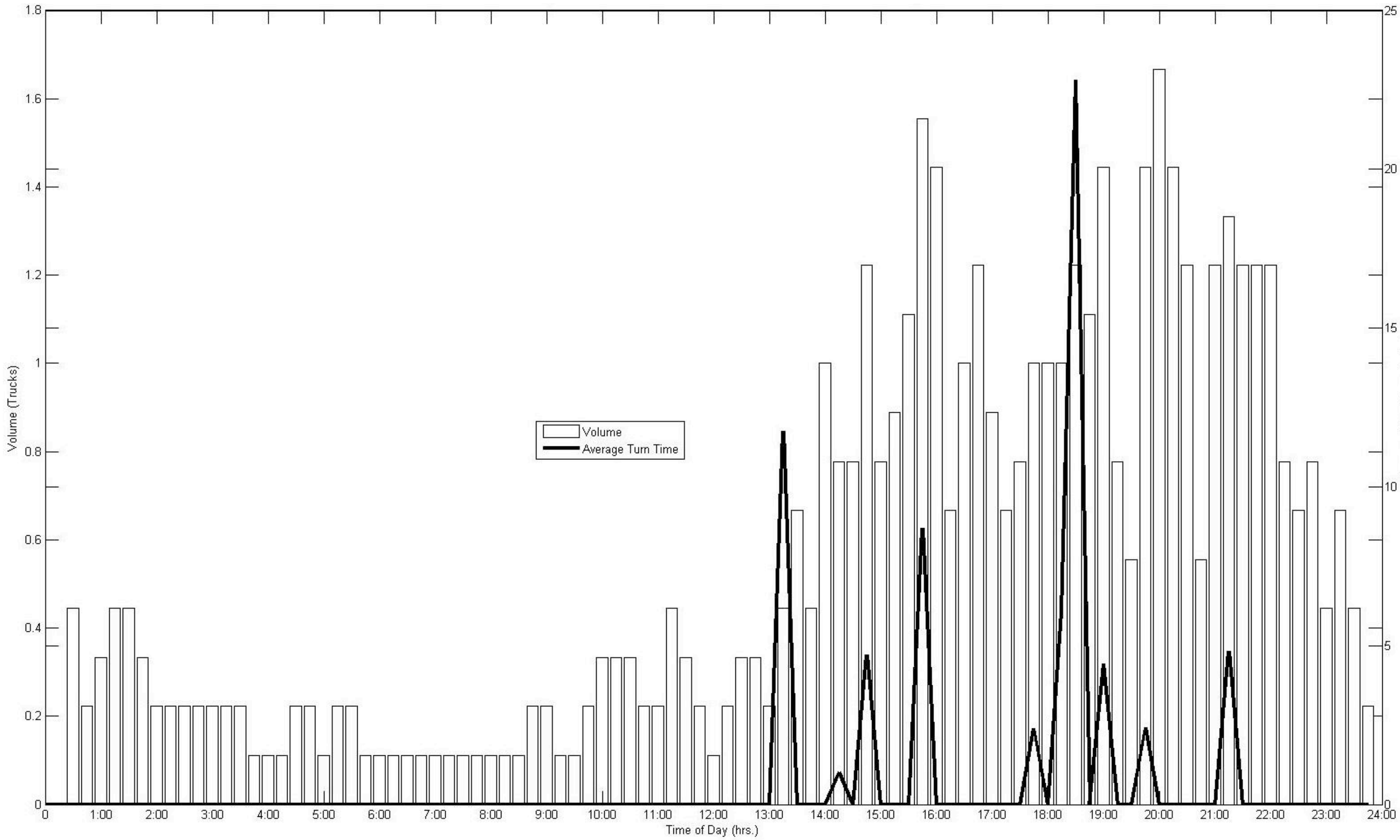


FIGURE C-10 Comparison of Weekday Volume and Average Turn Time for Distribution Facility A

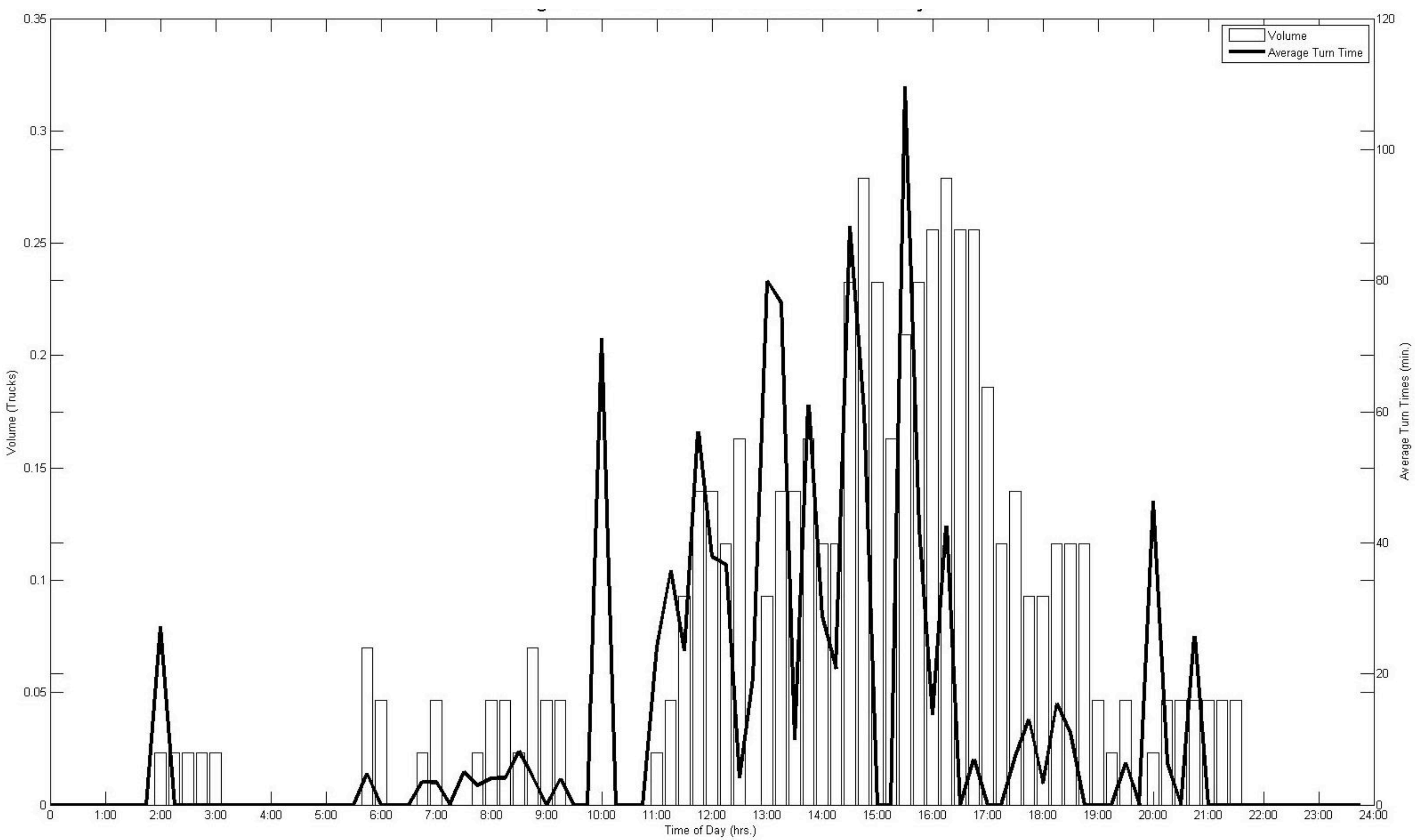


FIGURE C-11 Comparison of Weekday Volume and Average Turn Time for Distribution Facility B

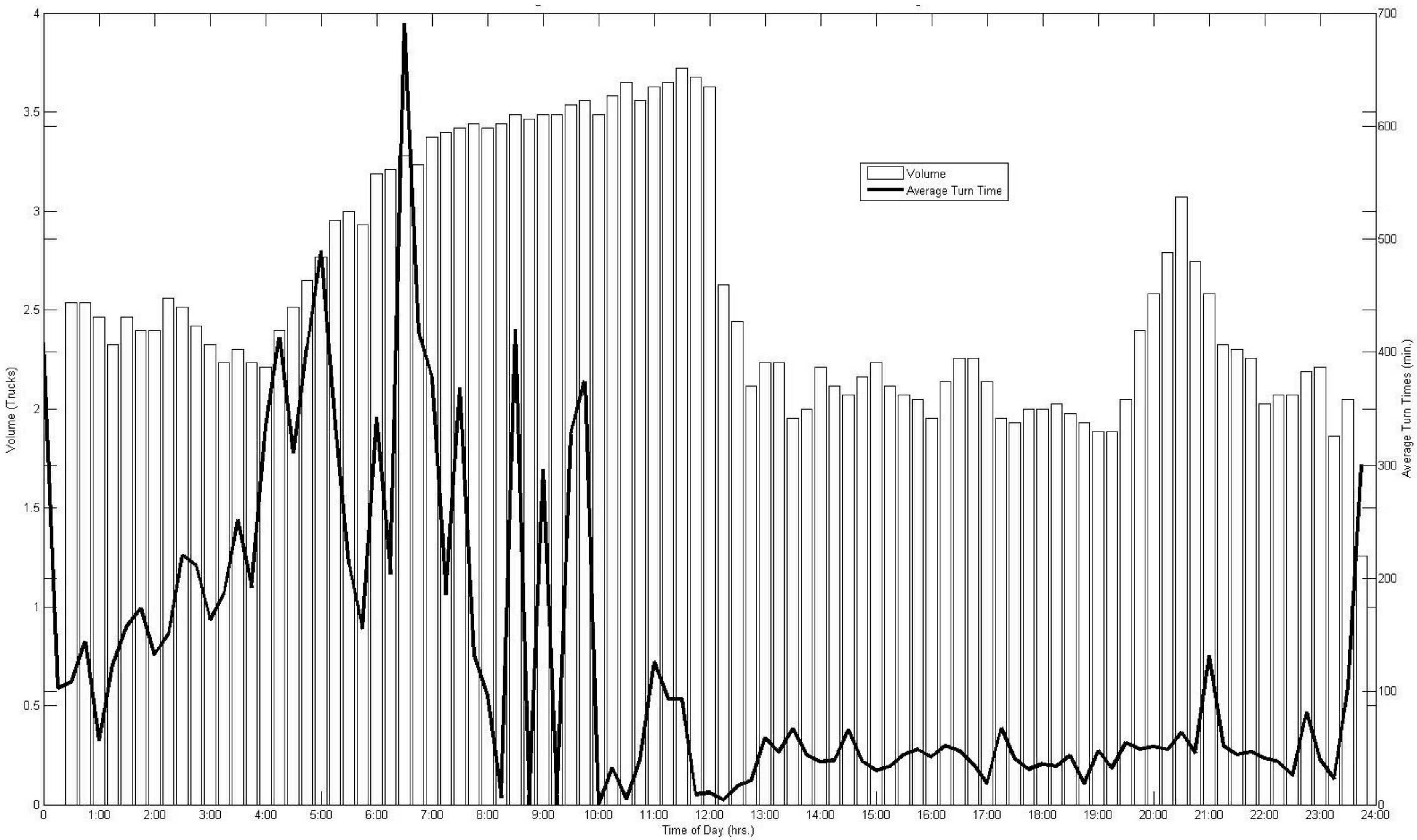


FIGURE C-12 Comparison of Weekday Volume and Average Turn Time for Distribution Facility C

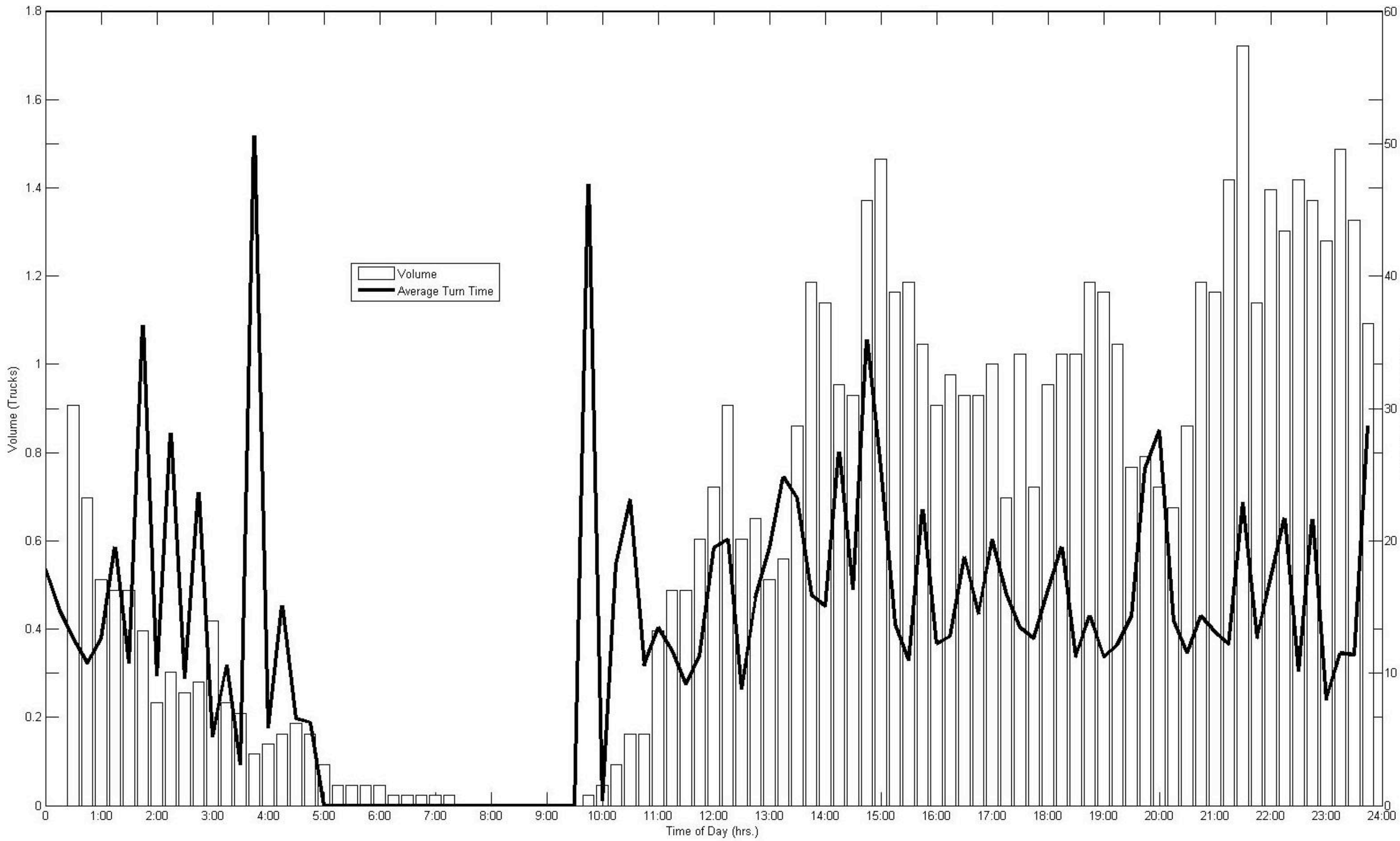


FIGURE C-13 Comparison of Saturday Volume and Average Turn Time for Distribution Facility C

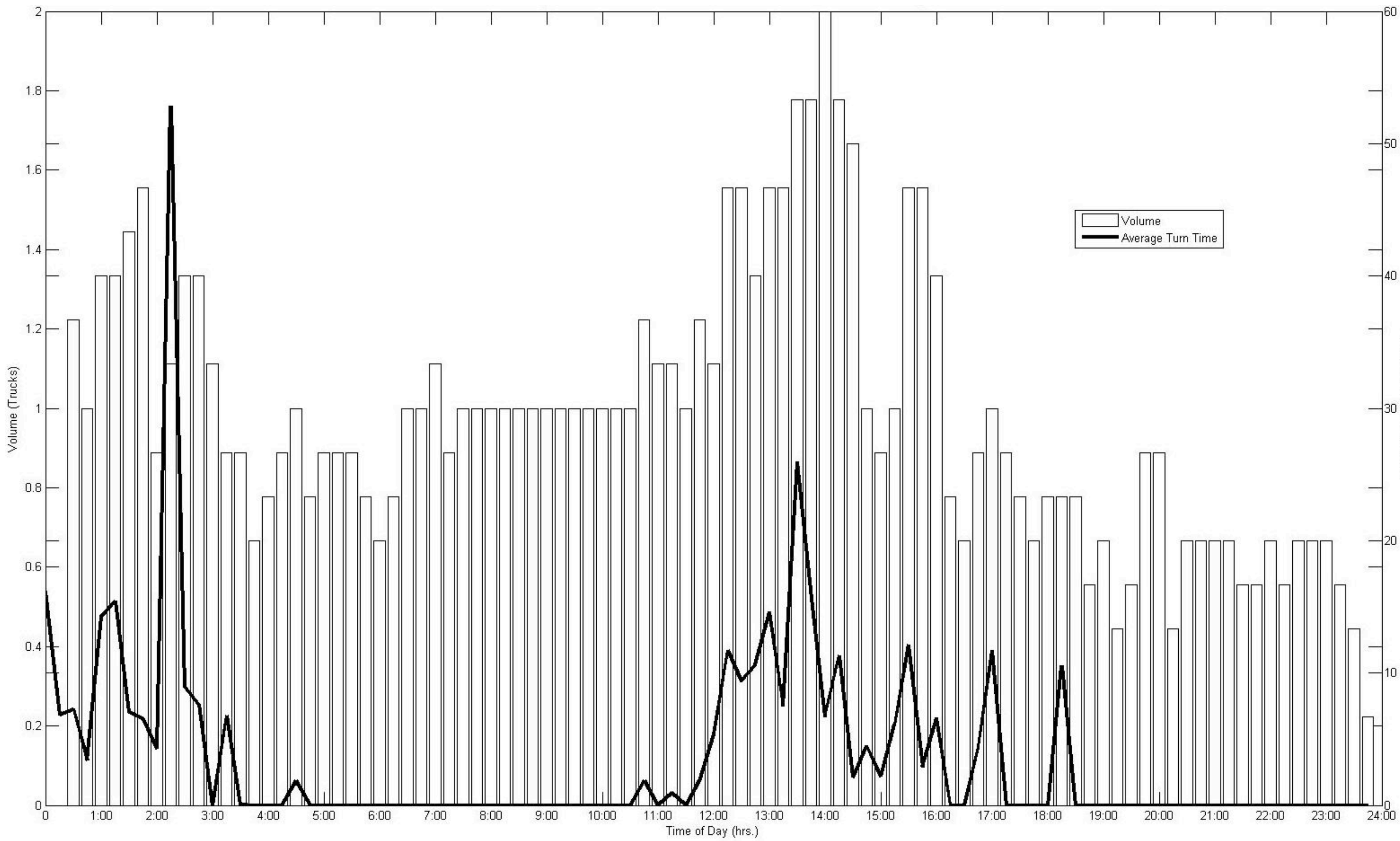


FIGURE C-14 Comparison of Weekday Volume and Average Turn Time for Distribution Facility D

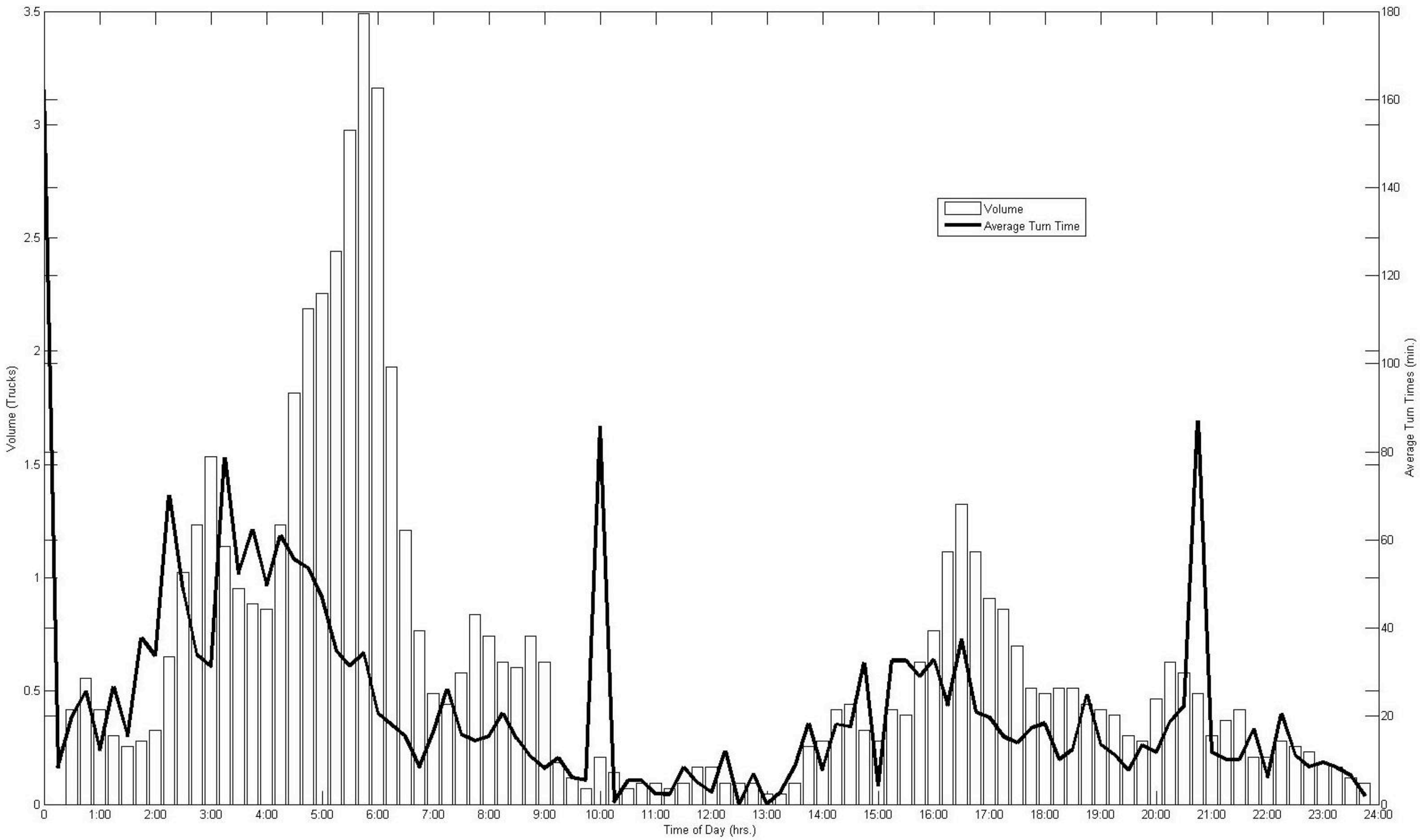


FIGURE C-15 Comparison of Weekday Volume and Average Turn Time for Distribution Facility E

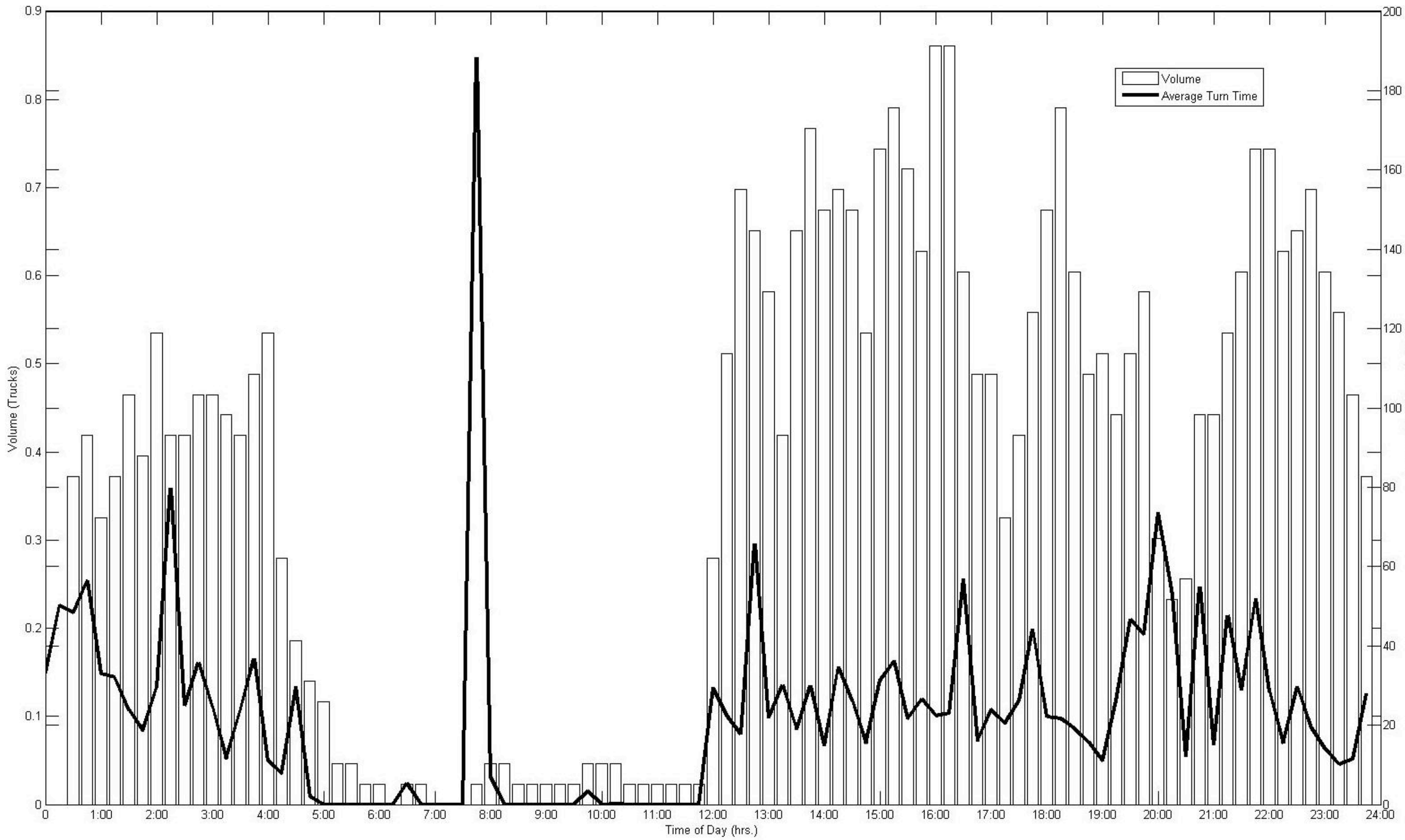


FIGURE C-16 Comparison of Weekday Volume and Average Turn Time for Warehouse Facility A

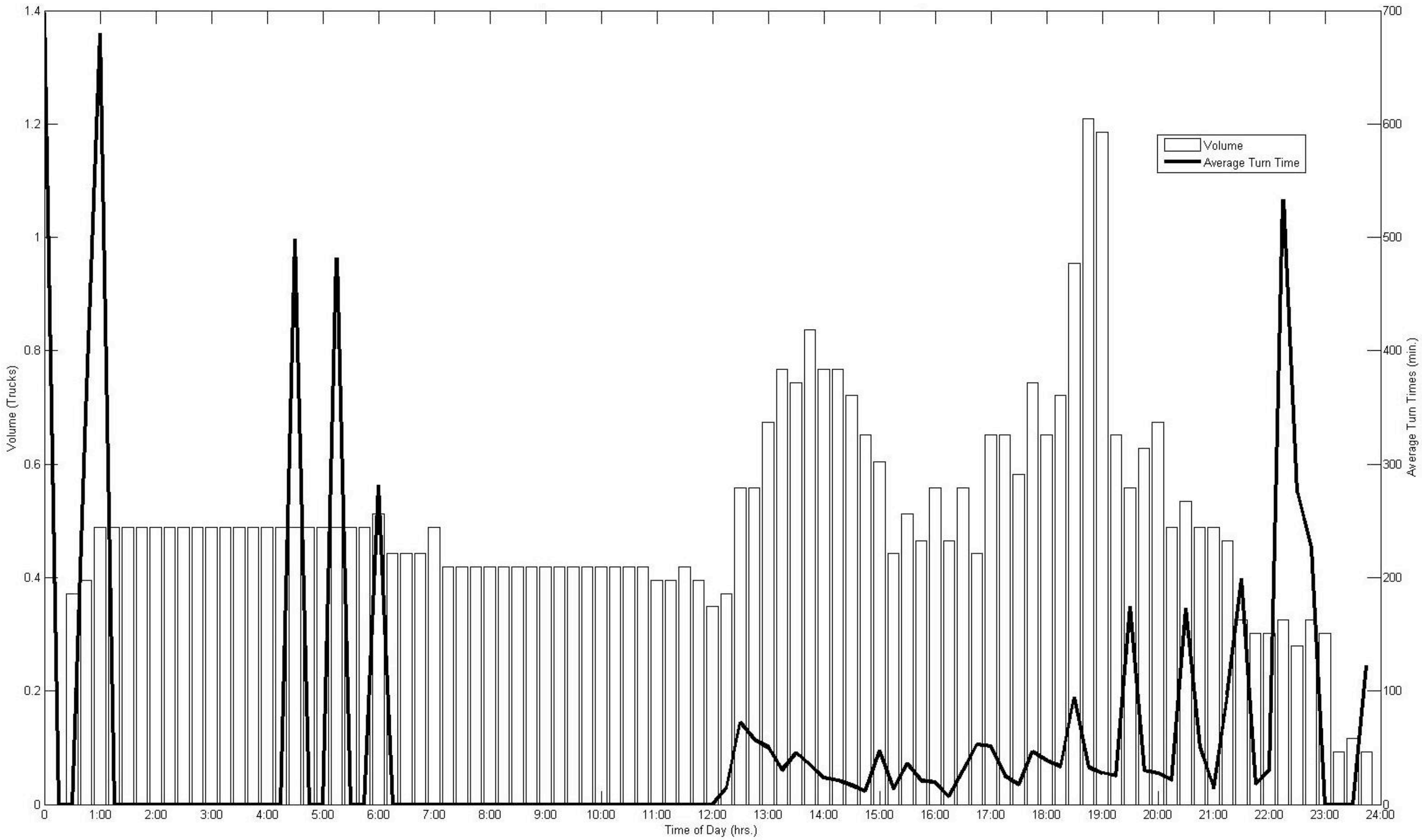


FIGURE C-17 Comparison of Weekday Volume and Average Turn Time for Warehouse Facility B

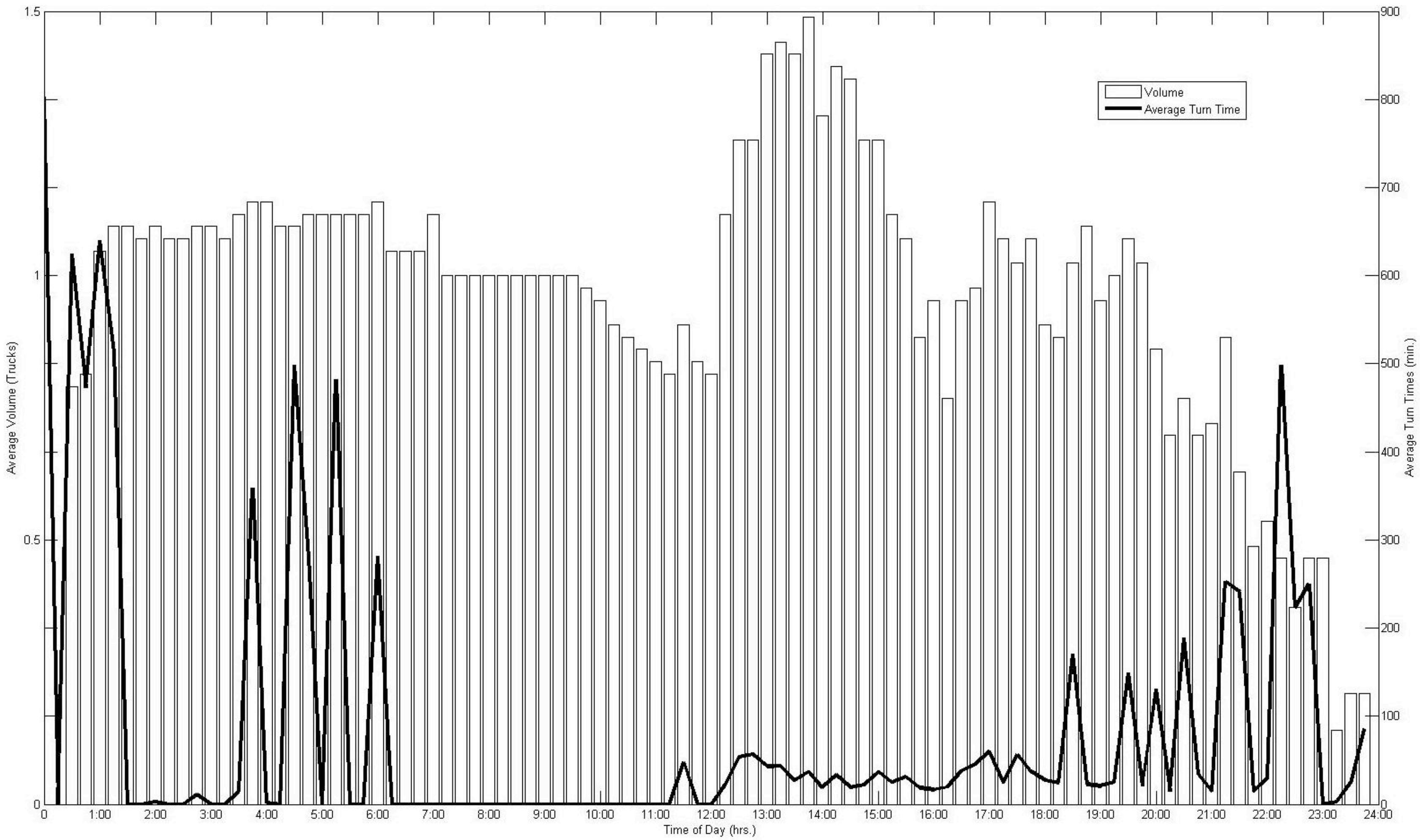


FIGURE C-18 Comparison of Weekday Volume and Average Turn Time for Warehouse Facility D

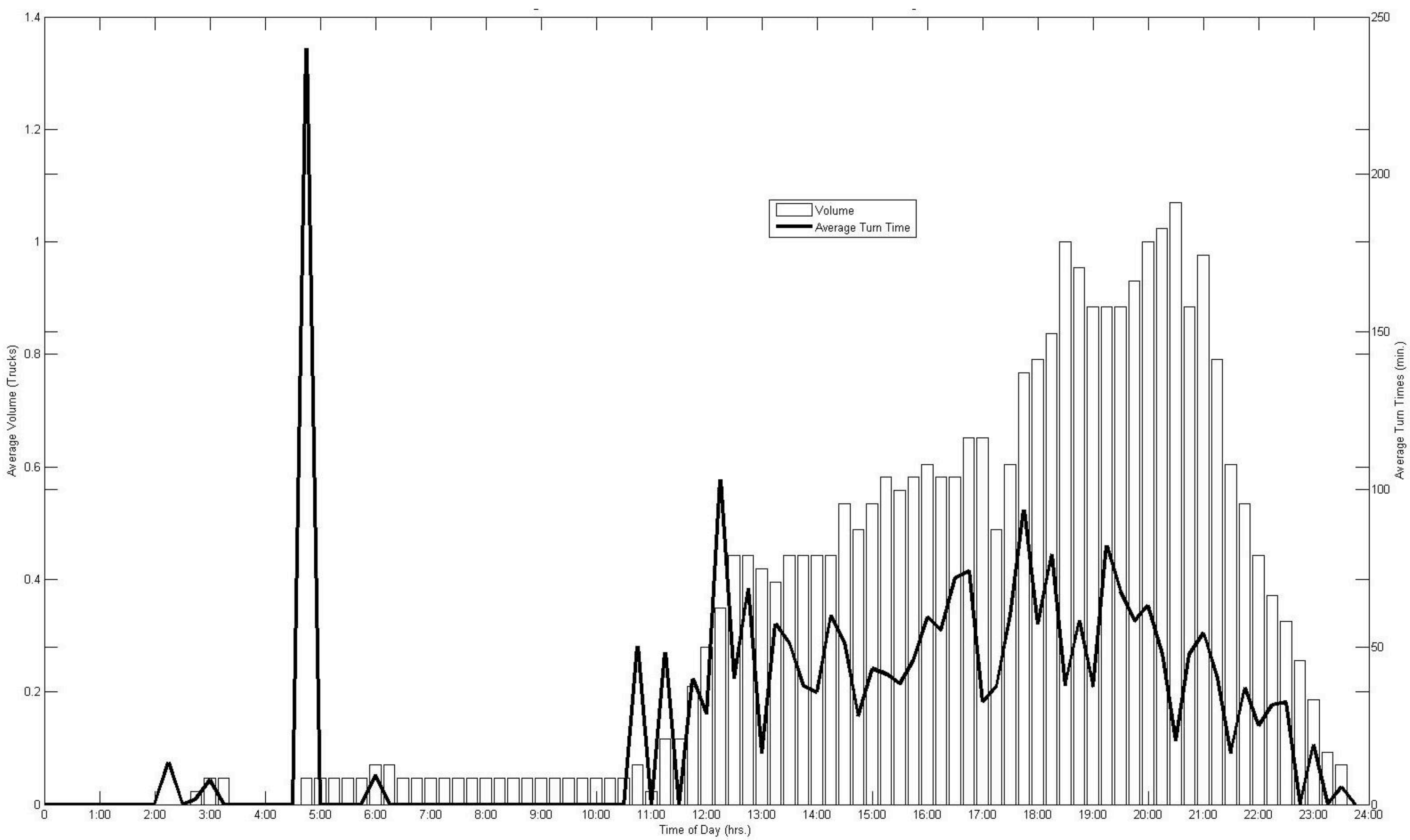


FIGURE C-19 Comparison of Weekday Volume and Average Turn Time for Warehouse Facility E

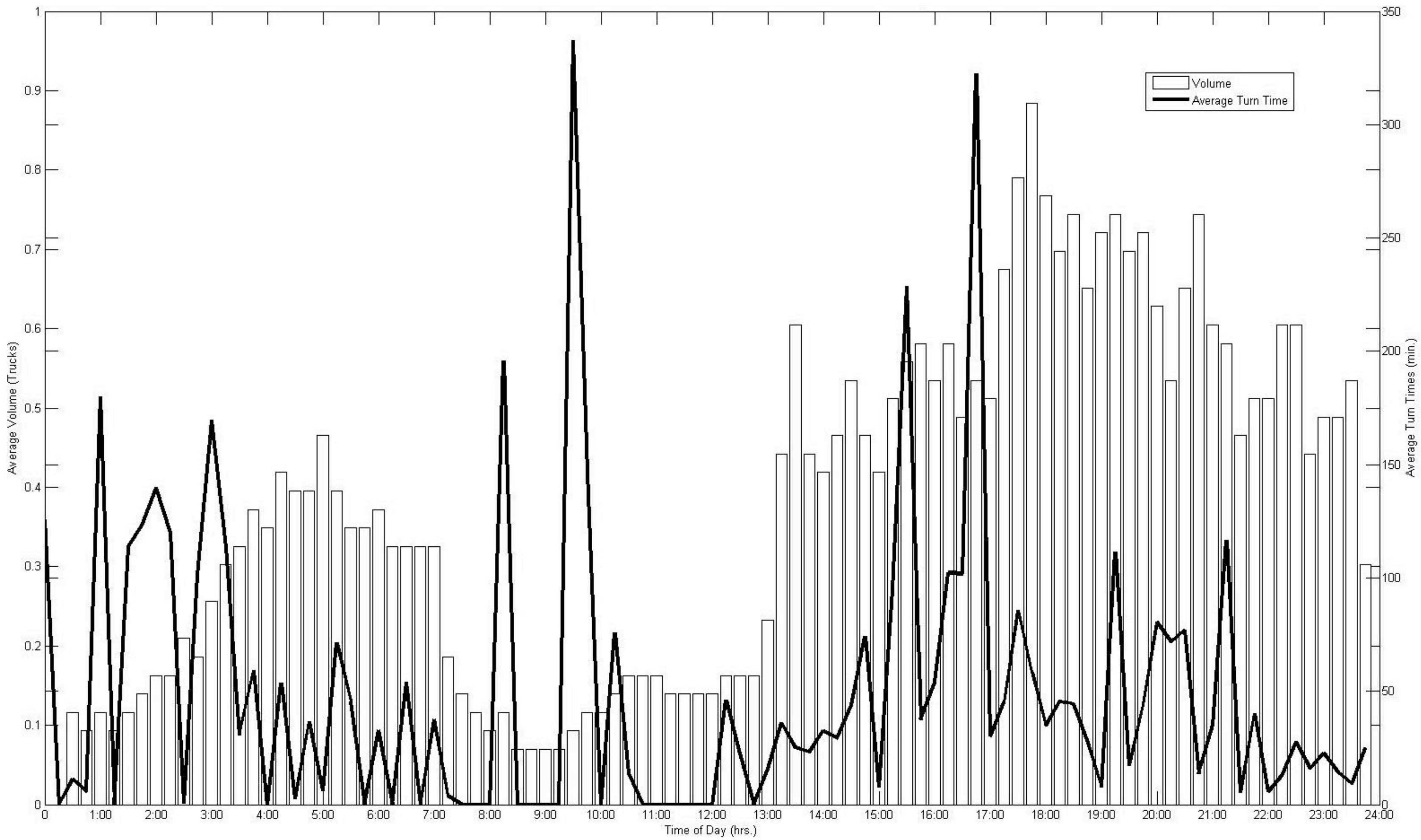


FIGURE C-20 Comparison of Weekday Volume and Average Turn Time for Warehouse Facility F

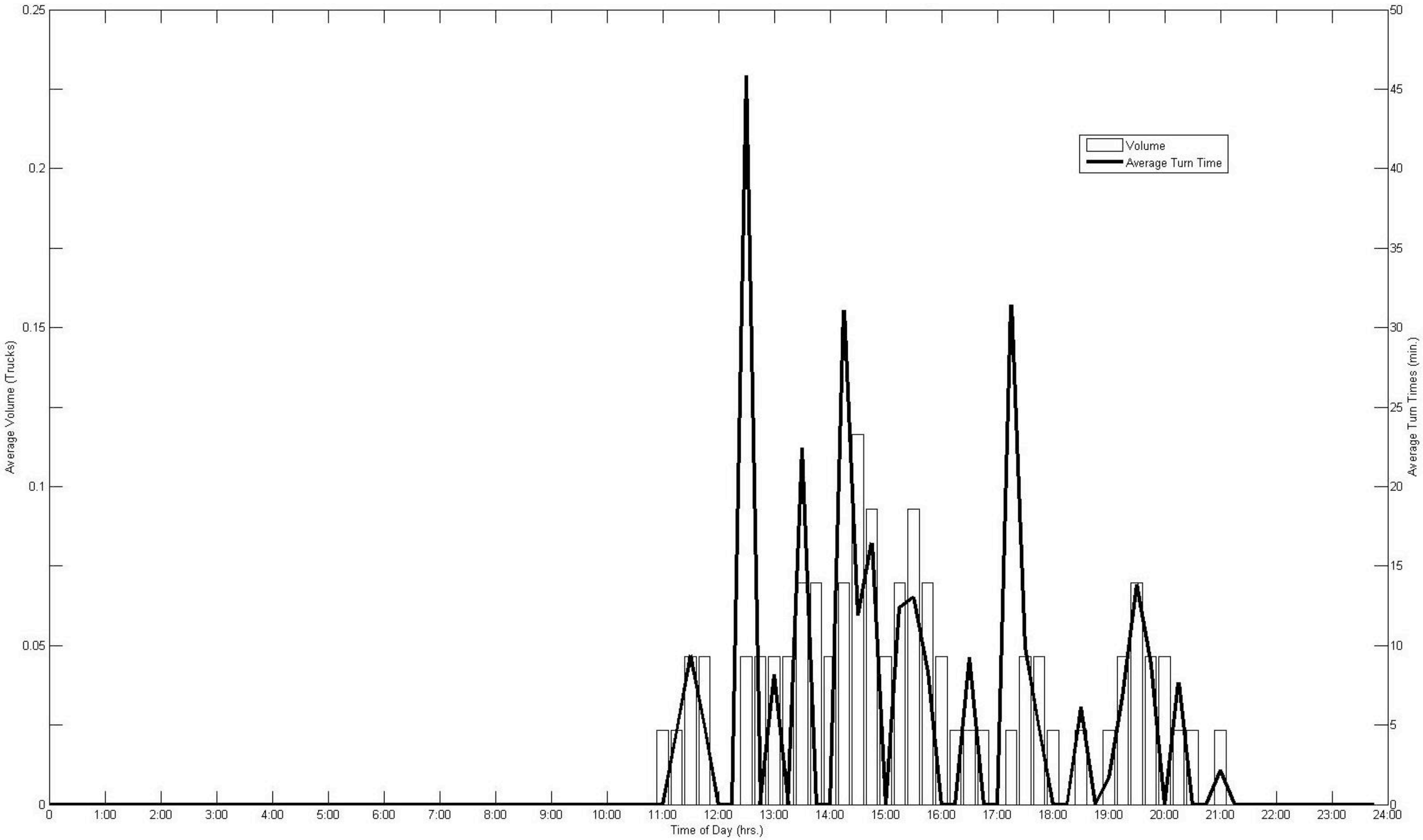


FIGURE C-21 Comparison of Weekday Volume and Average Turn Time for Warehouse Facility G

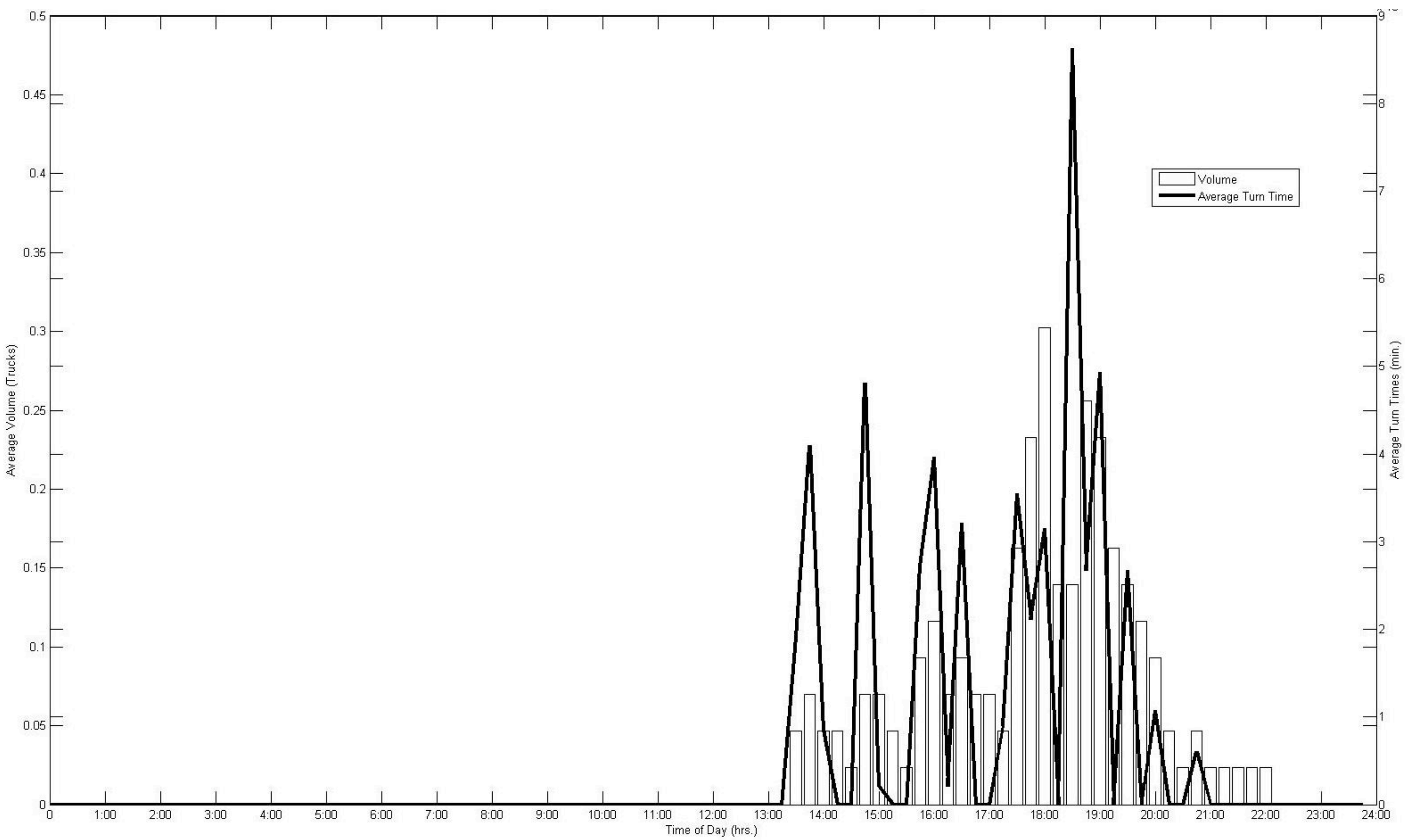


FIGURE C-22 Comparison of Weekday Volume and Average Turn Time for Private Warehouse Facility A

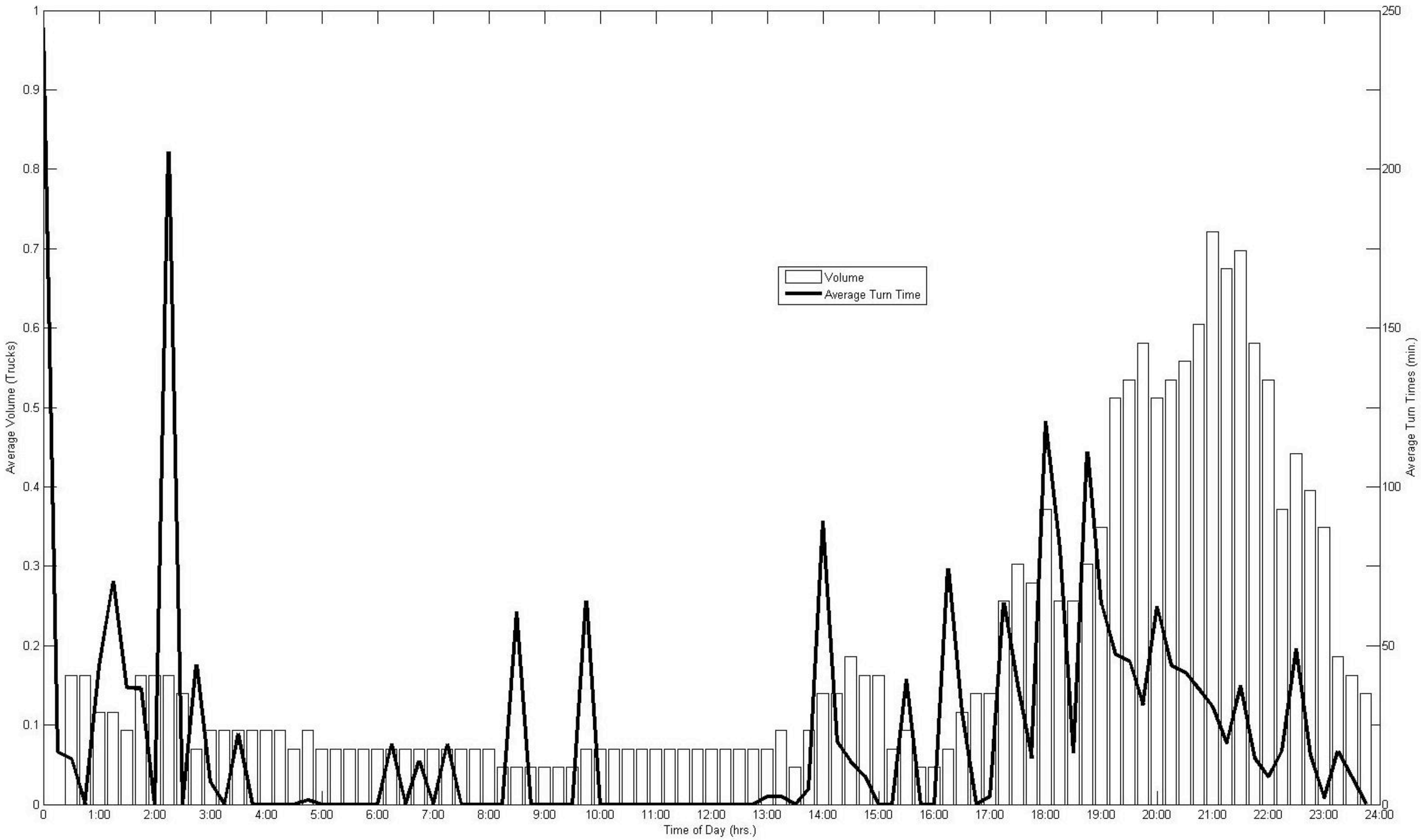


FIGURE C-23 Comparison of Weekday Volume and Average Turn Time for Private Warehouse Facility B

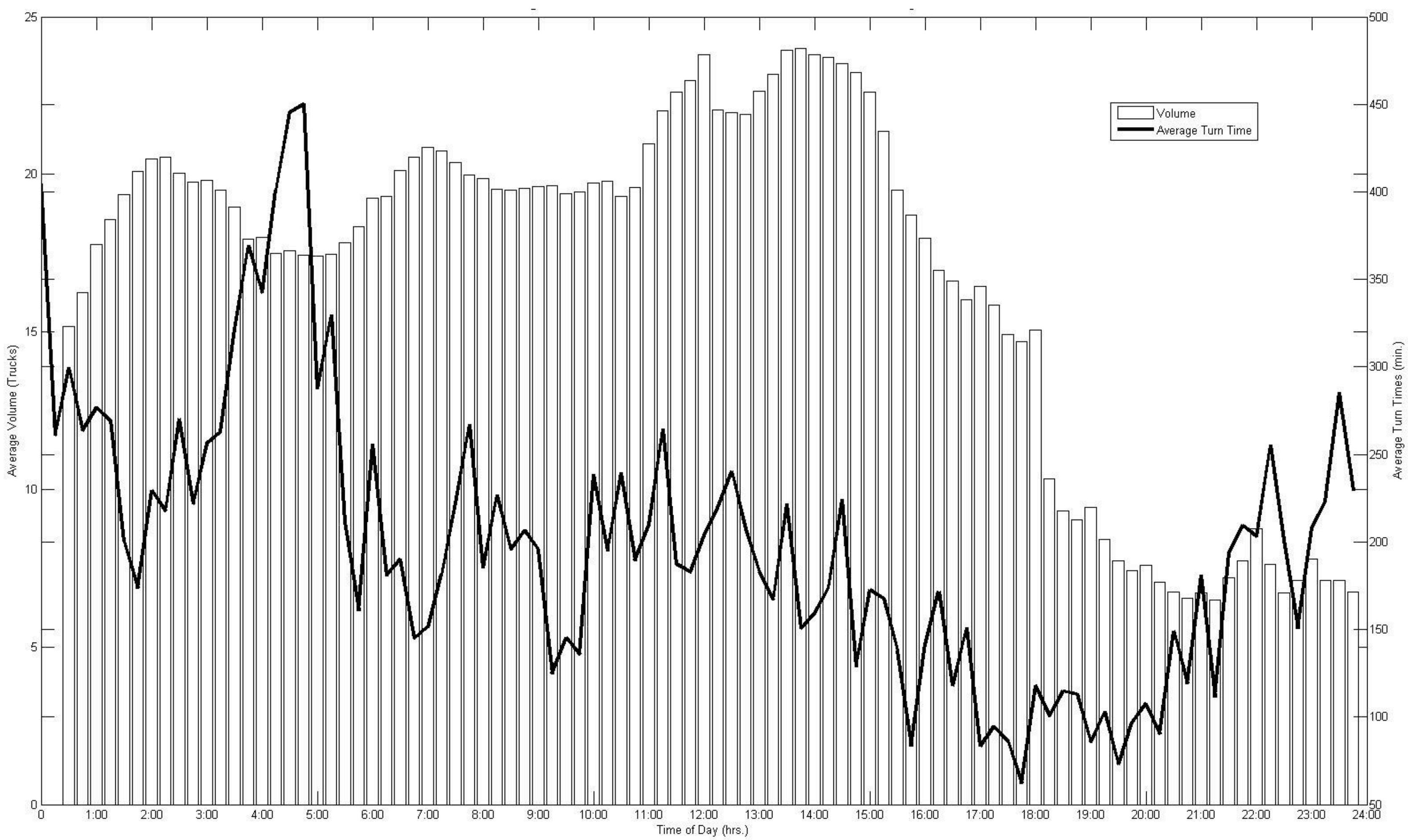


FIGURE C-24 Comparison of Saturday Volume and Average Turn Time for Private Warehouse Facility B

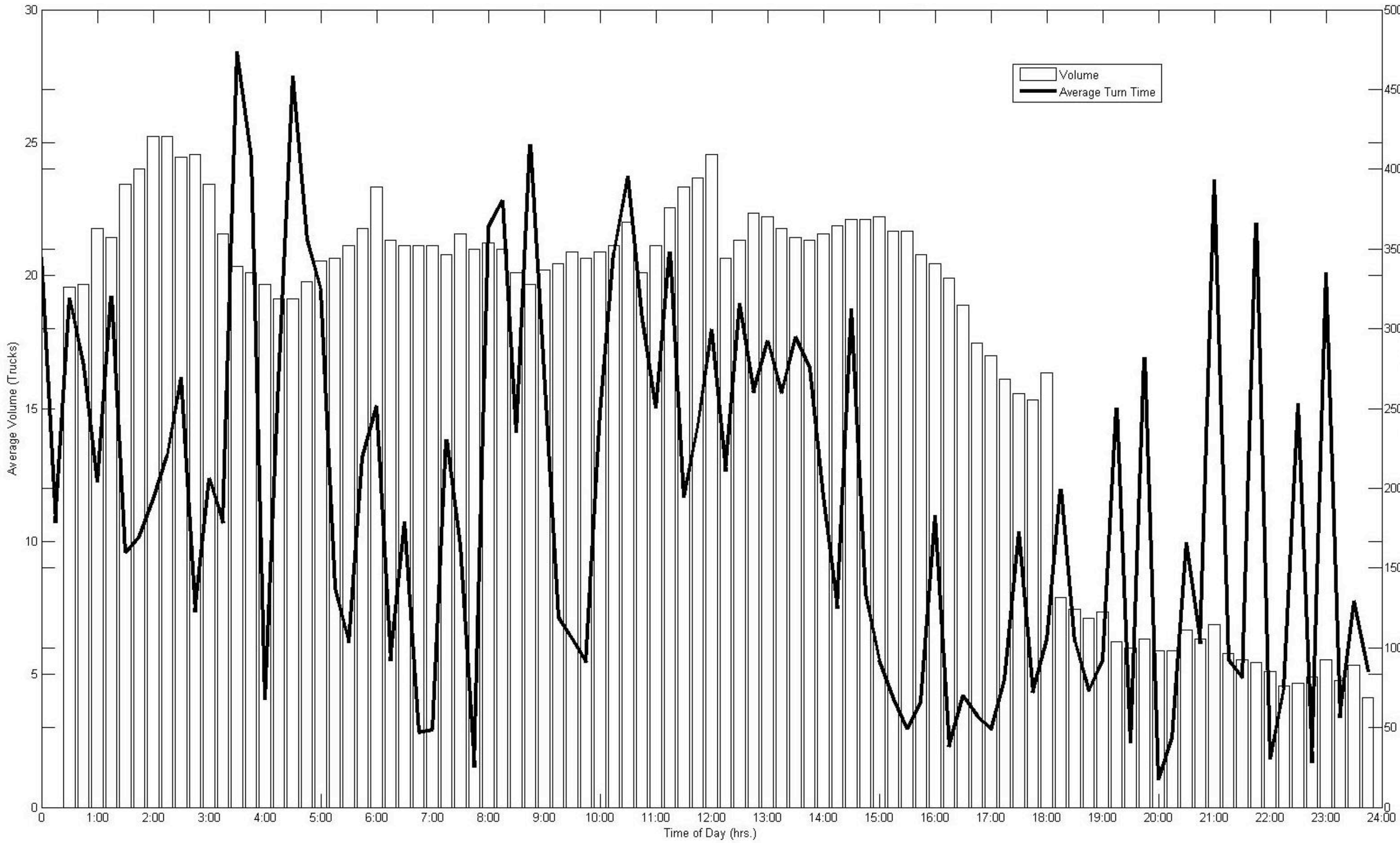


FIGURE C-25 Comparison of Sunday Volume and Average Turn Time for Private Warehouse Facility B

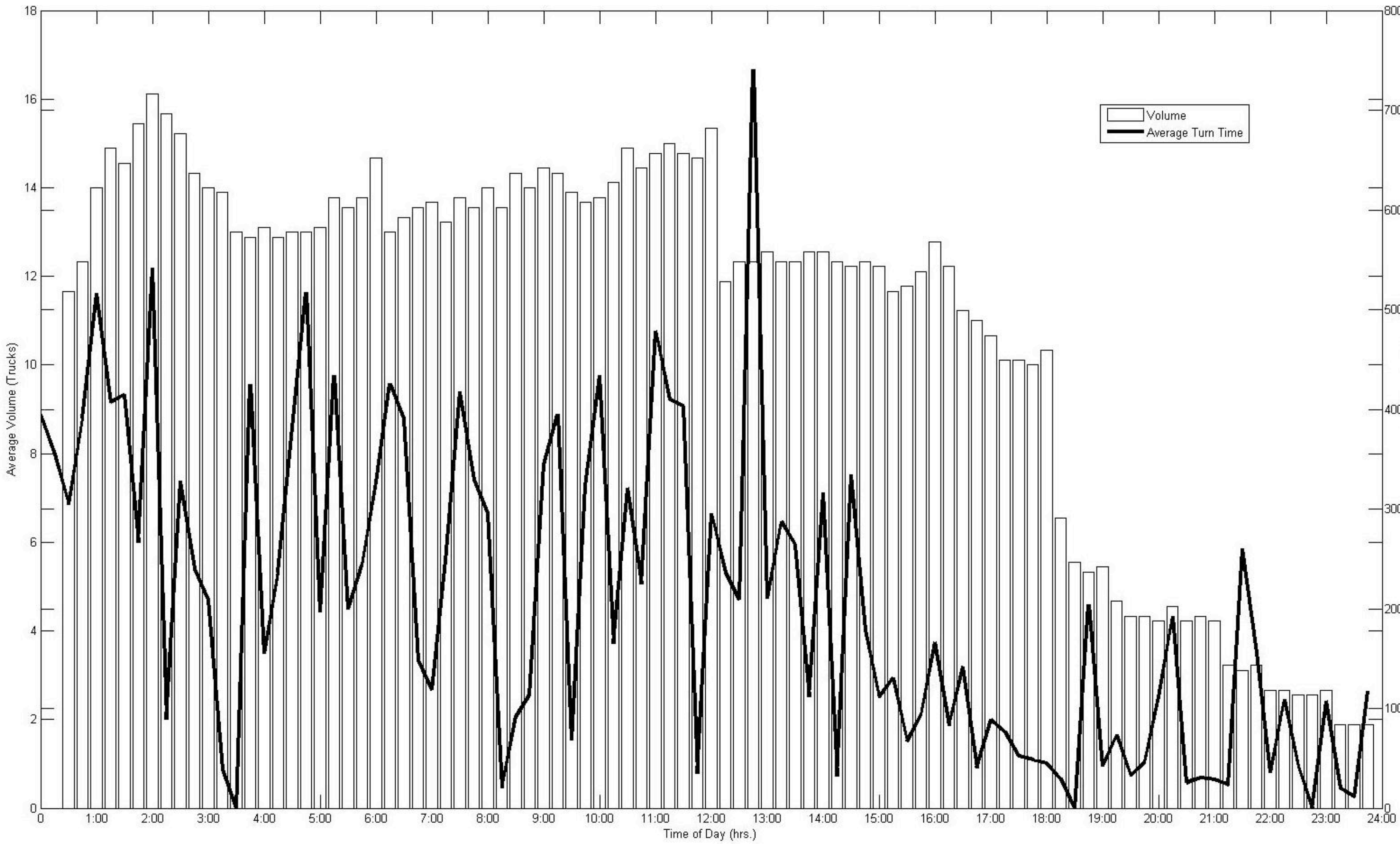


FIGURE C-26 Comparison of Weekday Volume and Average Turn Time for Private Warehouse Facility C

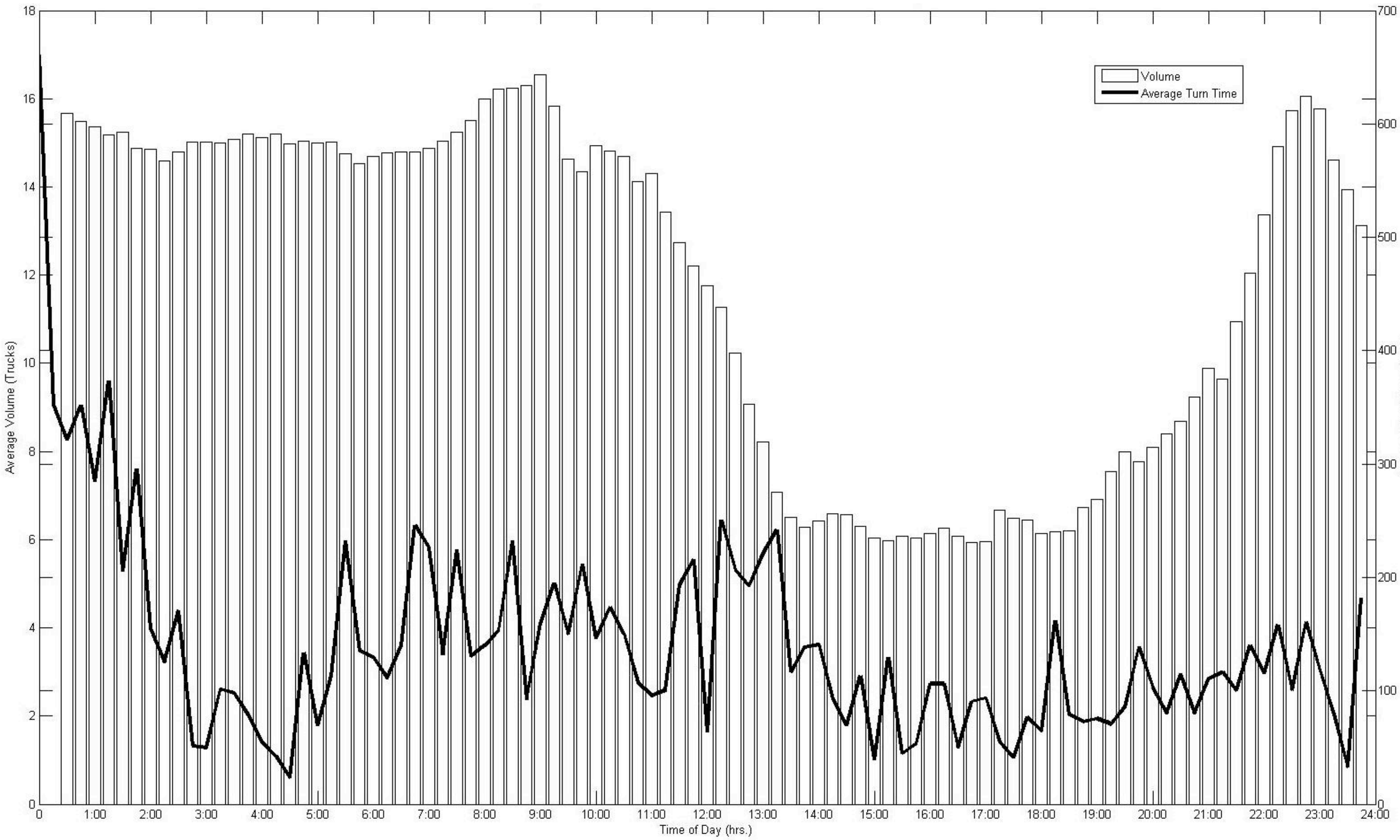


FIGURE C-27 Comparison of Saturday Volume and Average Turn Time for Private Warehouse Facility C

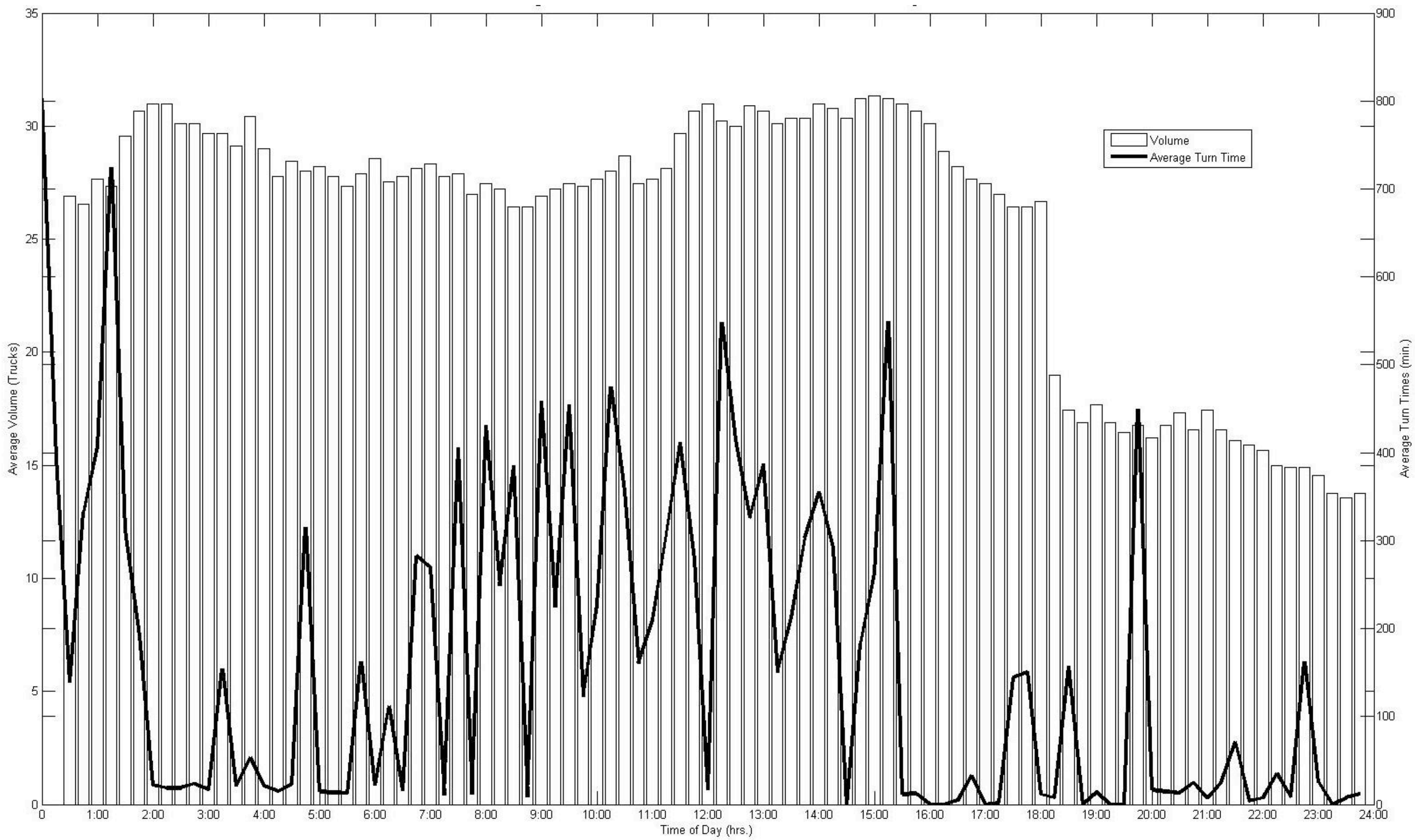


FIGURE C-28 Comparison of Sunday Volume and Average Turn Time for Private Warehouse Facility C