



Heavy-Duty Vehicle Activity Updates for MOVES Using NREL Fleet DNA and CE-CERT Data

Chen Zhang,¹ Karen Ficenec,¹ Andrew Kotz,¹ Kenneth Kelly,¹ Darrell Sonntag,² Carl Fulper,² Jessica Brakora,² Tiffany Mo,² and Sudheer Ballare³

1 National Renewable Energy Laboratory

2 U.S. Environmental Protection Agency

3 Oak Ridge Institute for Science and Education

Produced under direction of the U.S. Environmental Protection Agency by the National Renewable Energy Laboratory (NREL) under Interagency Agreements IAG-14-1954 and IAG-19-16388.



**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC**

Strategic Partnership Project Report
NREL/TP-5400-79509
Revised March 2022

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308



Heavy-Duty Vehicle Activity Updates for MOVES Using NREL Fleet DNA and CE-CERT Data

Chen Zhang,¹ Karen Ficenec,¹ Andrew Kotz,¹ Kenneth Kelly,¹
Darrell Sonntag,² Carl Fulper,² Jessica Brakora,² Tiffany Mo,²
and Sudheer Ballare³

1 National Renewable Energy Laboratory

2 U.S. Environmental Protection Agency

3 Oak Ridge Institute for Science and Education

Suggested Citation

Zhang, Chen, Karen Ficenec, Andrew Kotz, Kenneth Kelly, Darrell Sonntag, Carl Fulper, Jessica Brakora, Tiffany Mo, and Sudheer Ballare. 2021. *Heavy-Duty Vehicle Activity Updates for MOVES Using NREL Fleet DNA and CE-CERT Data*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-79509. <https://www.nrel.gov/docs/fy21osti/79509.pdf>.

**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Strategic Partnership Project Report
NREL/TP-5400-79509
Revised March 2022

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Support for the work was also provided by the U.S. Environmental Protection Agency (EPA) under Interagency Agreements IAG-14-1954 and IAG-19-16388. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Errata

This report, originally published in June 2021, has been revised in March 2022 to update the figures and tables after we updated our gap-filling assumption used to determine the vehicle soak time.

To be specific, in the Fleet DNA and CE-CERT data sets, there are instances of gaps in the time-series data, especially within the Fleet DNA long-haul combination truck vehicles. In instances of data gaps, we assumed the vehicle was turned off if the gap length was greater than 6 hours. If the gaps in data were less than 6 hours, we assumed the vehicles idled for the gap period, with no engine turn off and subsequent start. In this revision, we have revisited this assumption to assume that vehicles turned off if the gap is greater than 2 seconds.

The revised gap length had several impacts on the data and report, including:

1. The starts per day and starts distributions were updated to use the data using the updated gap length of 2 seconds. This change had the largest impact on long-haul combination trucks, where on average the weekday starts changed from 0.81 to 8.98 for the data from the original Fleet DNA database.
2. Idle estimates were updated to be consistent with the new gap length. The data in the `IdleEvents_final_all.csv` were updated to use the new gap-filling length of 2 seconds, which significantly reduced the idle time of the long-haul combination trucks.
3. In the previous report, the idle data reported in the figures and in the resolved data files (`IdleOperationByDateHour_final_all.csv`, `IdleOperationByDayHour_final_all.csv`, `idle_final_all_plot_vocation.csv`, and `idle_final_all_plot_divided_day.csv`) estimated idling from only the recorded idle data and did not use the gap length corrected data in the `IdleEvents_final_all.csv` data. In other words, the idle data in these files assumed that if there was any gap in the data, the vehicle was not operating. Now that we are assuming a gap length of 2 seconds, there is no noticeable difference between the idle time estimated from these files and the `IdleEvents_final_all.csv` file.
4. After updating the gap length, the temporal profile of starts and idling from the combination long-haul fleet compared well between the original Fleet DNA and the additional data. Although the trends differ from other comparable data sets, it appears to be representative of the driving behavior of the measured fleets. Previously, we attributed the differences to comparable data sets to potential errors in the time stamps of the long-haul data within Fleet DNA. We no longer believe there is an error in the time stamps of the data and have updated the report accordingly.

This report also clarifies the calculation of extended idle per miles driven with the addition of Equation 8 in Section 2.2.3.4 in the revised report. The extended idle/miles reported in the resolved data files were previously incorrect.

Acknowledgments

The authors would like to thank Sarah Hutchinson (EPA Pathways student trainee participant) and David Brzezinski and Gary Dolce (retired EPA employees) for their assistance in this project. We also acknowledge the contributions of Kanok Boriboonsomsin, Kent Johnson, George Scora, Daniel Sandez, Alexander Vu, Tom Durbin, and Yu (Jade) Jiang from the College of Engineering- Center for Environmental Research and Technology at the University of California at Riverside for sharing the instrumented data from their instrumented heavy-duty vehicle study (contract number 13-301) conducted for the California Air Resources Board which was analyzed in this report.

Sudheer Ballare is a former ORISE participant supported by an appointment to the Science Education and Workforce Development Programs at Oak Ridge National Laboratory, administered by ORISE through the U.S. Department of Energy Oak Ridge Institute for Science and Education.

List of Acronyms

CE-CERT	College of Engineering, Center for Environmental Research & Technology (University of California at Riverside)
EPA	U.S. Environmental Protection Agency
GPS	Global Positioning System
MOVES	MOtor Vehicle Emission Simulator
mph	miles per hour
NREL	National Renewable Energy Laboratory
rpm	revolutions per minute
SCR	selective catalyst reduction

Executive Summary

The U.S. Environmental Protection Agency's (EPA's) MOtor Vehicle Emission Simulator (MOVES) is a publicly available tool used by researchers and policymakers to help understand motor vehicle emission sources at a national, county, and project level. Estimates of heavy-duty activity in the most recent version of the model at the time this work was conducted, MOVES2014, was identified as an area in need of improvement. The start activity in MOVES2014 is based on a limited and dated data set. In addition, MOVES2014 relies on drive cycles that represent on-network activity but do not account for idling activity that occurs on off-network roads, such as at a distribution center, while the truck is queuing or during loading and unloading. As a result, MOVES2014 likely underestimate idle activity for heavy-duty trucks in real-world operation.

The National Renewable Energy Laboratory (NREL) has previously leveraged its expansive Fleet DNA database of heavy-duty vehicles to idle and start activity for six of the nine heavy-duty vehicle source types of classes in the MOVES model (EPA 2020b; Kotz and Kelly 2019). The data available in Fleet DNA from 416 conventional, diesel-powered vehicles provided activity estimates from more than 120,000 hours of operation throughout 14,682 vehicle days between October 2006 and January 2016. NREL calculated start fraction, starts per day, soak fraction, and idle fraction by hour of the day for each vehicle type, state, and vocation, and provided results in .CSV files that can be translated to MOVES table inputs. The idle and start activity from this initial analysis of Fleet DNA data was used to develop default idle and start data for heavy-duty vehicles in MOVES3 (EPA 2020b).

To build on the results from the Fleet DNA data used for MOVES3, the EPA asked NREL to extend the previous start and idle analysis using additional data from a larger number of vehicles for a potential future update to the MOVES model. Such a data set was achieved from a project led by the University of California at Riverside, College of Engineering, Center for Environmental Research & Technology (CE-CERT) and funded by California Air Resources Board. Specifically, this data set consists of 90 heavy-duty vehicles operated mainly in California, which can be separated into five of the nine heavy-duty vehicle classes in the MOVES model. In addition, the heavy-duty activity database collected by CE-CERT provided activity estimates from more than 44,000 hours of operation throughout 4,724 vehicle days between November 2014 and September 2016. This report includes details about the analysis of the heavy-duty activity database collected from University of California at Riverside by providing graphical analysis and context for the start, and idle distributions. The comparison of the related results from both the Fleet DNA and CE-CERT data sets are documented in this report as well.

Table of Contents

Executive Summary	v
1 Introduction	1
1.1 Background	1
1.2 Project Objective	1
1.3 Source Data	2
1.3.1 Original Data from Fleet DNA.....	2
1.3.2 Additional Data from Fleet DNA.....	2
1.3.3 Data from CE-CERT Project.....	2
1.4 2022 Revision.....	3
2 Analysis Approach	4
2.1 Vehicle Selection.....	4
2.1.1 Fleet DNA Database.....	4
2.1.2 CE-CERT Database.....	5
2.1.3 Combination of Two Databases	7
2.2 Methodology	8
2.2.1 Database Description.....	8
2.2.2 Preprocessing	9
2.2.3 Calculations.....	11
3 Result and Discussion	17
3.1 CE-CERT	18
3.1.1 Result by Vehicle Type	18
3.1.2 Results by Vehicle Type and Vocation	21
3.2 Fleet DNA	23
3.2.1 Results by Vehicle Type	24
3.2.2 Results by Vehicle Type and Vocation	26
3.2.3 Additional Long-Haul Data Added into Fleet DNA	30
3.3 Comparison Between Fleet DNA and CE-CERT Results.....	33
3.3.1 Other Bus	35
3.3.2 Transit Bus	36
3.3.3 Refuse.....	37
3.3.4 Single-Unit Short Haul.....	37
3.3.5 Combination-Unit Short Haul	38
3.4 Results of Combined Fleet DNA and CE-CERT Data.....	39
4 Conclusion	42
References	44
Appendix A: MOVES Definitions	45
Appendix B: Gap Length Analysis	48
Appendix C: Averaging Methods Evaluation	51
Appendix D: Start and Soak Plots – CE-CERT Data	56
Appendix E: Hourly Idle Plots – CE-CERT Data	62
Appendix F: Result by Vocation – CE-CERT Data	65
Appendix G: Start and Soak Plots – Original Fleet DNA Data	84
Appendix H: Hourly Idle Plots – Original Fleet DNA Data	91
Appendix I: Result by Vocation – Fleet DNA Data	94
Appendix J: Original and Additional Data in Fleet DNA	120
Appendix K: Analytical Results from Combined Data	122
Appendix L: Average Starts per Day from Fleet DNA and CE-CERT	133
Appendix M: Results File List	136
Appendix N: Quality Assurance Evaluation	162

List of Figures

Figure 1. Diagram of CE-CERT database file structure	9
Figure 2. Soak fraction multiplied by start fraction vs. hour of the day for weekdays.....	19
Figure 3. Extended and workday idle fractions vs. day type and vehicle type	20
Figure 4. Extended and workday idle fractions vs. vehicle type for weekdays	20
Figure 5. Vocational differences between beverage distribution and construction trucks in single-unit short haul.....	22
Figure 6. Vocational differences between line-haul, agricultural, and drayage vehicles in combination-unit short haul.....	22
Figure 7. Vocational distributions of (a) vehicle idle operation and (b) average starts per day	23
Figure 8. Soak fraction multiplied by start fraction vs. hour of the day for weekdays – Fleet DNA	24
Figure 9. Extended and workday idle fractions vs. day type and vehicle type – Fleet DNA.....	25
Figure 10. Extended and workday idle fractions vs. vehicle type for weekdays – Fleet DNA.....	26
Figure 11. Vocational differences between beverage and parcel delivery combination trucks	27
Figure 12. Start and soak distributions for single-unit delivery vehicles.....	28
Figure 13. Vocational distributions of (a) vehicle idle operation and (b) average start per day in Fleet DNA data	29
Figure 14. Comparison of start, soak, and idle performances of original 131 vehicles (left) and additional 64 vehicles (right) in the Fleet DNA database	31
Figure 15. Start, soak and idle performance of combination-unit long haul in current Fleet DNA.....	33
Figure 16. Comparisons of start, soak, and idle performance of other buses on weekdays.....	35
Figure 17. Comparisons of start, soak, and idle performance of transit buses on weekdays.....	36
Figure 18. Comparisons of start, soak, and idle performance of refuse trucks on weekdays	37
Figure 19. Comparisons of start, soak, and idle performance of single-unit short haul on weekdays.....	38
Figure 20. Comparisons of start, soak, and idle performance of combination-unit short haul on weekdays	39
Figure 21. Soak fraction multiplied by start fraction vs. hour of the day for weekdays (combined data)..	40
Figure 22. Extended and workday idle fractions vs. day type and vehicle type (combined data)	41
Figure 23. Extended and workday idle fractions vs. vehicle type for weekdays	42
Figure B1. Comparison of start fraction for original (top) and additional (bottom) long haul fleet under 6 hours’ time gap assumption	49
Figure B2. Comparison of start fraction for original (top) and additional (bottom) long haul fleet under 2 seconds’ time gap assumption.....	50
Figure C1. Idle fraction calculated using Method 1 and Method 3.....	54
Figure C2. Start and soak fraction calculated using Method 1 and Method 3	55
Figure D1. Soak fraction and start fraction vs. hour of the day for “other bus”	56
Figure D2. Soak fraction and start fraction vs. hour of the day for transit bus.....	57
Figure D3. Soak fraction and start fraction vs. hour of the day for refuse truck	58
Figure D4. Soak fraction and start fraction vs. hour of the day for single-unit short haul	59
Figure D5. Soak fraction and start fraction vs. hour of the day for combination-unit short haul	60
Figure D6. Extended and workday idle fractions vs. day type and vehicle type	61
Figure E1. Hourly idle fraction vs. hour of the day for “other bus”	62
Figure E2. Hourly idle fraction vs. hour of the day for transit bus	62
Figure E3. Hourly idle fraction vs. hour of the day for refuse truck.....	63
Figure E4. Hourly idle fraction vs. hour of the day for single-unit short haul.....	63
Figure E5. Hourly idle fraction vs. hour of the day for combination-unit short haul	64
Figure F1. Vocation-based idle fraction distribution.....	65
Figure F2. Vocation-based average start per day distribution	66
Figure F3. Start, soak, and idle performance of “other bus” (airport shuttle).....	67
Figure F4. Start, soak, and idle performance of transit bus	68

Figure F5. Start, soak, and idle performance of refuse	69
Figure F6. Start, soak, and idle performance of single-unit short haul – construction	70
Figure F7. Start, soak, and idle performance of single-unit short haul – beverage delivery	71
Figure F8. Start, soak, and idle performance of single-unit short haul – towing.....	72
Figure F9. Start, soak, and idle performance of single-unit short haul – freeway work.....	73
Figure F10. Start, soak, and idle performance of single-unit short haul – street sweeper	74
Figure F11. Start, soak, and idle performance of single-unit short haul – local moving	75
Figure F12. Start, soak, and idle performance of single-unit short haul – utility truck	76
Figure F13. Start, soak, and idle performance of combination-unit short haul – cement mixers	77
Figure F14. Start, soak, and idle performance of combination-unit short haul – line haul.....	78
Figure F15. Start, soak, and idle performance of combination-unit short haul – municipal work	79
Figure F16. Start, soak, and idle performance of combination-unit short haul – food distribution.....	80
Figure F17. Start, soak, and idle performance of combination-unit short haul – construction.....	81
Figure F18. Start, soak, and idle performance of combination-unit short haul – drayage	82
Figure F19. Start, soak, and idle performance of combination-unit short haul – agricultural	83
Figure G1. Soak fraction and start fraction vs. hour of the day for transit bus.....	84
Figure G2. Soak fraction and start fraction vs. hour of the day for school bus	85
Figure G3. Soak fraction and start fraction vs. hour of the day for refuse truck	86
Figure G4. Soak fraction and start fraction vs. hour of the day for single-unit short haul	87
Figure G5. Soak fraction and start fraction vs. hour of the day for combination-unit short haul	88
Figure G6. Soak fraction and start fraction vs. hour of the day for combination-unit long haul	89
Figure G7. Extended and workday idle fractions vs. day type and vehicle type	90
Figure H1. Hourly idle fraction vs. hour of the day for transit bus.....	91
Figure H2. Hourly idle fraction vs. hour of the day for school bus	91
Figure H3. Hourly idle fraction vs. hour of the day for refuse truck	92
Figure H4. Hourly idle fraction vs. hour of the day for single-unit short haul	92
Figure H5. Hourly idle fraction vs. hour of the day for combination-unit short haul.....	93
Figure H6. Hourly idle fraction vs. hour of the day for combination-unit long haul.....	93
Figure I1. Vocation-based idle fraction distribution.....	94
Figure I2. Vocation-based average start per day distribution	95
Figure I3. Start, soak, and idle performance of transit bus	96
Figure I4. Start, soak, and idle performance of school bus.....	97
Figure I5. Start, soak, and idle performance of refuse pickup	98
Figure I6. Start, soak, and idle performance of single-unit short haul – warehouse delivery.....	99
Figure I7. Start, soak, and idle performance of single-unit short haul – concrete	100
Figure I8. Start, soak, and idle performance of single-unit short haul – towing.....	101
Figure I9. Start, soak, and idle performance of single-unit short haul – propane tank	102
Figure I10. Start, soak, and idle performance of single-unit short haul – parcel delivery	103
Figure I11. Start, soak, and idle performance of single-unit short haul – delivery.....	104
Figure I12. Start, soak, and idle performance of single-unit short haul – linen delivery.....	105
Figure I13. Start, soak, and idle performance of single-unit short haul – dump truck.....	106
Figure I14. Start, soak, and idle performance of single-unit short haul – snow plow.....	107
Figure I15. Start, soak, and idle performance of single-unit short haul – food delivery.....	108
Figure I16. Start, soak, and idle performance of single-unit short haul – shredder	109
Figure I17. Start, soak, and idle performance of combination-unit short haul – transfer truck	110
Figure I18. Start, soak, and idle performance of combination-unit short haul – regional haul.....	111
Figure I19. Start, soak, and idle performance of combination-unit short haul – dump truck	112
Figure I20. Start, soak, and idle performance of combination-unit short haul – drayage.....	113
Figure I21. Start, soak, and idle performance of combination-unit short haul – beverage delivery	114
Figure I22. Start, soak, and idle performance of combination-unit short haul – food delivery	115
Figure I23. Start, soak, and idle performance of combination-unit short haul – dry van	116

Figure I24. Start, soak, and idle performance of combination-unit short haul – local delivery.....	117
Figure I25. Start, soak, and idle performance of combination-unit short haul – parcel delivery.....	118
Figure I26. Start, soak, and idle performance of combination-unit long haul	119
Figure J1. Start, soak, and idle performance of original combination-unit long haul.....	120
Figure J2. Start, soak, and idle performance of additional combination-unit long haul	121
Figure K1. Soak fraction and start fraction vs. hour of the day for “other bus”	122
Figure K2. Soak fraction and start fraction vs. hour of the day for transit bus.....	123
Figure K3. Soak fraction and start fraction vs. hour of the day for school bus	124
Figure K4. Soak fraction and start fraction vs. hour of the day for refuse truck	125
Figure K5. Soak fraction and start fraction vs. hour of the day for single-unit short haul	126
Figure K6. Soak fraction and start fraction vs. hour of the day for combination-unit short haul	127
Figure K7. Soak fraction and start fraction vs. hour of the day for combination-unit long haul	128
Figure K8. Hourly idle fraction vs. hour of the day for “other bus”.....	129
Figure K9. Hourly idle fraction vs. hour of the day for transit bus.....	129
Figure K10. Hourly idle fraction vs. hour of the day for school bus	130
Figure K11. Hourly idle fraction vs. hour of the day for refuse truck	130
Figure K12. Hourly idle fraction vs. hour of the day for single-unit short haul	131
Figure K13. Hourly idle fraction vs. hour of the day for combination-unit short haul.....	131
Figure K14. Hourly idle fraction vs. hour of the day for combination-unit long haul.....	132
Figure L1. Average starts per day distribution based on vehicle types in CE-CERT (left) and Fleet DNA (right)	133
Figure L2. Detailed comparison of average starts per distribution in weekday from the common vocations between CE-CERT and Fleet DNA	133
Figure L3. Average starts per day distribution based on vehicle vocations in CE-CERT	134
Figure L4. Average starts per day distribution based on vehicle vocations in Fleet DNA	135

List of Tables

Table 1. Heavy-Duty Vehicle Types with Population of Conventional Vehicles in Current Fleet DNA.....	4
Table 2. Final Vehicles Sample in CE-CERT Database (Boriboonsomsin et al. 2017)	5
Table 3. Heavy-Duty Vehicle Types with Population of Vehicles in CE-CERT Database.....	6
Table 4. Vocation Makeup for Short-Haul Classes in CE-CERT Data	7
Table 5. Heavy-Duty Vehicle Types with Population of Vehicles in Combined Database.....	8
Table 6. MOVES Soak Time Operation Modes	16
Table 7. Summary Statistics: Weekday Averages by Vehicle Type ^a	18
Table 8. Average Daily Distance by Vocation for Short-Haul Vehicle Types – CE-CERT	21
Table 9. Average Daily Distance by Vocation for Short-Haul Vehicle Types – Fleet DNA	27
Table 10. Summary Statistics: Weekday Average for Long-Haul Data	30
Table 11. Statistical Comparisons Between Fleet DNA and CE-CERT Data	34
Table 12. Summary Statistics: Weekday Averages by Vehicle Type in Combined Data Set	39
Table A1. MOVES Road Types	45
Table A2. Heavy-Duty Vehicle MOVES Vehicle Types	45
Table A3. MOVES Day Types	45
Table A4. MOVES Hour Types.....	46
Table A5. MOVES Soak Time Operation Modes	47
Table B1. Starts per Day Comparison Across Different Fleets and Different Time Gaps Assumption	48

1 Introduction

1.1 Background

The U.S. Environmental Protection Agency's (EPA's) Motor Vehicle Emission Simulator (MOVES) is a publicly available tool used by researchers and policymakers to help understand motor vehicle emission sources at a national, county, and project level (EPA 2020a).

MOVES2014 was the most recent version of MOVES available at the time this work was initiated. However, estimates of heavy-duty start activity in MOVES2014 were based on a limited and dated data set.¹ Further, MOVES2014b did not account for off-network activity.

In 2018, the National Renewable Energy Laboratory (NREL), under the guidance and expertise of the EPA, leveraged its extensive Fleet DNA database of heavy-duty vehicles to reinforce the data set behind the next public version of the MOVES model and enhance vehicle idle rates and start activity for six of the nine heavy-duty vehicle classes in MOVES. Definitions of these activity types are available in Section 2.2.3. The idle and start activity from this initial analysis of Fleet DNA data was used to develop default idle and start data for heavy-duty vehicles in MOVES3 (EPA 2020b).

As an effort to further improve the fidelity of future versions of the MOVES model, EPA requested that NREL investigate the similar start and idling activity on a heavy-duty activity data set collected by the University of California at Riverside, College of Engineering, Center for Environmental Research & Technology (CE-CERT), which includes 90 vehicles in 17 vocations that mainly operated in California. As a result, not only can additional data reflecting more vehicles start and idling activities be added into the next MOVES model, but the accuracy of such activities in MOVES3 can be validated by comparing these two data sets in this report.

1.2 Project Objective

The objectives of this continued project are to:

1. Document the Fleet DNA results developed for MOVES3 in the interim report (Kotz and Kelly 2019), along with subsequent updates in one final report.
2. Investigate the start and idle vehicle activities using the CE-CERT data and provide clear visualizations to interpret the results. In order to provide more insightful information, the related results will be broken down based on different source types defined by MOVES, vehicle operation dates, and the corresponding vocations.
3. Update the Fleet DNA results by adding more vehicle activities that are collected after the last interim report (Kotz and Kelly 2019).
4. Compare the outcomes achieved from both Fleet DNA and CE-CERT and document the related analysis.
5. Integrate the Fleet DNA and CE-CERT results and provide EPA with the final results representing the start and idle activities and the related data in .CSV files.

¹ The starts and soak lengths in MOVES2014 were derived from data sets that tested 124 trucks in the late 1990s and early 2000s. The MOVES inputs for most of the heavy-duty source types were estimated using less than 200 vehicle trips from these trucks per source type (EPA 2016).

1.3 Source Data

Besides previous Fleet DNA data (NREL 2019), two additional data sources were utilized in this project: (1) data from two additional fleets collected by NREL after the interim report (Kotz and Kelly 2019), which will be integrated into the Fleet DNA database in the near future, and (2) the data from the CE-CERT heavy-duty activity project supported by the California Air Resources Board, consisting of 90 heavy-duty vehicles from 17 vocations and 23 fleets in California.

1.3.1 Original Data from Fleet DNA

Under the guidance and expertise of the EPA, NREL leveraged its expansive Fleet DNA database of heavy-duty vehicles to reinforce the data set behind the MOVES3 model and enhance idle and start activity for six of the nine heavy-duty vehicle classes, including transit buses, school buses, refuse trucks, single-unit short-haul trucks, combination-unit short-haul trucks, and combination-unit long-haul trucks. The data available in Fleet DNA from 416² conventional, diesel-powered vehicles provided activity estimates from more than 120,000 hours of operation throughout 14,682 vehicle days between October 2006 and January 2016.

1.3.2 Additional Data from Fleet DNA

With a target on evaluating the real-world performance of alternative fuel and advanced vehicle technologies deployed in medium- and heavy-duty vehicles, the Commercial Vehicle Technologies team in NREL's Center for Integrated Mobility Sciences is continuing its efforts to cooperate with fleet and industry partners and collect real-time, on-road data while vehicles operate across the country. Specifically, high-quality data from two additional fleet were collected after the last interim report. The first fleet includes 53 Class 8 regional hauls, which operate mainly in the Midwest and the state of Texas. The other fleet consists of 11 Class 8 long hauls, which typically operate across multiple states within one or two weeks. Similar to the existing Fleet DNA database, the data captured from the two fleets are 1-Hz telematics Global Positioning System (GPS) data as well as engine Controller Area Network bus data. In sum, the two additional fleet data represent 64 vehicles with over 12,300 hours of operation, which—if added into the MOVES model—will inevitably enhance the fidelity of vehicle idle and start activity for the combination-unit long-haul trucks source type. In this report, we refer to the conventional heavy-duty data from Fleet DNA as the Fleet DNA database.

1.3.3 Data from CE-CERT Project

In order to characterize the activity profiles of heavy-duty diesel vehicles in different types of vocations and identify vehicle operations where the selective catalyst reduction (SCR) system may not function effectively, the California Air Resources Board sponsored CE-CERT to collect both vehicle and engine activity data from 90 heavy-duty vehicles operating in California. These vehicles consist of 19 different groups defined by a combination of vocational uses, gross vehicle weight rating, and geographic region. Almost all the vehicles are model year 2010 or newer and are equipped with SCR systems. The collected data included vehicle position, speed, and engine parameters and were then used to analyze several vehicle activity statistics related to engine start, engine soak, idle activity, and the temperatures of exhaust gases entering the SCR system. For

² The previous interim report includes only 415 vehicles. After a thorough check, one combination-unit shot haul is added in this analysis. The vehicle was removed previously since it uses bio-diesel as the fuel. However, it is included herein since its start and idle performances should be similar to conventional diesel vehicles.

more information about this database, please refer to Boriboonsomsin et al. (2017). In this report, we refer to the activity data from this study as the CE-CERT database.

1.4 2022 Revision

This version of the report revised several issues in the previously published report. Most significantly, we updated the gap-filling assumptions. In the Fleet DNA and CE-CERT datasets there are instances of gaps in the time-series data, especially within the Fleet DNA long-haul combination truck vehicles. In instances of data gaps, we assumed the vehicle was turned-off if the gap length was greater than 6 hours. If the gaps in data were less than 6 hours, we assumed the vehicles idled for the gap period, with no engine turn off and subsequent start. In this revision, we have revisited this assumption to assume that vehicles turned off if the gap is greater than 2 seconds. Additional discussion on the revised gap length is included in Section 2.2.2 and Appendix B.

The revised gap length had several impacts on the data and report, including:

1. The starts per day, and starts distributions were updated to use the data using the updated gap length of two seconds. This change had the largest impact on long haul combination trucks, where on average the weekday starts changed from 0.81 to 8.98 for the data from the original Fleet DNA database.
2. Updated idle estimates were updated to be consistent with the new gap length. The data in the IdleEvents_final_all.csv was updated to use the new gap filling length of two seconds, which significantly reduced the idle time of the long-haul combination trucks.
3. In the previous report, the idle data reported in the figures, and in the resolved data files: IdleOperationByDateHour_final_all.csv, IdleOperationByDayHour_final_all.csv, idle_final_all_plot_vocation.csv, and idle_final_all_plot_divided_day.csv estimated idling from only the recorded idle data and did not use the gap length corrected data in the IdleEvents_final_all.csv data. In other words, the idle data in these files, assumed if there was any gap in the data, the vehicle was not operating. Now that we are assuming a gap length of two seconds, there is no noticeable difference between the idle time estimated from these files and the IdleEvents_final_all.csv file.
4. After updating the gap length, the temporal profile of starts and idling from the combination long-haul fleet compared well between the original Fleet DNA and the additional data. Although the trends differ from other comparable datasets, it appears to be representative of the driving behavior of the measured fleets. Previously, we attributed the differences to comparable datasets to potential errors in the time stamps of the long-haul data within Fleet DNA. We no longer believe there is an error in the time stamps of the data and have updated the report accordingly.

The report figures, tables, and discussion were updated to be consistent with the gap length updates summarized above. The resolved data were also updated stored here: <https://data.nrel.gov/submissions/168>.

This report also clarifies the calculation of extended idle per miles driven with the addition of Equation 8 in Section 2.2.3.4. The extended idle/miles reported in the resolved data files were previously incorrect. We have updated the extended idle/miles reported in the

idle_final_all_plot_vocation.csv and idle_final_all_plot_divided_day.csv files stored <https://data.nrel.gov/submissions/168>.

2 Analysis Approach

This report provides an analysis of heavy-duty idle and start activity in accordance with the EPA’s direction. Activity data in the default MOVES database are differentiated according to road type, vehicle type, day type of either weekday or weekend, and hour of the day. The formal definitions of these distinctions are provided in Appendix A. The following sections provide the methodology of NREL’s analysis.

2.1 Vehicle Selection

Although both Fleet DNA and CE-CERT data include vehicles with a wide range of powertrains and fuels, a more limited selection containing only diesel vehicles (battery electric, hybrid, and compressed natural gas vehicles were removed) was identified for this project to ensure the analysis was representative of traditional operation and not modified to accommodate vehicle architecture. In addition, vehicles with missing or erroneous engine data were filtered out.

2.1.1 Fleet DNA Database

Previously, 416 diesel-powered conventional vehicles were selected from the Fleet DNA database for the analysis and used to provide default start and idle data for MOVES3. These 416 vehicles can be separated into six of the nine source types defined in the MOVES model. The definitions of the MOVES source types are included in the *Population and Activity of Onroad Vehicles in MOVES3* report (EPA 2020b). The detailed statistics of previous Fleet DNA data can be viewed in Kotz and Kelly (2019).

In this study, an additional 64 vehicles with 1,122 vehicle days have been added in the Fleet DNA data subset. Based on the information of the fleet, as well as the vehicles’ operation styles, all of these vehicles are classified into the combination-unit long-haul type. The resulting final statistics for the vehicle population selected from the Fleet DNA database are shown in Table 1.

Table 1. Heavy-Duty Vehicle Types with Population of Conventional Vehicles in Current Fleet DNA

MOVES Vehicle ID	Vehicle Type	Vehicles in Fleet DNA	Days of Data
41	Other Buses	0	0
42	Transit Buses	16	810
43	School Buses	7	246
51	Refuse Trucks	37	641
52	Single-Unit Short-Haul Trucks	119	2,794
53	Single-Unit Long-Haul Trucks	0	0
54	Motor Homes	0	0
61	Combination-Unit Short-Haul Trucks	106	2,631
62	Combination-Unit Long-Haul Trucks	195	8,682
	Total	480	15,804

2.1.2 CE-CERT Database

The CE-CERT database was compiled by CE-CERT researchers in 2017. This data set provides an accurate characterization of current heavy-duty vehicle activity, mainly in California, aimed at enlightening the regional emission inventory for on-road heavy-duty mobile sources. This database includes vehicle and engine activity data from 90 heavy-duty vehicles in 23 fleets that make up 19 different groups defined by a combination of vocational use, gross vehicle weight rating, and geographic region (Boriboonsomsin et al. 2017). The final vehicle samples in CE-CERT are summarized in Table 2.

Table 2. Final Vehicles Sample in CE-CERT Database (Boriboonsomsin et al. 2017)

Category No.	Vocation	No. of Vehicles	No. of Fleets	Region
1a	Line Haul – out of state	3	1	North California
1b	Line Haul – in state	3	1	South California
2a	Drayage	1	1	North California
2b	Drayage	5	1	South California
3	Agricultural	8	1	South California
4a	Construction	6	3	Both
4b	Cement Mixers	5	2	Both
5a	Food Distribution	5	1	South California
5b	Beverage Distribution	6	1	South California
5c	Local Moving	1	1	South California
6	Airport Shuttle	5	1	North California
7	Refuse	6	1	North California
8a	Urban Buses	6	1	North California
8b	Express Buses	5	1	South California
9a	Freeway Work	5	1	Both
9b	Sweeping	5	1	Both
9c	Municipal Work	3	1	South California
9d	Towing	7	2	Both
10	Utility Repair	5	1	North California
	Total	90	23	

Based on the vehicle classification provided by the EPA corresponding to the MOVES inputs, the vehicles in the CE-CERT data set can be separated into five groups: other buses, transit buses, refuse trucks, single-unit short-haul trucks, and combination-unit short-haul trucks. The corresponding number of vehicles, as well as the number of vehicle days in each source type, are listed in Table 3.

Table 3. Heavy-Duty Vehicle Types with Population of Vehicles in CE-CERT Database

MOVES Vehicle ID	Vehicle Type	Vehicles in CE-CERT	Days of Data
41	Other Buses	5	724
42	Transit Buses	5	233
43	School Buses	0	0
51	Refuse Trucks	6	724
52	Single-Unit Short-Haul Trucks	30	3,248
53	Single-Unit Long-Haul Trucks	0	0
54	Motor Homes	0	0
61	Combination-Unit Short-Haul Trucks	38	2,732
62	Combination-Unit Long-Haul Trucks	0	0
	Total	84	7,661

Among these vehicles in the CE-CERT database, six vehicles in the urban buses category (No. 8a in Table 2) have been removed because they include diesel-powered hybrid powertrain architectures, which we anticipated would produce significantly different idle and start activities compared to conventional diesel-power vehicles. In addition, due to the specific driving behavior result from the fleet, five vehicles in the airport shuttle category (No. 6 in Table 2) are grouped in “other buses” as described by the MOVES model.³ Finally, even though the CE-CERT database classifies some vehicles as long-haul trucks (No. 1a and No. 1b in Table 2), EPA and NREL found that the activity of such vehicles did not include the multiday trips expected from the long-haul vehicle definition in the MOVES model, and thus reclassified them as short haul in the rest of the analysis.⁴ As a result, there are no long-haul trucks in the CE-CERT data.

Table 4 includes a detailed breakdown of the vocations in the short-haul classes in the CE-CERT data set. The corresponding classifications are generated based on multiple criteria, including vehicle specification, vehicle model, gross vehicle weight rating, and average daily distance.

³ EPA suggests the airport shuttles be classified as “other buses” because they are not operated by a transit authority, consistent with their updated definition of “other buses” in MOVES3 (EPA 2020b).

⁴ To develop default data for MOVES, the EPA does not have information about the routes or duty cycles of the vehicles. As such, EPA classifies combination trucks as long-haul combination if they travel more than 200 miles per day, using the assumption that most of the vehicles that travel over 200 miles are conducting multiday trips that include overnight hotelling activity. As shown in Table 8, the combination line-haul vehicles in the CE-CERT database travel more than 200 miles per day. However, because the vehicles instrumented in the CE-CERT database leave and return to the same depot each day, we classified them as short-haul combination vehicles as recommended by EPA.

Table 4. Vocation Makeup for Short-Haul Classes in CE-CERT Data

Combination-Unit Short-Haul	Number	Single-Unit Short-Haul	Number
Agricultural	8	Beverage Distribution	6
Cement Mixers	5	Construction	1
Construction	5	Freeway Work	5
Drayage	6	Local Moving	1
Food Distribution	5	Sweeping	5
Line Haul	6	Towing	7
Municipal Work	3	Utility Repair	5
Total	38	Total	30

2.1.3 Combination of Two Databases

Because the vehicles in the two databases were separated into the same source types defined by the MOVES model, it was possible to combine them together and form the final data set used for this project. General information about these combined databases, including the total number of vehicles and the total vehicles days in each source type, is listed in Table 5.

Table 5. Heavy-Duty Vehicle Types with Population of Vehicles in Combined Database

MOVES Vehicle ID	Database	Vehicles	Days of Data
41 Other Buses	Fleet DNA	0	0
	CE-CERT	5	724
	Sum	5	724
42 Transit Buses	Fleet DNA	16	810
	CE-CERT	5	233
	Sum	21	1,043
43 School Buses	Fleet DNA	7	246
	CE-CERT	0	0
	Sum	7	246
51 Refuse Trucks	Fleet DNA	37	641
	CE-CERT	6	724
	Sum	43	1,365
52 Single-Unit Short-Haul Trucks	Fleet DNA	119	2,794
	CE-CERT	30	3,248
	Sum	149	6,042
53 Single-Unit Long-Haul Trucks	Fleet DNA	0	0
	CE-CERT	0	0
	Sum	0	0
54 Motor Homes	Fleet DNA	0	0
	CE-CERT	0	0
	Sum	0	0
61 Combination-Unit Short-Haul Trucks	Fleet DNA	106	2,631
	CE-CERT	38	2,732
	Sum	144	5,363
62 Combination-Unit Long-Haul Trucks	Fleet DNA	195	8,682
	CE-CERT	0	0
	Sum	195	8,682
Total		564	23,465

2.2 Methodology

2.2.1 Database Description

The CE-CERT database includes comprehensive 1-Hz data broadcasting over the vehicle Controller Area Network bus per SAE J1939 standards (SAE International 2010). For this analysis, the following parameters were selected for subsequent analysis: vehicle speed, engine

speed, and time. Prior to calculation and preprocessing, the data are collected from the database, which involves loading and combining all 1-Hz data into a single one-dimensional data array for each parameter. Each data file is arranged in the database by vehicle, day, and parameter as shown in Figure 1.

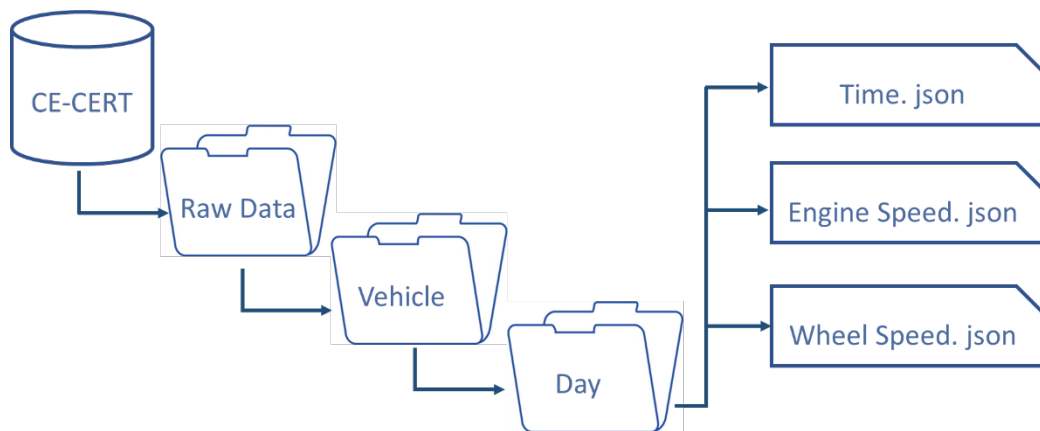


Figure 1. Diagram of CE-CERT database file structure

2.2.2 Preprocessing

Two key parameters in the database are engine speed in revolutions per minute (rpm) and wheel speed in miles per hour (mph). An engine speed greater than 0 rpm indicates that the vehicle engine is running, and a wheel speed greater than 0 mph signifies that the vehicle is in motion. In this analysis, vehicle starts are calculated by identifying the transition from an engine speed of 0 rpm to greater than 0 rpm. Vehicle soak is defined as the length of time between engine off (engine speed of 0 rpm) and the next time it is started (engine speed greater than 0 rpm), and a vehicle is considered to be idling when its wheel speed is less than 1 mph and the engine speed is greater than 0 rpm. Accurate characterization of vehicle start performance depends on accurate reporting of the engine speed data as well as the other parameters; therefore, data preprocessing was performed to eliminate erroneous information.

These calculations depend on accurate reporting of the vehicle data, so data preprocessing is performed to eliminate erroneous information. The first preprocessing step is to filter out unrealistic parameter values. Some vehicle networks will report a meaningless default value (usually this is the “FF” or highest value in hex notation) prior to powering down, which causes the engine speed to falsely exceed 8,000 rpm after the engine shuts off and could then be mischaracterized as a new start. The preprocessing filter removes data points with engine speeds greater than 7,000 rpm to account for this issue. On top of these intrinsic idiosyncrasies, malfunctions and defects can further hinder data quality. For instance, if the wheel speed sensor is broken or not properly installed, it may still report values of 0 mph, causing the vehicle to seem as though it is idling throughout the entire operation of the vehicle. Therefore, during preprocessing, if the wheel speed is reported as 0 mph for the entire vehicle operation, we assume a wheel sensor error and use speed from the GPS as a substitute for wheel speed.

Another common vehicle data characteristic is “jumps” or “gaps” in time stamps between data points. It is reasonable to expect that a vehicle may slow to zero, shut down the engine, and soak for long periods, such that the next time stamp recorded is an hour or more from the previous

time stamp. Alternatively, the GPS may cause a gap in time (generally an hour) when it updates the data logger's clock as the vehicle crosses a time zone, or a gap in time may be generated by the data logger if the recording is paused while saving a log file to memory. Furthermore, if the logger was taken off a vehicle on the West Coast and placed on a vehicle on the East Coast, it is possible for the time stamp to jump 3 hours at the beginning of logging once the GPS updates the internal clock to local time. These are trivial instances in which there is a logical explanation for a gap in time with near-contiguous data that are valuable to keep. However, in some instances, a data logger will shut off prior to recording 0-rpm engine speed, and it is unclear from the data if the engine turned off. As a result, a corresponding soak time and start may be inaccurately categorized or missed altogether. This is addressed during the preprocessing as described below.

The next step of data preprocessing uses a gap-filling algorithm to try to infer engine stops and starts that may have been missed in these nontrivial events by identifying leaps or gaps in time stamp from one data point to the next. If the algorithm finds a time gap larger than 2 seconds, 0 rpm is added to the start and end of the engine speed data to trigger a shutoff and start determination. Two seconds is selected herein to reflect the data information as accurate as possible and avoid any assumptions subject to arbitrary experiences or engineering judgement.

In addition, a specific zero-speed drift filter was developed and employed in the data preprocessing. Zero-speed drift appears when the engine is stopped for a prolonged period while the vehicle key is still on. During such an extended-duration soak time, the installed data logger may record a very small engine speed due to the sudden signal jump. Such a small fluctuation on engine speed, if not removed, would incorrectly be considered an engine start. To remove the zero-speed drift, the designed filter examined the value of each individual engine speed point in the data set in relation to its nearest neighbor. If a given engine speed recorded value was nonzero and the neighboring points on each side are both 0 rpm, the nonzero engine speed point is replaced by 0 rpm to eliminate the zero-speed drift. This simple filter significantly improved both the continuity of the raw data and the characterization of the start performance.

The preprocessing steps are summarized as follows:

1. Filter out unrealistic values
2. Fill time gaps greater than 2 seconds with an engine start
3. Apply the zero-speed drift filter.

CE-CERT researchers applied different preprocessing methods to remove erroneous values. For example, CE-CERT used 300 rpm as the threshold for engine off to avoid possible noise in rpm data near 0. We compared the starts per day by vocation from the vehicles analyzed by CE-CERT in this report and as reported from Table 5-6 from CE-CERT's report results (Boriboonsomsin et al. 2017) to examine if these caused significant differences in the results. The starts per day by vocation on weekdays were within $\pm 20\%$, with the difference being less than ± 1.2 starts per weekday for 15 of the 17 truck vocations reported in the CE-CERT dataset. The largest differences were observed for construction and cement mixer trucks which were ~ 3 starts per weekday higher ($\sim 56\%$ and 60% higher) in the NREL analysis than the CE-CERT report. The differences in the preprocessing methods likely led to these differences, however, the

impact on the overall results averaged by MOVES source type (Table 11) are driven by vocational differences, not data processing methods.

2.2.3 Calculations

Vehicle activity values in MOVES are intended to represent average activity at a national scale. This section discusses the calculations we used to calculate starts per day, idle fraction, start fractions, and soak fractions from the data collected from the individual vehicles.

2.2.3.1 Starts Per Day

For starts per vehicle per day, we calculated the average starts per vehicle per day by day type (weekday or weekend day) and then averaged across all vehicles within a source type as shown in Equation 1. Each instrumented vehicle contributes equally to the average starts, regardless of the number of days each vehicle was instrumented.

$$Start\ per\ day_{s,d} = \frac{\sum (starts_{d,i} / days_i)}{n_s} \quad (1)$$

Where:

i = individual vehicle ID

$days_i$ = days vehicle i is instrumented

s = source type ID

d = day type ID (weekday or weekend day)

n = number of vehicles instrumented of source type s .

As an alternative approach, the average starts per day can be calculated by first summing the number of starts across all vehicles in a source type and dividing by the total number of days sampled by those vehicles:

$$Start\ per\ day_{s,d} = \frac{\sum starts_{d,i}}{\sum days_i} \quad (2)$$

Where:

i = individual vehicle ID

$days_i$ = days vehicle i is instrumented

s = source type ID

d = day type ID (weekday or weekend day)

n = number of vehicles instrumented of source type s .

Equation 2 would essentially weight each of the average starts from each vehicle according to the number of days the vehicle was sampled. We did not use this second approach because the number of days sampled was determined for other reasons (e.g., availability of the truck, funding constraints, time needed to classify the vehicles' duty cycle) and was not intended to be representative of vehicle in the national fleet. For example, the CE-CERT vehicles were sampled on average for ~91 days and the Fleet DNA vehicles for ~33 days, but we do not have reason to believe that the CE-CERT vehicles are three times as representative of start activity compared to the Fleet DNA data. Thus, we treated each vehicle equally using Equation 1.

2.2.3.2 Overview of Idle, Start, and Soak Fraction Calculations

To calculate idle fractions, start fractions, and soak fractions, we evaluated three approaches for conducting the average fractions, including calculating averages of individual vehicle fractions, weighting the average according to the total instrumentation time of each vehicle, and weighting the average according to the daily average activity (starts, operation time, or idling time). We evaluated each of these approaches as discussed in Appendix C and chose to use the third approach, which weights the average according to the daily average activity. Such an approach normalizes the recorded activity by the amount of time each vehicle was instrumented and avoids over representative activity values from vehicles that had very little operation.

In general, the developed approach includes the following two steps:

1. Calculate the daily and hourly averages for operation time, idle time, and starts for each individual vehicle
2. Derive the idle fractions, start fractions, and soak fractions by dividing the sum of the average statistic of interest (e.g., daily average idle time) by the denominator of the corresponding statistic (e.g., daily operation time) summed across all vehicles within the same vehicle and day type.

2.2.3.3 Idle Fraction

Currently in MOVES, off-network activity includes starts, soak, and idling (both extended idle and auxiliary power unit operation for long-haul combination trucks). On-network activity includes speed distributions as well as the idling that takes place at intersections and on congested roadways. On-network idling is represented in the MOVES driving cycles selected based on the average speed distributions. None of these driving cycles include a full estimate of “workday idle,” which also includes the idling that takes place both on and off the road network, such as at distribution centers while the truck is queuing, loading, and unloading. To supplement these gaps in idle activity information, total, workday, and extended idle fractions were calculated for the vehicles in Table 5.

The idle activity analysis provided by NREL calculates total idle, workday idle, and extended idle fraction for each vehicle type and day type. However, this is limited to engine idling and does not include additional “hotelling” activity from devices such as auxiliary power units, auxiliary battery power, auxiliary heating units, and other engine-off hotelling operation. MOVES defines hotelling as any long period of time (e.g., >1 hour) that drivers spend in their vehicles during mandated rest times during long-distance deliveries by tractor/trailer combination heavy-duty trucks (EPA, 2016).

After preprocessing, idle is calculated when a vehicle's wheel speed is less than 1 mph and engine speed is greater than 0 rpm. Using these two logic statements, a binary output indicates if a vehicle is idling or not. Next, periods of contiguous idle are identified by the length and the day type corresponding to the start of the idle. If an idle period starts on one day type and ends on another, that activity will only be counted for the day type in which it started. For this analysis, operating time is defined as the total time when engine speed is greater than 0 rpm.

To calculate the idle fraction for an individual vehicle and specific day type (weekday or weekend), the sum of the idle time is divided by the sum of operation taking place within each day type for each individual vehicle:

$$\text{Idle fraction}_{i,d} = \frac{\sum \text{idle hours}_{i,d}}{\sum \text{operating hours}_{i,d}} \quad (3)$$

Where:

i = individual vehicle ID

d = day type ID (weekday or weekend day).

To accommodate the request for workday and extended idle fractions, the idle segments were further classified into segments less than or equal to 3,600 seconds (1 hour) as workday idle and greater than 3,600 seconds as extended idle. The workday and extended idle fractions were then calculated using Equations 4 and 5, respectively, such that the sum of the workday and extended idle is equal to the total idle as shown in Equation 6 for each day and individual vehicle type.

$$\text{Workday idle fraction}_{i,d} = \frac{\sum \text{Workday Idle hours}_{i,d}}{\sum \text{Operating hours}_{i,d}} \quad (4)$$

$$\text{Extended idle fraction}_{i,d} = \frac{\sum \text{Extended Idle hours}_{i,d}}{\sum \text{Operating hours}_{i,d}} \quad (5)$$

$$\text{Workday Idle fraction}_{i,d} + \text{Extended Idle fraction}_{i,d} = \text{Idle fraction}_{i,d} \quad (6)$$

Where:

i = individual vehicle ID

d = day type ID (weekday or weekend day).

Afterwards, the sum of the average idle time across each vehicle within a day and source type is divided by the sum of the average operation time within each day and source type. In this approach, the idle fraction is representative of the average operation activity by source type and day. Equation 7 provides the calculation of the average idle fraction for each day and source type:

$$\text{Fleet Idle fraction}_{s,d} = \frac{\sum (\text{idle hours}_i / \text{days}_i)}{\sum (\text{operating hours}_i / \text{days}_i)} = \frac{\sum \text{Average Idle Time}_{i,d}}{\sum \text{Average Operating Time}_{i,d}} \quad (7)$$

Where:

i = individual vehicle ID

$days_i$ = number of days vehicle i is instrumented

s = source type ID

d = day type ID (weekday or weekend day).

This calculation was performed for idle fraction, workday idle, and extended idle by vehicle source type and day type. Idle fraction was also calculated within a vehicle source type (e.g., short-haul combination truck) by vocation. In addition, the hourly idle fraction was calculated by vehicle type, day type, and hour ID using the same equations.

2.2.3.4 Extended Idle Per Miles Driven

MOVES estimates extended idle for long-haul combination trucks as a subset of hotelling activity. Default hotelling activity for long-haul combination trucks in MOVES is estimated using a ration of hotelling hours per miles driven on restricted access roadways. To aid in this calculation, the extended idle per miles driven is calculated for each source type in MOVES, using Equation 8:

$$\text{Extended Idle per miles driven}_{s,d} = \frac{\sum(\text{extended idle hours}_i / \text{days}_i)}{\sum(\text{miles driven}_i / \text{days}_i)} = \frac{\sum \text{Average Extended Idle Time}_{i,d}}{\sum \text{Average Miles Driven}_{i,d}} \quad (8)$$

Where:

i = individual vehicle ID

$days_i$ = number of days vehicle i is instrumented

s = source type ID

d = day type ID (weekday or weekend day).

2.2.3.5 Start Fraction

Within the MOVES model, start fraction distributes engine starts temporally throughout the day. Start estimates in MOVES2014 are based on a limited data set of heavy-duty commercial vehicles, prompting the concern that the model may not adequately represent the wide range of heavy-duty vocations. Further, additional data allow for differentiation between vehicle types, resulting in a more robust and highly resolved answer.

Starts are calculated using the engine speed data and identifying instances when the engine speed transitions from 0 rpm to greater than 0 rpm, reporting a start instance each time the vehicle starts. To calculate the start fraction for an individual vehicle and specific day type (weekday or

weekend), the sum of the starts taking place within a specific hour ID and day type are divided by the sum of all starts occurring for that day type, as shown in Equation 9. If the data logger was installed but did not record any activity, the hourly and daily starts are zero for that specific day; however, if the data logger was not installed for a complete specific day, those values are denoted as “nan” (not-a-number) and are removed from the results. The sum of the hourly fractions across all hours of the day is 1.

$$Start\ Fraction_{i,h} = \frac{\sum Hourly\ starts_{i,d,h}}{\sum Daily\ starts_{i,d}} \quad (9)$$

Where:

i = individual vehicle ID

h = hour ID (1–24)

d = day type ID (weekday or weekend day).

With this information, starts within each day type and hour of the day are counted and then divided by the number of unique days of measurement to get a daily average start per hour for each individual vehicle. The average hourly starts from each individual vehicle are added together within each hour and divided by the average daily starts of each vehicle for each day and vehicle type (Equation 10). In this approach, the start fraction is representative of the average start activity by source type and day.

$$Fleet\ Start\ Fraction_{h,s,d} = \frac{\sum (starts_{h,i}/days_i)}{\sum (starts_i/days_i)} = \frac{\sum Average\ hourly\ starts_{i,h}}{\sum Average\ daily\ starts_i} \quad (10)$$

Where:

h = hour of the day

i = individual vehicle ID

$days_i$ = days vehicle i is instrumented

s = source type ID

d = day type ID (weekday or weekend day).

This calculation was performed for each source type and day type and will sum to 1 within each source type and day type across all hours of the day. Start fraction was also calculated within a vehicle source type by vocation.

2.2.3.6 Soak Fraction

Emissions from vehicle starts are dependent on the vehicle’s engine and aftertreatment temperature prior to start. In MOVES, the starts are classified since last active operation or “soak” time. Vehicle soak is defined as the time between when an engine stops and the next time

the engine starts. This is calculated by taking the time difference between when the engine speed transitions from >0 rpm to 0 rpm for the stop and from 0 rpm to >0 rpm for the start. This calculation is shown in Equation 11, and the results are binned according to the soak length bin defined in Table 6, resulting in an output table containing soak length bin and time stamps.

$$\text{Soak Time} = \text{Start Time} - \text{Stop Time (prior to the start)} \quad (11)$$

To calculate the soak fraction for an individual vehicle, the sum of the starts of a given soak time (also referred to as operating mode) within a specific hour ID and day type are divided by the sum of all starts occurring for that hour ID and day type, as shown in Equation 12. The sum of the eight soak fractions will equal 1 within each day type and hour of the day. If no starts occurred within that day type and hour ID, the sum of the eight bin fractions would equal 0.

$$\text{Soak Fraction}_{i,h,o,d} = \frac{\sum \text{Starts}_{i,d,h,o}}{\sum \text{Starts}_{i,d,h}} \quad (12)$$

Where:

o = soak length bin or operating mode ID (101–108)

h = hour of the day

i = individual vehicle ID

d = day type ID (weekday or weekend day).

Table 6. MOVES Soak Time Operation Modes

MOVES Bin ID	Soak Length Bin Description
101	Soak Time < 6 minutes
102	6 minutes ≤ Soak Time < 30 minutes
103	30 minutes ≤ Soak Time < 60 minutes
104	60 minutes ≤ Soak Time < 90 minutes
105	90 minutes ≤ Soak Time < 120 minutes
106	120 minutes ≤ Soak Time < 360 minutes
107	360 minutes ≤ Soak Time < 720 minutes
108	720 minutes ≤ Soak Time

In this study, starts within each soak length bin, day type, and hour of the day are counted and then divided by the number of unique days of measurement to get an average hourly starts by soak length bin and day type for each individual vehicle. The average hourly starts by soak length bin from each individual vehicle are added together and divided by the sum of all starts for each hour of the day, day type, and vehicle type (Equation 13). In this approach, the soak fraction is influenced more by the vehicles with the most starts in that specific hour of the day.

$$\text{Fleet Soak Fraction}_{s,d,h,o} = \frac{\sum (\text{starts}_{h,i,o} / \text{days}_i)}{\sum (\text{starts}_{h,i} / \text{days}_i)} = \frac{\sum \text{Average hourly starts}_{i,o}}{\sum \text{Average hourly starts}_i} \quad (13)$$

Where:

h = hour of the day

i = vehicle ID

o = operating mode (soak length)

$days_i$ = days vehicle $_i$ is instrumented

s = source type ID

d = day type ID (weekday or weekend day).

This calculation was performed for each source type, day type, and hour of the day. Soak fraction was also calculated by vocations in short-haul vehicle types.

2.2.3.7 Daily Operation

The daily operation is the average hours each vehicle is in operation per operational day. The daily operation is not an input for MOVES but was calculated for each source type and dataset to understand the variation in usage rates of vehicles included in the Fleet DNA and CE-CERT datasets.

The daily operation is calculated in Equation 14 by source type and day type. This calculates the average daily operation per vehicle, and then calculates across all vehicles with a source type and day type.

$$Daily\ Operation_{s,d} = \frac{\sum(\text{operation hours}_{d,i} / \text{op-days}_i)}{n_s} \quad (14)$$

Where:

i = individual vehicle ID

$op\text{-}days_i$ = days vehicle i is operated

s = source type ID

d = day type ID (weekday or weekend day)

n = number of vehicles instrumented of source type s .

3 Result and Discussion

This section visualizes the related results from this project and documents the corresponding discussion in detail. The analytical results from the CE-CERT data are presented first. This analysis comes from 84 heavy-duty vehicles with over 7,600 days of operation, providing a diverse data set encompassing 17 vehicle vocations mainly operated in California. In order to provide more insightful information about vehicles' driving patterns, such results are separated by vehicle source types defined by the MOVES model, as well as vehicle vocations recorded by the CE-CERT data. Comparisons of the analytical results between the CE-CERT data and Fleet DNA database are also described. It should be noted that in this comparison, the Fleet DNA

database includes the additional 64 vehicles investigated in this study. The comparison clearly reflects the similarities and differences of the driving behaviors from the same vehicle source types in the two data sets. Finally, the corresponding results reflecting the start and idle activity from the combined data sets are archived.

3.1 CE-CERT

3.1.1 Result by Vehicle Type

The current resulting set includes idle and start activity for the five different conventional vehicle types provided in the CE-CERT data. Table 7 summarizes the average results by vehicle type, which includes daily operation time, start per day, fraction of workday idle and fraction of extended idle (idling that is over 1 hour in duration).

Table 7. Summary Statistics: Weekday Averages by Vehicle Type^a

Vehicle Type	Daily Operation	Starts per Day	Workday Idle	Extended Idle
Other Bus	8.73 hours	10.07	50.52%	0.83%
Transit Bus	9.13 hours	8.69	31.08%	13.45%
Refuse	6.13 hours	4.93	46.08%	1.53%
Single-Unit Short-Haul	3.73 hours	8.38	38.77%	2.46%
Combination-Unit Short-Haul	6.45 hours	13.22	31.22%	2.00%

^a Daily operation like starts per day is calculated on a vehicle basis (each vehicle is weighted equally). Workday idle and extended idle are calculated using the final approach outlined in Section 2.2.3, which is weighted to the average vehicle operation times.

On average, combination-unit short-haul vehicles showed the largest number of starts per day, whereas refuse vehicles showed the fewest. Furthermore, both bus types had the longest daily operation hours—over 8 hours—whereas the refuse and combination-unit short-haul vehicles averaged over 6 hours daily and single-unit short-haul only averaged around 3–4 hours per day. Almost all the vehicle types have very limited extended idle fraction (less than 2.5%), except the transit bus, which had around 14% extended idle time. It should be noted that in the CE-CERT data, the transit buses are intercity buses that may idle for a long period for waiting passengers.

The detailed analyses start with the examination of start, soak and idle fractions of each vehicle type using the analysis approach described earlier. Figure 2 shows the vehicle type-specific start fraction multiplied by the soak bin fraction as a function of hour of the day for weekdays, providing context as to the types of start emissions and the relative impact for each hour. The start fraction sums to 1 across all hours of the day, and the soak bin fraction sums to 1 within each hour of the day. By multiplying the two together, the graphs display the percentage of starts that occur at a given hour of the day and of a given soak length.

For the single-unit and combination-unit short-haul vehicles, the largest portion of starts took place around midday, coinciding with operation during business hours, with frequent starts with minimal soak time likely due to stopping for deliveries or implementation of idle shut-off

programs such as California’s Clean Idle program (California Air Resources Board 2008). For refuse trucks, the majority of starts and largest portion of soak fractions longer than 12 hours occur in the early morning, between 4 a.m. and 6 a.m., corresponding to the start of the business day, suggesting this is the period most drivers start their refuse collection routes.

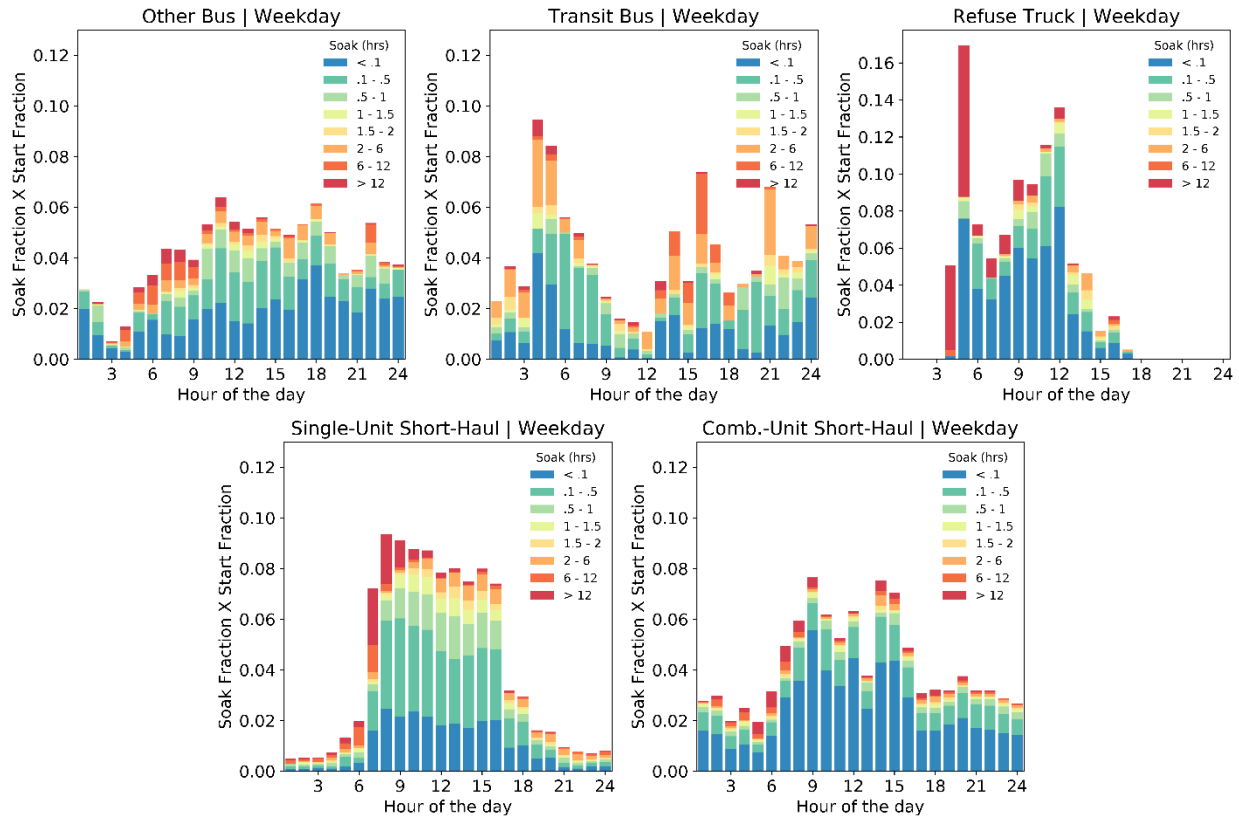


Figure 2. Soak fraction multiplied by start fraction vs. hour of the day for weekdays

For other buses (which are shuttle buses around an airport), the start fraction is increased from 3 a.m. to 9 a.m. and sustains at a similar level the rest of the day. In addition, the soak periods of other buses are longer around 3 a.m. to 9 a.m. (large fraction for soak period longer than 12 hours) and are much shorter afterwards. The transit buses (which are intercity buses in CE-CERT data) show three distinct peaks around 4–5 a.m., 4 p.m., and 9 p.m. These may be attributed to the start point, intermediate stop, and final destination of the trip. It is intuitive that the start peaks in the early morning also had high fractions of longer soak period. The remaining plots showing soak bin fraction multiplied by start fraction at any hour of the day for each vehicle and day type are provided in Appendix D.

Idle fraction is defined as the fraction of operation time while the vehicle is traveling less than 1 mph. The periods that last longer than 1 hour are considered extended idle periods. Figure 3 provides the workday and extended idle fractions by vehicle types and day types (CE-CERT lacks data from school bus and combination-unit long-haul vehicle types). Consistent with Table 7, transit bus has the largest extended idle fraction and total idle fraction of all the vehicles in the CE-CERT sample.

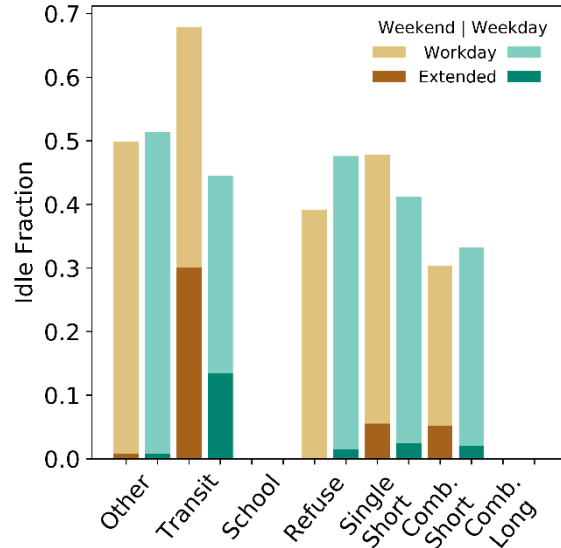


Figure 3. Extended and workday idle fractions vs. day type and vehicle type

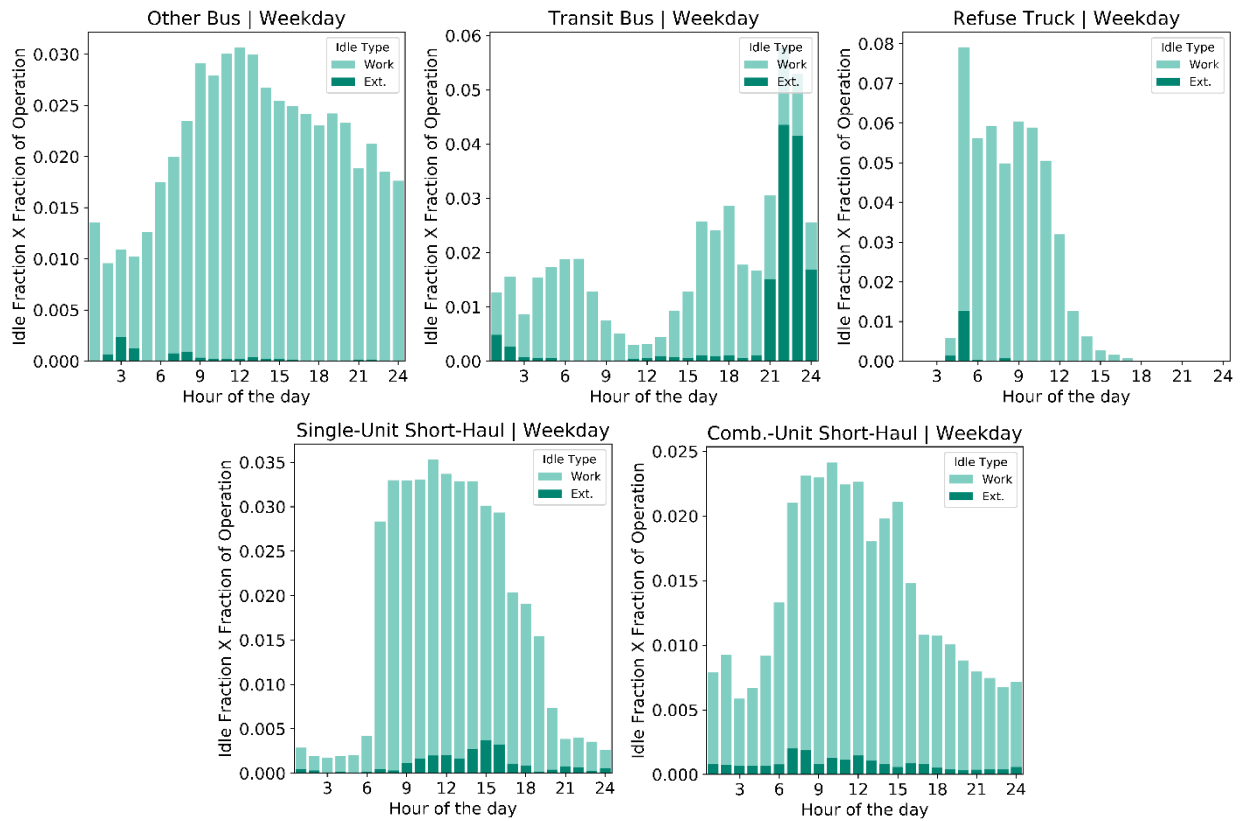


Figure 4. Extended and workday idle fractions vs. vehicle type for weekdays

To gain a better understanding of idle fraction, Figure 4 examines weekday idle fraction multiplied by the fraction of operation as a function of hour and vehicle type.⁵ Put another way, each bar in Figure 4 is the fraction of the total operation that the idle from that hour contributes. It is clear that all the vehicle types except transit bus have limited extended idle throughout the day, with workday idle being the main contributor and a peak around midday. The transit buses show a distinct trend with peak idle just around midnight and a substantial contribution from extended idle that persists throughout all hours. This is likely a result of the engine idling while the driver is waiting at a transit stop for passengers. Transit buses also show morning and afternoon peaks that coincide with traffic. Finally, the plot for refuse trucks shows the majority of idle concentrated around business hours, when refuse vehicles are making frequent stops at trash pickup locations. Similar plots showing the hourly extended and workday idle fractions of each vehicle type on weekends are provided in Appendix E.

3.1.2 Results by Vehicle Type and Vocation

Single-unit and combination-unit short-haul MOVES source types contain multiple vocations compared to the others, and the resulting activity is sensitive to the vocational distribution within each source type. Table 8 provides a breakdown of vocations for both short-haul vehicle types along with the average daily distance for each vocation to highlight the operational differences among the vocations.

Table 8. Average Daily Distance by Vocation for Short-Haul Vehicle Types – CE-CERT

Single-Unit Short Haul			Combination-Unit Short Haul		
Vocation	Vehicles	Avg. Miles	Vocation	Vehicles	Avg. Miles
Beverage Distribution	6	26.62	Agricultural	8	95.13
Construction	1	126.19	Cement Mixers	5	85.88
Freeway Work	5	46.16	Construction	5	132.75
Local Moving	1	60.36	Drayage	6	63.54
Sweeping	5	36.71	Food Distribution	5	183.27
Towing	7	142.38	Line Haul	6	358.22
Utility Repair	5	32.85	Municipal Work	3	134.15

For single-unit short-haul trucks, the operational differences among the vocations are significant. For example, the construction trucks travel more than 120 miles per day on average, compared to only around 26 miles for beverage distribution trucks. The start and soak fractions for those two vehicle types, shown in Figure 5, illustrate the stark operational differences as well. The beverage distribution vehicles have their peak starts during normal business hours, whereas construction vehicles have a relatively flat distribution of starts while operating.

⁵ The operation fraction is the sum of operation within 1 hour divided by the sum of operation in all hours for a day and vehicle type. This estimates the percentage of vehicle operation that occurs at different hours of the day, and sums to 1 across all hours of the day. The idle fraction is the fraction of the total vehicle operation within each hour that is idling.

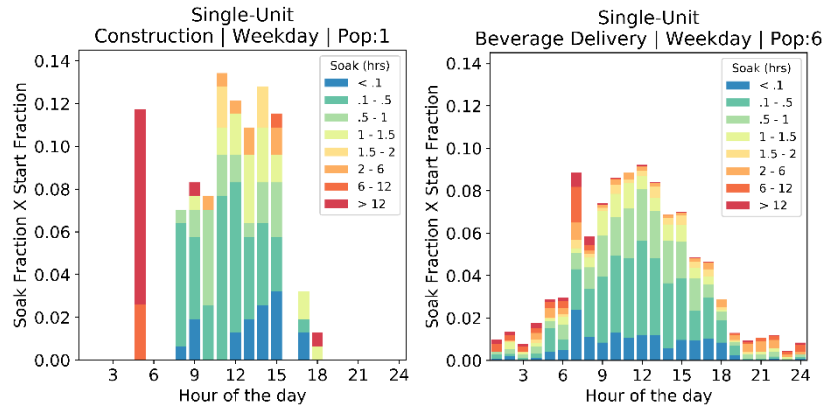


Figure 5. Vocational differences between beverage distribution and construction trucks in single-unit short haul

Most combination-unit short-haul trucks drive about 100 to 150 miles per day. However, the line-haul trucks travel an average of more than 350 miles per day, whereas the drayage trucks only drive around 60 miles per day. Considering the distinct driving behavior for these two vocations, the substantial difference between the average daily driven mileages is reasonable.

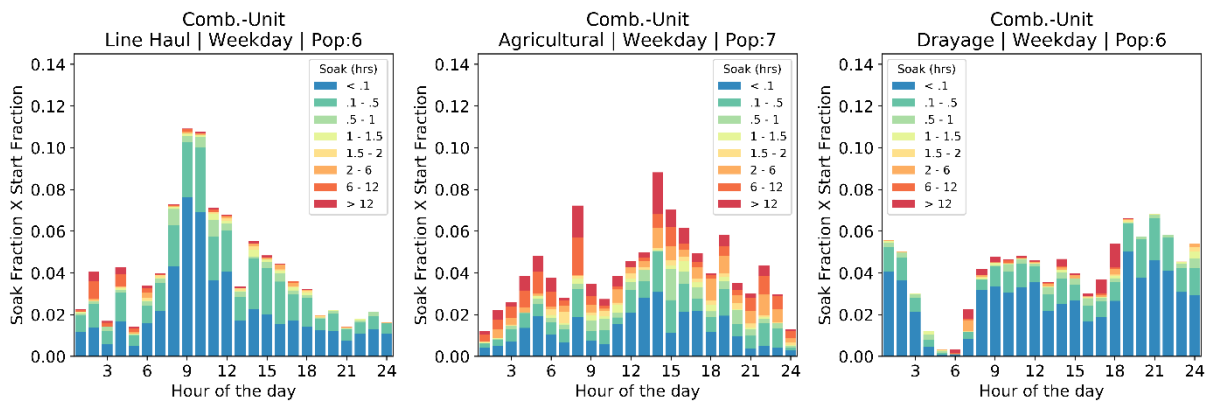
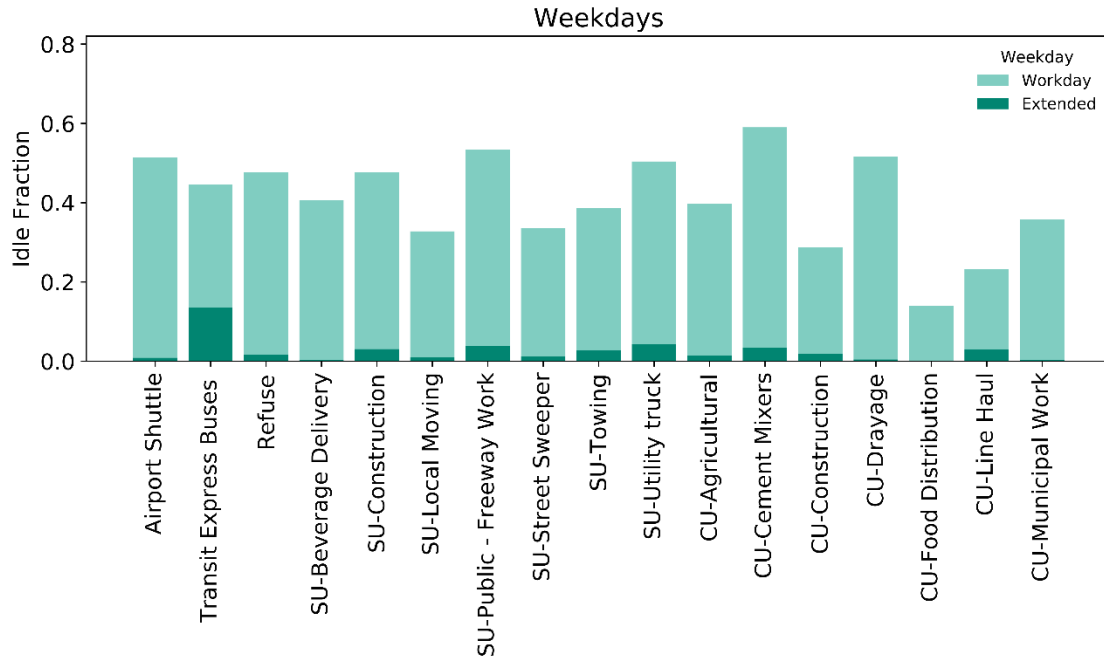


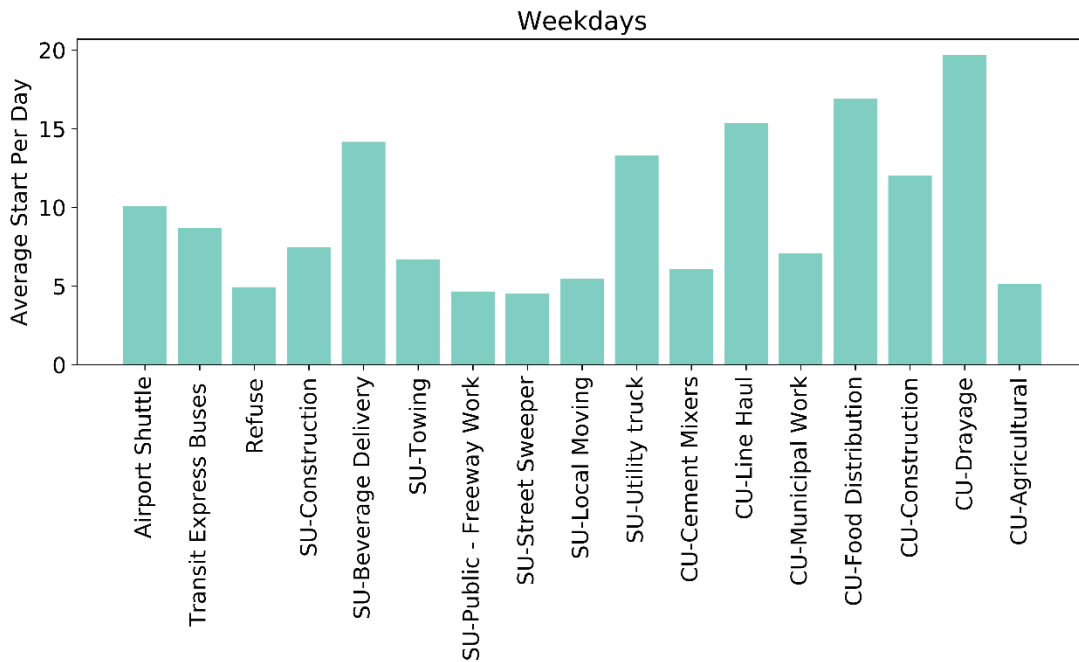
Figure 6. Vocational differences between line-haul, agricultural, and drayage vehicles in combination-unit short haul

Figure 6 shows the distinct start and soak differences between various vocations such as line-haul trucks, agricultural trucks, and drayage. The line hauls show the highest fraction of starts around 9 a.m., whereas the agricultural vehicles have two start peaks in the morning and afternoon and the drayage vehicles show even start fractions in almost all hours of the day except 4–5 a.m. In addition, the agricultural vehicles have a relatively large fraction of the longest soak period in each hour, whereas the shortest soak period dominates in the other two truck vocations.

The idle operation and average start per day are also affected by vehicle vocation, as shown in Figure 7. Appendix F lists the remaining results about vehicle behavior in different vocations.



(a)



(b)

Figure 7. Vocational distributions of (a) vehicle idle operation and (b) average starts per day

(SU = single-unit, CU = combination-unit)

3.2 Fleet DNA

This section summarizes results from the interim report (Kotz and Kelly 2019). The results by vehicle type and vocations are presented in a format consistent with the data from the CE-CERT database. More details are documented in the interim report. For example, the interim report

analyzes data by U.S. state. However, the largest difference among the vehicle activities appeared to be due to vocation and operation by different fleets, and we have not included the U.S. state comparison in this final report. In addition to the summarized results from the interim report, we have since incorporated vehicle activity data from two additional fleets of long-haul combination trucks, which are analyzed and compared with the previous Fleet DNA results.

3.2.1 Results by Vehicle Type

Figure 8 shows the Fleet DNA vehicle type-specific start fraction multiplied by the soak bin fraction as a function of hour of the day for weekdays. From Figure 8, the following conclusions can be drawn.

For single-unit short-haul vehicles, the largest portion of starts took place around midday, coinciding with operation during business hours, with frequent starts with minimal soak time likely due to stopping for deliveries or implementation of idle shut-off programs such as California’s Clean Idle program (California Air Resources Board 2008).

Conversely, the combination-unit trucks in the Fleet DNA dataset have a larger fraction of starts at the afternoon. As discussed below, the temporal profile of extended idling for long-haul combination trucks do not appear to be representative of the national average extended idling activity. Similarly, the temporal profile of starts from the long-haul combination trucks may not be representative of the national average, but of the measured long-haul combination fleet.

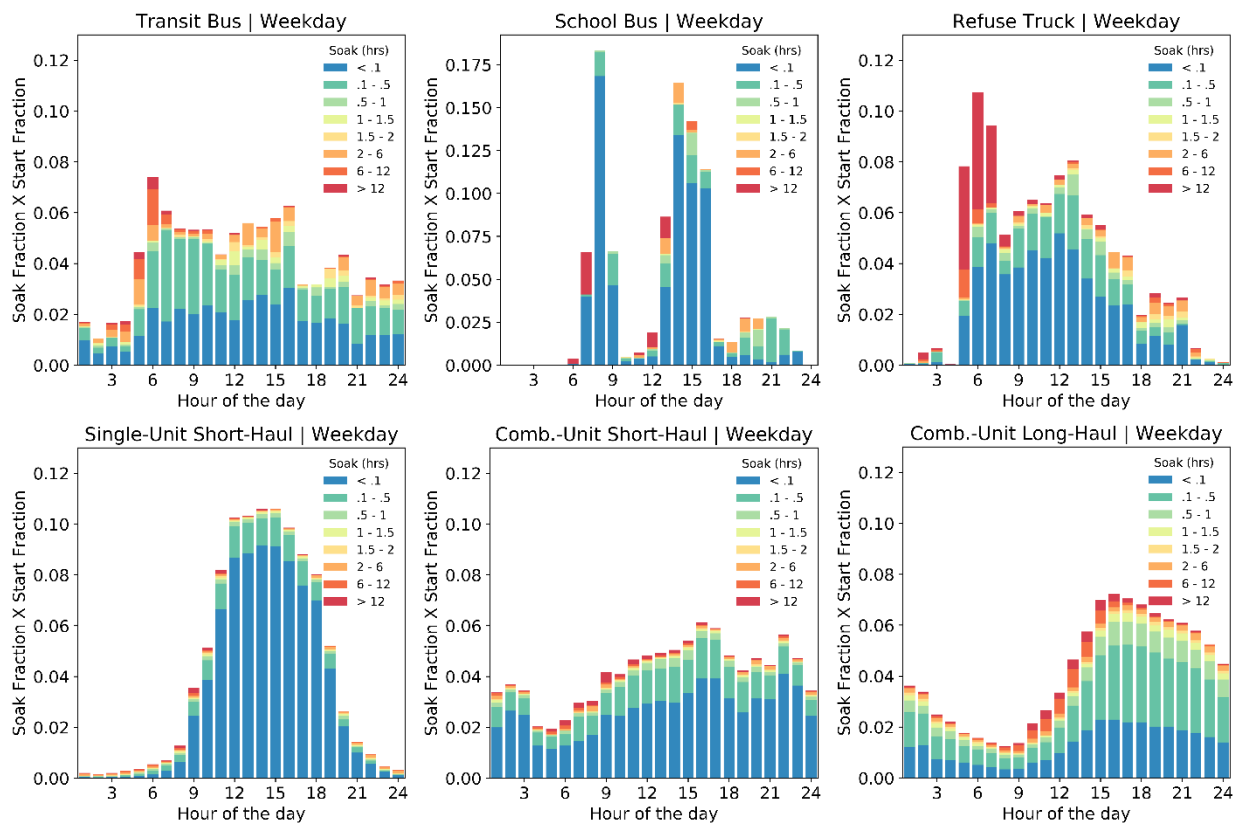


Figure 8. Soak fraction multiplied by start fraction vs. hour of the day for weekdays – Fleet DNA

For refuse trucks, the majority of starts and largest portion of soak fractions longer than 12 hours occur between 5 a.m. and 8 a.m., corresponding to the start of the business day, suggesting this is the time period most drivers start their refuse collection routes.

Similarly, transit buses have the largest start fraction around 6 a.m.; however, the peak is less pronounced and at a similar level to the rest of the day, in contrast to the refuse operation. Further, there are far shorter soak periods for the transit buses, indicating high frequency of starts per vehicle. Finally, school buses show two very distinct peaks coinciding with the beginning and end of the school day, as well as midday pickup, though due to the small sample size of vehicles in the school bus data set, values are likely to differ from the nationwide average and do not cover summer operations. The remaining plots of soak bin fraction multiplied by start fraction by hour of the day are provided in Appendix G for each vehicle and day type.

Figure 9 provides the workday and extended idle fractions by vehicle type and day type in the original Fleet DNA data set. Refuse trucks operating on weekdays have the largest idle fraction of all the vehicle and day types, whereas the school buses have no idle on weekends because none of the buses operated on those days. The long-haul class has the largest extended idle fraction of all vehicle types for both day types.

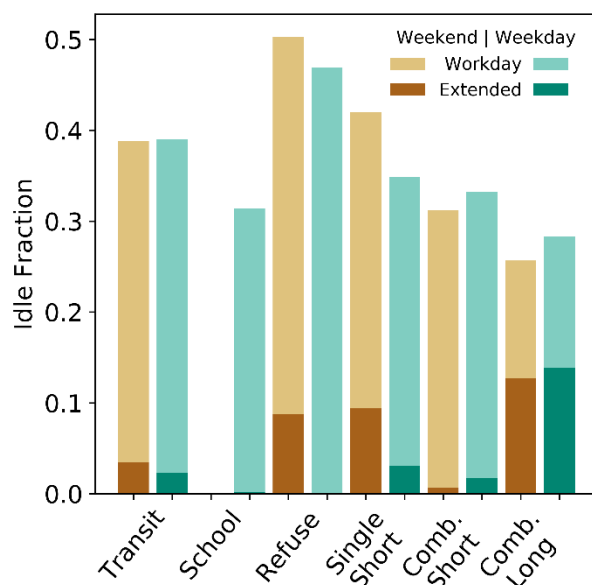


Figure 9. Extended and workday idle fractions vs. day type and vehicle type – Fleet DNA

To gain a better understanding of idle fraction, Figure 10 examines weekday idle fraction multiplied by the fraction of operation as a function of hour and vehicle type. From Figure 10, it is clear that short-haul vehicles have minimal extended idle throughout the day, with workday idle being the main contributor and a peak around midday. Both transit and school buses show morning and afternoon peaks that coincide with traffic for the transit buses and morning and afternoon pickup for school buses.

Long-haul vehicles show a substantial contribution from extended idle that persists throughout all hours, with most extended idling occurring between 4 am and 12 noon. The EPA compared the hourly distribution of extended idling from these data to hourly truck stop use and extended

idling data from another instrumented truck study (EPA 2020b). The comparison studies suggest that idling time is longest during the night-time hours and minimal from mid-morning to early afternoon. The hourly distribution from the long-haul trucks within Fleet DNA, may not be representative of the national average. These data also suggests that there may be significant variability in the temporal profiles of long-haul combination trucks across different fleets.

Finally, the plot for refuse trucks shows the majority of idle concentrated around business hours, with the peak around 9 a.m. when refuse vehicles are making frequent stops at trash pickup locations. The plots for weekend day types are provided in Appendix H.

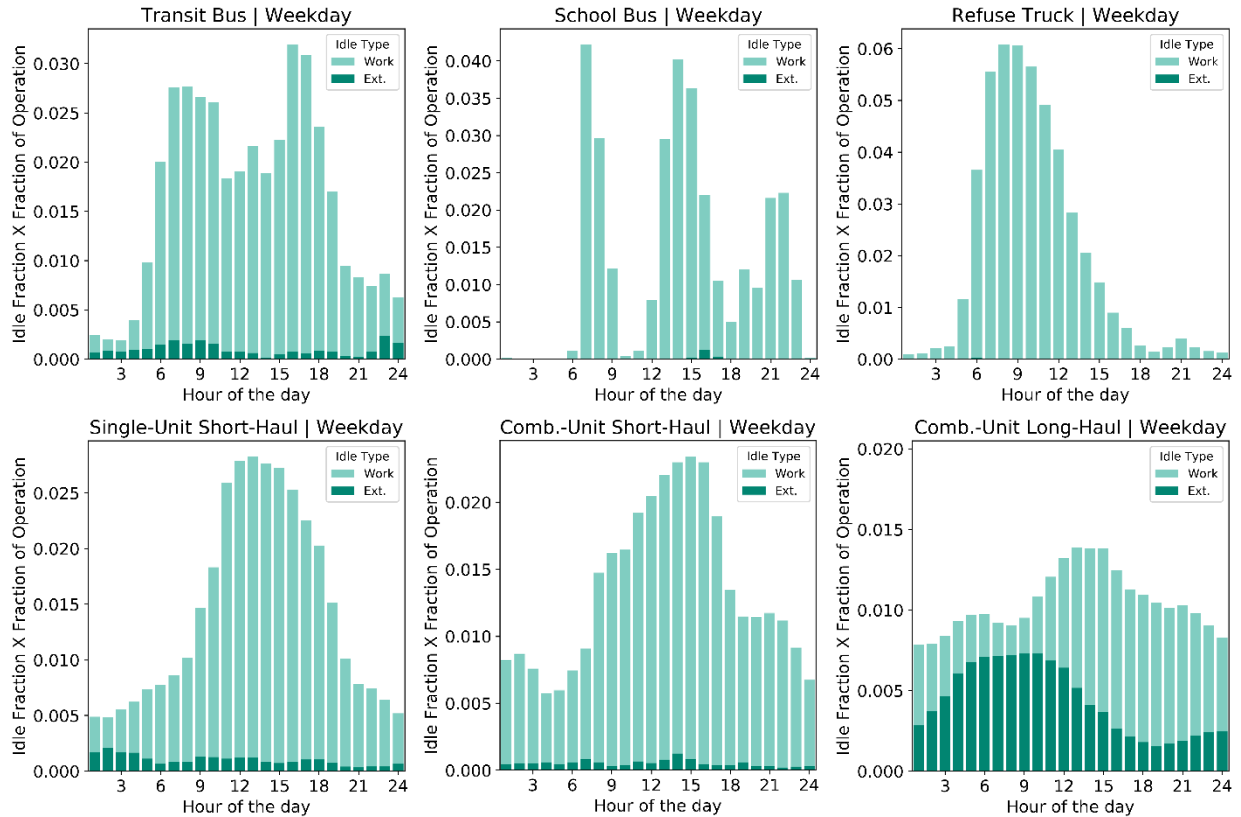


Figure 10. Extended and workday idle fractions vs. vehicle type for weekdays – Fleet DNA

3.2.2 Results by Vehicle Type and Vocation

Single-unit and combination-unit short-haul classes contain multiple vocations compared to the others and would be more sensitive to vocational differences. Table 9 provides a breakdown of vocations for both short-haul vehicle types along with the average daily distance for each vocation to highlight the operational differences among vocations.

Table 9. Average Daily Distance by Vocation for Short-Haul Vehicle Types – Fleet DNA

Single-Unit Short Haul			Combination-Unit Short Haul		
Vocation	Vehicles	Avg. Miles	Vocation	Vehicles	Avg. Miles
Concrete	3	79.79	Beverage Delivery	10	95.71
Delivery	1	294.41	Drayage	28	119.18
Dump Truck	3	70.53	Dry Van	3	99.13
Food Delivery	30	49.88	Dump Truck	4	143.77
Linen Delivery	17	65.65	Food Delivery	13	161.52
Parcel Delivery	39	52.47	Local Delivery	7	101.31
Propane Tank	1	6.72	Parcel Delivery	5	573.83
Shredder	1	9.15	Regional Haul	7	118.34
Snow Plow	11	27.12	Transfer Truck	28	174.27
Towing	4	33.79			
Warehouse Delivery	9	79.21			

For combination-unit short-haul trucks, the six parcel delivery trucks travel nearly 500 miles per day on average, compared to less than 100 miles per day for the beverage delivery trucks. The start and soak fractions for a subset of those vehicles, shown in Figure 11, also illustrate the stark operational differences. The beverage delivery vehicles have their peak starts during normal business hours, whereas these parcel delivery vehicles have a relatively flat distribution of starts around the clock. This is a result of the parcel delivery vehicles operating multiple shifts, with local delivery during the day and inter-depot delivery at night.

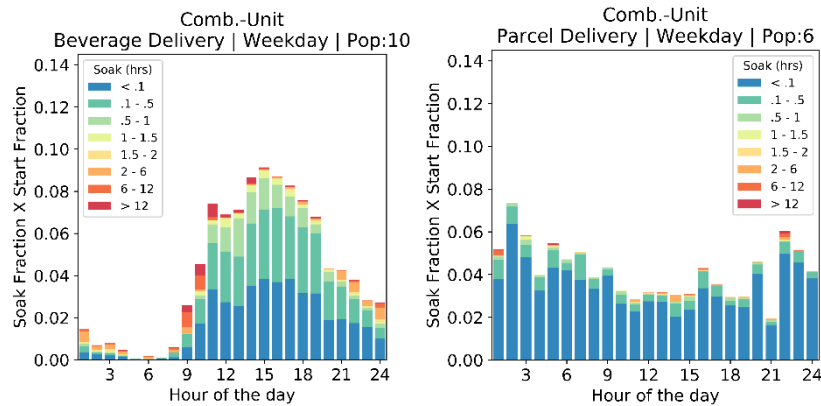


Figure 11. Vocational differences between beverage and parcel delivery combination trucks

Narrowing the scope to short-haul vocational trucks, Figure 12 shows distinct differences between various delivery vehicle vocations. Linen delivery vehicles show the highest fraction of starts around 2 p.m. and longer soak times toward the beginning of the day, whereas parcel delivery vehicles have the bulk starts in the afternoon and warehouse delivery vehicles show starts in nearly all hours of the day. The shapes of these start distributions, soak fractions associated with each start, and populations of vehicles within the analysis may impact emissions timing throughout the day.

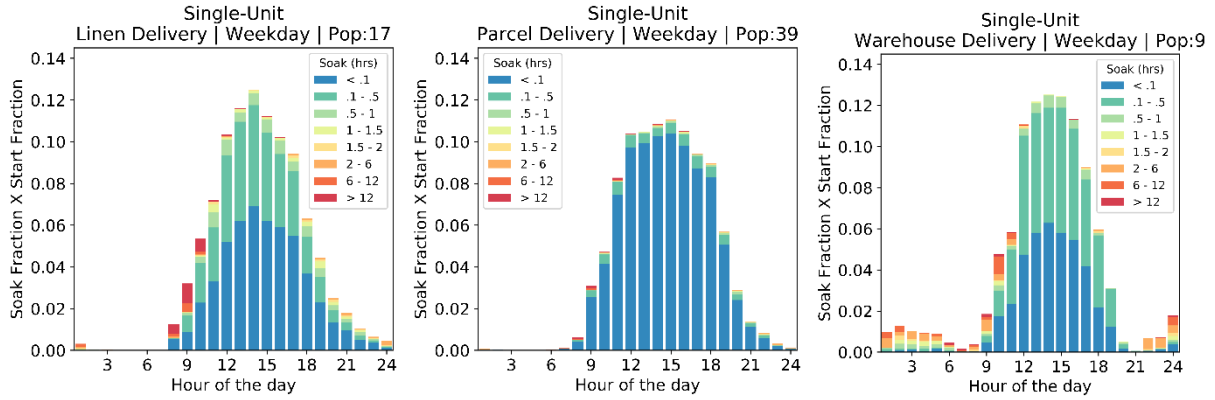
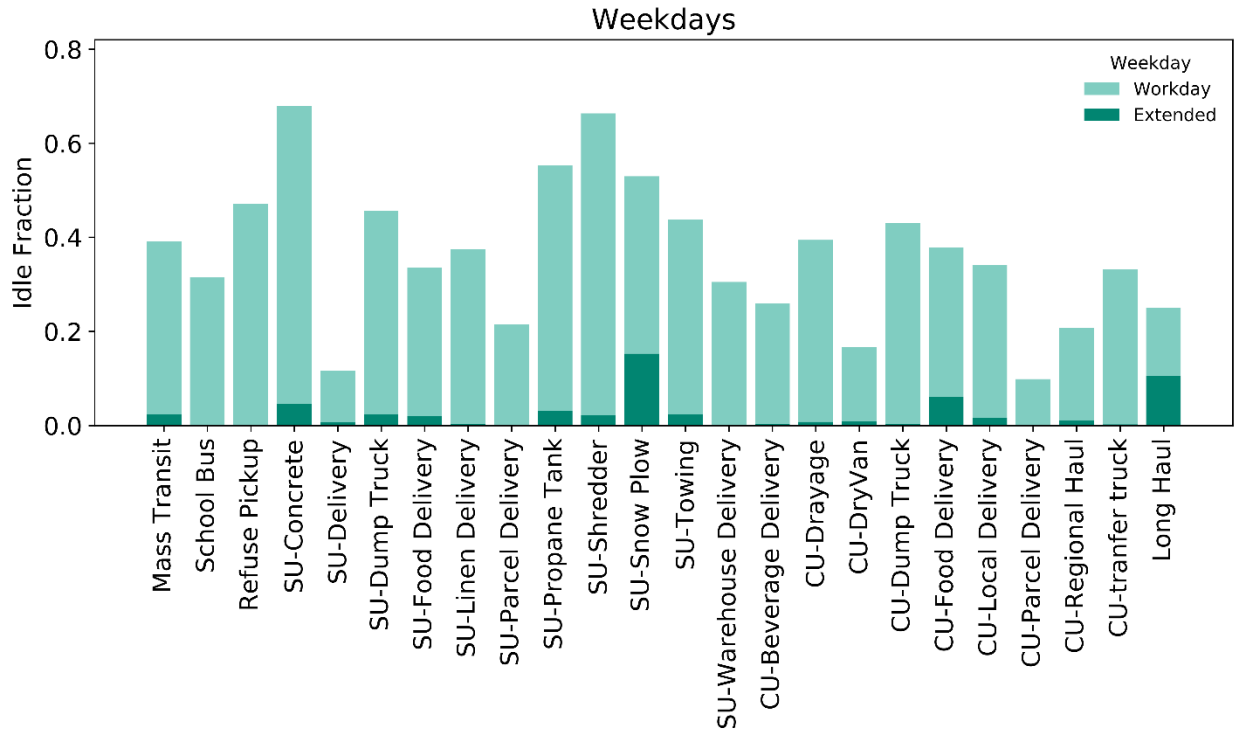
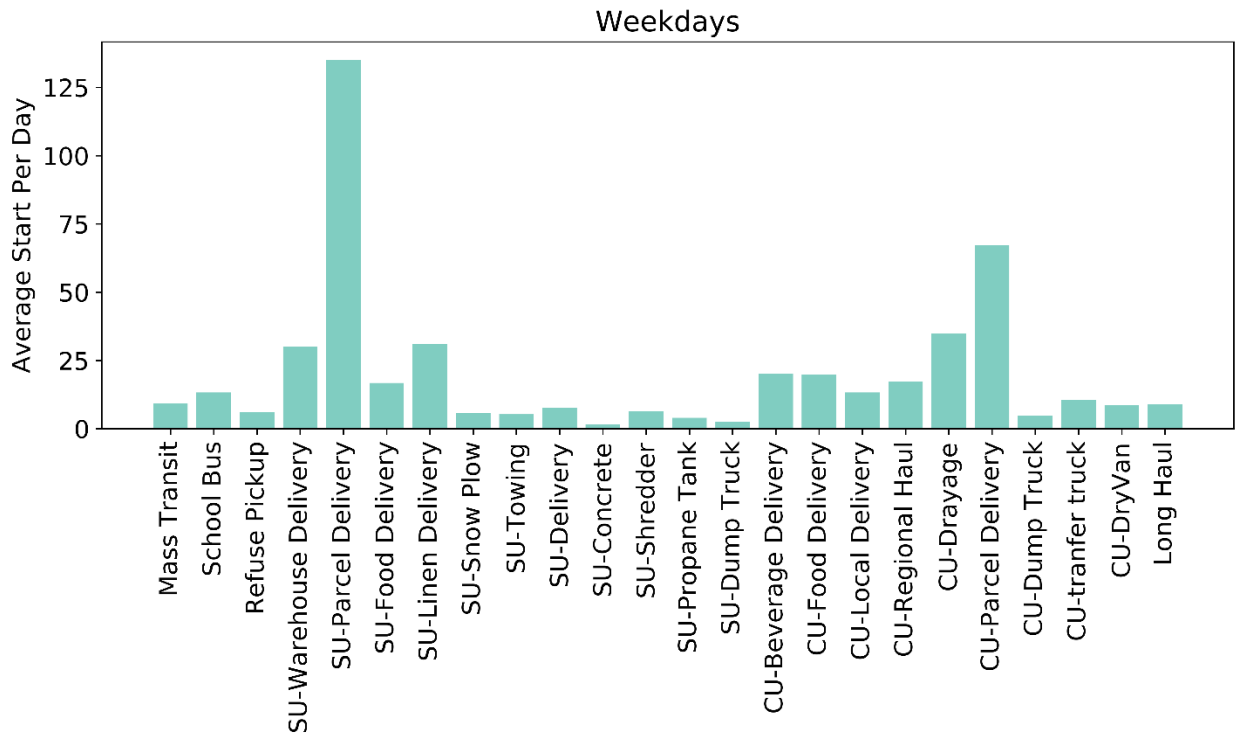


Figure 12. Start and soak distributions for single-unit delivery vehicles

Idle operation and average start per day are also affected by vehicle vocation, as shown in Figure 13. The remaining results about the Fleet DNA vehicle behaviors in different vocations are listed in Appendix I.



(a)



(b)

Figure 13. Vocational distributions of (a) vehicle idle operation and (b) average start per day in Fleet DNA data

(SU = single unit, CU = combination unit)

3.2.3 Additional Long-Haul Data Added into Fleet DNA

Because the Fleet DNA database is growing continuously, 64 combination-unit long-haul vehicles have been added into the database since the interim report. This subsection compares the driving behavior between these additional 64 vehicles and the original 131 vehicles. The updated results for the final combination-unit long-haul vehicles (195 vehicles) in the Fleet DNA database are also presented.

Table 10. Summary Statistics: Weekday Average for Long-Haul Data

Parameters	Original	Additional	Combined
Vehicle Number	131	64	195
Vehicle Days	7,560	1,122	8,682
Daily Operation	9.65 hours	10.00 hours	9.77 hours
Starts per Day	8.98	17.40	9.81
Workday Idle	14.58%	8.78%	12.81%
Extended Idle	10.51%	2.41%	8.05%

As can be seen in Table 10, the two data subsets have similar average daily operation activity, but quite different starts and idle behavior. The original 131 vehicles show fewer starts per day (8.98 starts per day) and much higher extended idle fraction (over 10%). These phenomena are mainly due to the vehicle not operating some days, overnight idling for hotelling purposes, and the limited amount of stops long-haul trucks make. However, the additional vehicles average more than 15 starts per day and have much less extended idle fraction. It should be mentioned that for the additional 64 vehicles, the majority are from fleets that encourage team shift driving. It is possible that the higher number of starts per day and less extended idle fraction are due to this fact because the team driving requires more stops to change the driver and has no need for overnight hotelling. Another reason for this difference may be idling regulations (e.g., California’s Clean Idle standard, which prevents idling over 5 minutes for vehicles that are not Clean Idled certified and could increase the number of starts per day).

Figure 14 shows the detailed comparisons of the weekday’s start, soak, and idle behaviors between the original and additional long-haul vehicles in Fleet DNA. Both the original 131 vehicles and additional 64 vehicles have similar start distribution with more starts after 3 p.m., while additional vehicles have relatively large fraction of short soak events (less than 6 minutes).

The idle behaviors are also distinct with these two data sets. However, the comparison between the two data sets shows that the original data set has a higher average workday and extended idle fractions across all hours compared to the additional data set. For the previous data, the peak idle fractions are located from around noon to 3 p.m., which is consistent with its start distribution. The additional vehicles have a relatively even distribution of the idle fraction in any hour of the day. The fractions of the extended idle are high during the night (11 p.m. to 9 a.m.) and are almost zero during the afternoon (3–6 p.m.).

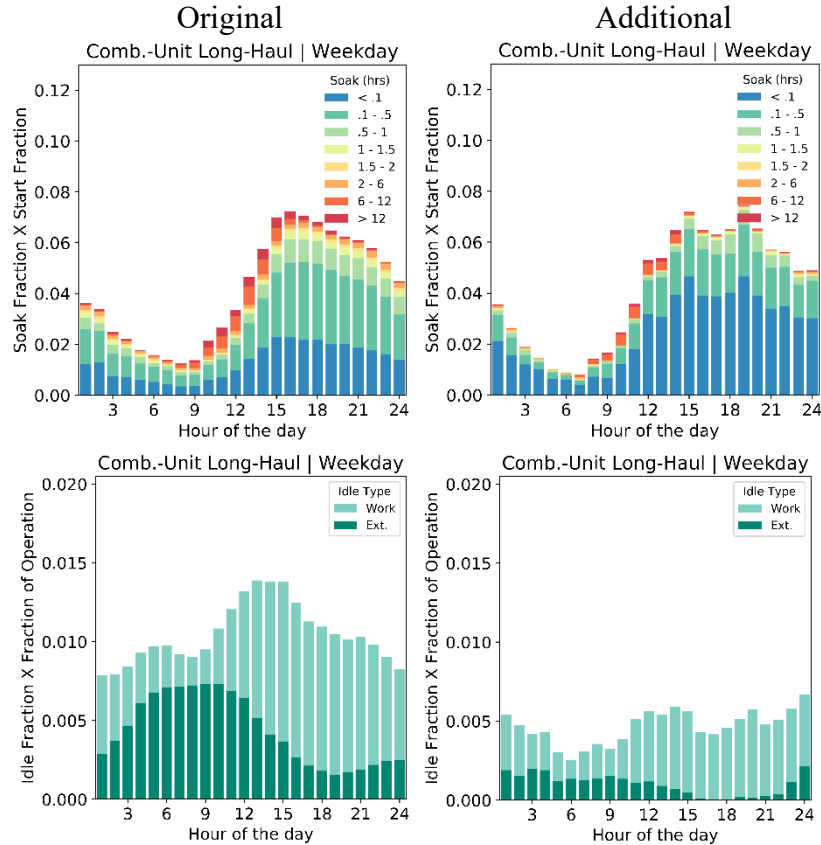


Figure 14. Comparison of start, soak, and idle performances of original 131 vehicles (left) and additional 64 vehicles (right) in the Fleet DNA database

Other results related to this comparison are listed in Appendix J for reference. It is worth noting that even though the driving behaviors are substantially distinct with the two data subsets, the additional 64 vehicles provide MOVES with more data from which to estimate nationally representative data, across additional fleets and diverse types of driving. This large difference is believed to be caused by the fact that the additional 64 vehicles are mainly driven by a team with shifts on the road. Considering the fact that some fleets prefer team driving to increase fleet effectiveness, we recommend that the MOVES model consider including these additional driving behavior data in conjunction with other fleet data to be representative of national combination long-haul truck activity.

Both long-haul combination fleets had similar start and idle temporal profile. When compared to other studies, the peak extended idling in the Fleet DNA long-haul trucks occurs later in the day than expected. Additionally, the number of starts peak in the afternoon, rather than in the morning hours. This behavior may not be representative of national averages long-haul activity but suggests that there is significant variation in temporal activity in long-haul activity. Because both fleets exhibited this activity, it may indicate a trend of long-haul combination truck operators to shift operation to later hours to avoid traffic congestion in the morning and noon hours.

Because the additional 64 vehicles are either line-haul or regional-haul trucks, only the combination-unit long-haul results need to be updated for Fleet DNA. Table 10 also lists the weekday statistics of the combined data and Figure 15 shows the related results. Clearly, the

soak and start performance of the combined data are similar to the additional vehicle data set because its start and soak events dominate the combined sample. The influence of the original data is shown in the larger fractions of the longer soak period (longer than 6 hours). Conversely, the idle performance of the final data is similar to the original 131 vehicles due to its large number of idle operations. However, the idle fraction in each hour is reduced due to the additional vehicles. Once again, these results need to be investigated further due to the time stamp issue in the original data.

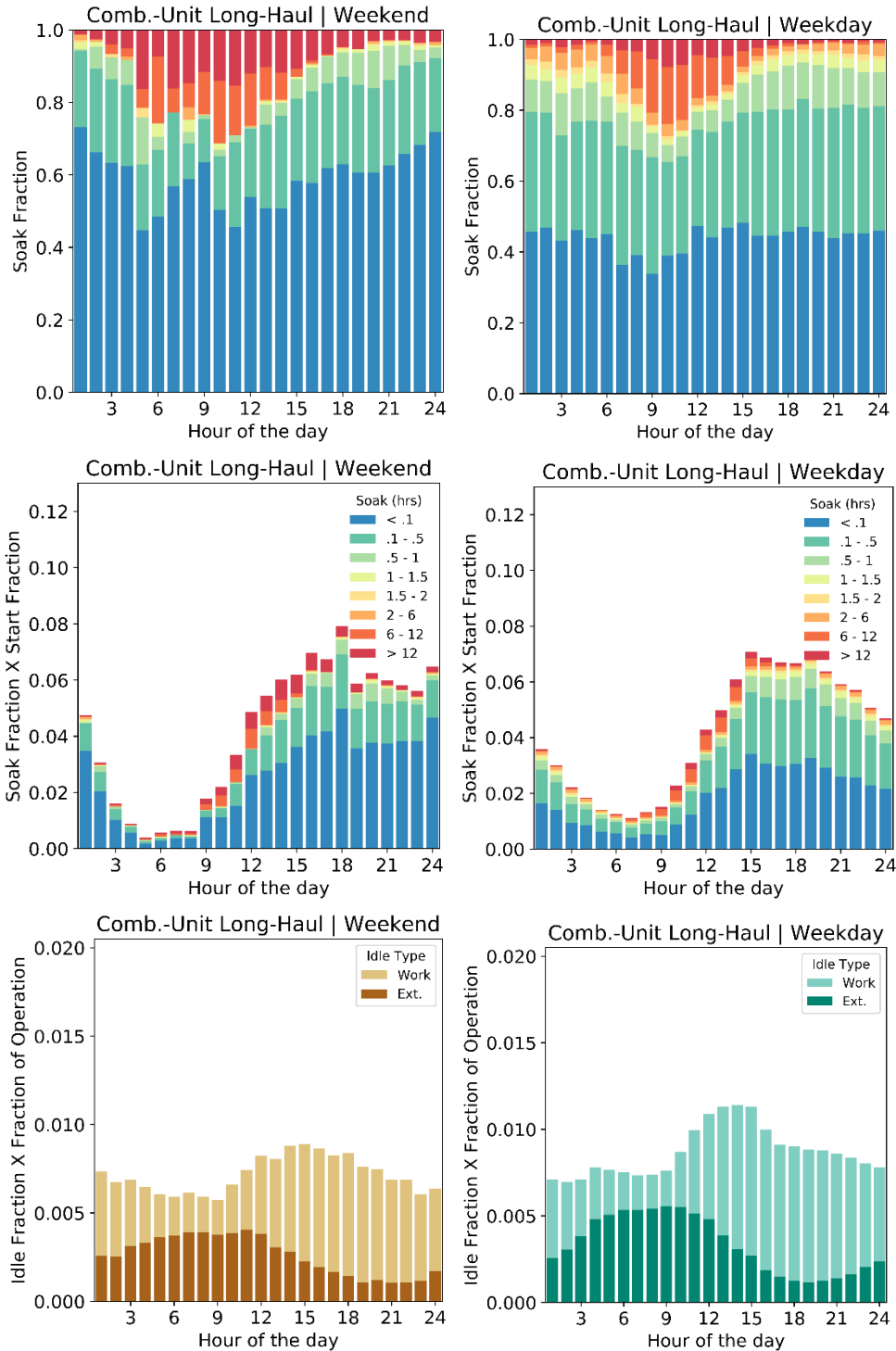


Figure 15. Start, soak and idle performance of combination-unit long haul in current Fleet DNA

3.3 Comparison Between Fleet DNA and CE-CERT Results

Within these two databases, there are five vehicle types in common: other bus, transit bus, refuse, single-unit short haul, and combination-unit short haul. Because EPA classified all of the combination vehicles from the CE-CERT data set as combination-unit short haul trucks, the

combination-unit long haul trucks from Fleet DNA, including the additional 64 combination-unit long-haul vehicles recently added to Fleet DNA, are not included in this comparison, nor are school buses from the Fleet DNA database. Table 11 lists the related statistics for these five types that are compared. In CE-CERT, airport shuttles are identified as “other bus” in the MOVES model, although their driving behavior is assumed to be similar to the transit bus type currently in MOVES3.

Table 11. Statistical Comparisons Between Fleet DNA and CE-CERT Data

Vehicle Types	Fleet (# of vehicles)	Daily Operation	Starts per Day	Workday Idle	Extended Idle
Other bus^a	Fleet DNA (#16)	9.04 hours	9.26	36.84%	2.34%
	CE-CERT (#5)	8.73 hours	10.07	50.52%	0.83%
Transit bus	Fleet DNA (#16)	9.04 hours	9.26	36.84%	2.34%
	CE-CERT (#5)	9.13 hours	8.69	31.08%	13.45%
Refuse	Fleet DNA (#37)	5.19 hours	6.11	47.13%	0.04%
	CE-CERT (#6)	6.13 hours	4.92	46.07%	1.53%
Single-unit short haul	Fleet DNA (#119)	3.07 hours	44.44	32.12%	2.42%
	CE-CERT (#30)	3.73 hours	8.38	38.77%	2.46%
Combination-unit short haul	Fleet DNA (#106)	6.55 hours	20.34	31.32%	1.21%
	CE-CERT (#38)	6.45 hours	13.22	31.22%	2.01%

^a Transit bus in the Fleet DNA is compared with the “other bus” type in CE-CERT data because there is no “other bus” type in the Fleet DNA data set.

As can be seen in Table 11, the daily operation and starts per day for the other bus, transit bus and refuse truck types are quite similar between these two databases, although the idle performance is distinct. For the other bus type, the vehicles from CE-CERT have a higher fraction of workday idle and lower extended idle fraction. Noted again that the other bus type includes airport shuttle and car parking lot shuttle vehicles that are usually driven continuously between airport and parking lots. Conversely, the transit bus and refuse trucks in CE-CERT data had a similar workday idle fraction and much longer extended idle fraction compared to Fleet DNA.

The statistical information related to single- and combination-unit short hauls are almost identical between these two data sets. The only apparent difference is the average starts per day in the single-unit short haul—Fleet DNA has 44.44 and CE-CERT has only 8.38. The reason for this difference comes from the fact that the single-unit short-haul type in Fleet DNA includes parcel delivery trucks with over 100 engine starts per day. Such a high number of starts per day is likely caused by specific fleet policy that asks drivers to turn off the engine while delivering parcels to customers.

In the following subsections, the detailed weekday starts and idle performance from all the vehicle types in both the Fleet DNA and CE-CERT databases will be illustrated for a clear

comparison. Other related figures, including the corresponding driving performance on weekends and average start per day distributions, are available in Appendices D–I.

3.3.1 Other Bus

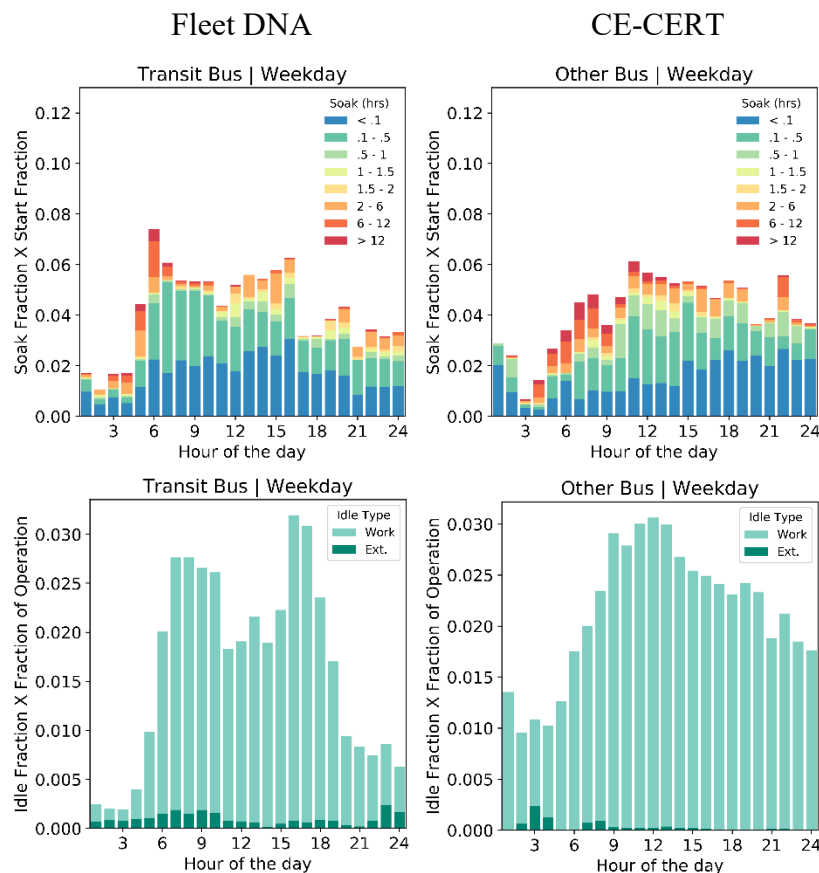


Figure 16. Comparisons of start, soak, and idle performance of other buses on weekdays

The start, soak, and idle performance of the “other bus” on weekdays are shown in Figure 16. In the absence of “other buses” in the Fleet DNA data, we compared “other buses” in CE-CERT data with transit buses in Fleet DNA. Overall, the start distributions are similar. However, the transit bus in Fleet DNA has a start peak around 6 a.m. and much fewer starts after 6 p.m., whereas the “other bus” in CE-CERT has a relatively even start distribution from 11 a.m. to 10 p.m. The soak distribution is even closer between these two. The fraction of longer soak period is slightly higher in the “other bus” type in CE-CERT compared to the transit bus in Fleet DNA.

Referring to idle performance, both vehicle types have a broad idle peak during normal business hours (it seems transit bus in Fleet DNA has two peaks at the start and end of the business day). Meanwhile, the transit bus in Fleet DNA may operate in extended idle mode in each hour of the day. The “other bus” in CE-CERT only has extended idle operation during the early morning (3–8 a.m.).

3.3.2 Transit Bus

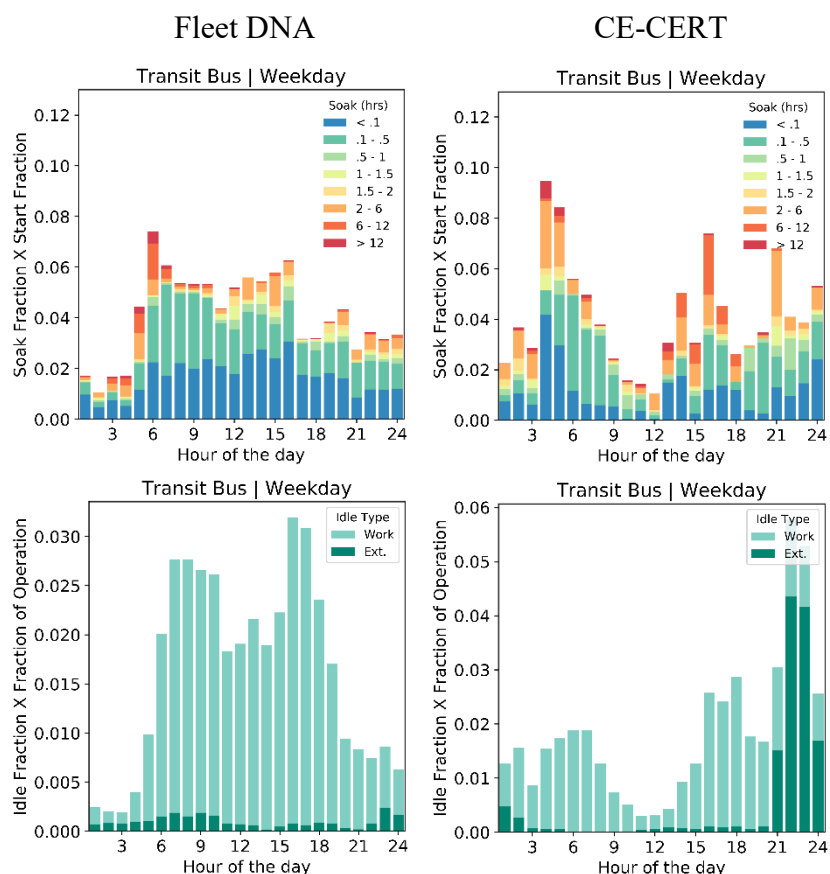


Figure 17. Comparisons of start, soak, and idle performance of transit buses on weekdays

Figure 17 shows the weekday start, soak, and idle performance of the transit bus from the two databases. It is surprising that the driving behaviors from this vehicle type are so different at first glance. For example, the transit bus in Fleet DNA has a higher start fraction during business hours, with the peak around 6 a.m., whereas the CE-CERT data have much fewer starts from 8 a.m. to noon but frequent starts at night. Meanwhile, there is a large fraction of idle operation (mostly extended idle) during the middle of the night for the transit bus in CE-CERT data, whereas the counterpart in Fleet DNA has no such phenomenon.

An in-depth background check then revealed that the transit buses in CE-CERT were actually intercity transit buses that usually transport passengers from one city to the other, rather than metro-city transit buses, which mainly operate in downtown areas with frequent stops. The high fraction of start and idle operation in the CE-CERT data can then be explained. It is highly possible that such a transit bus needs to wait in the bus terminal for a long time to pick up passengers during the night.

3.3.3 Refuse

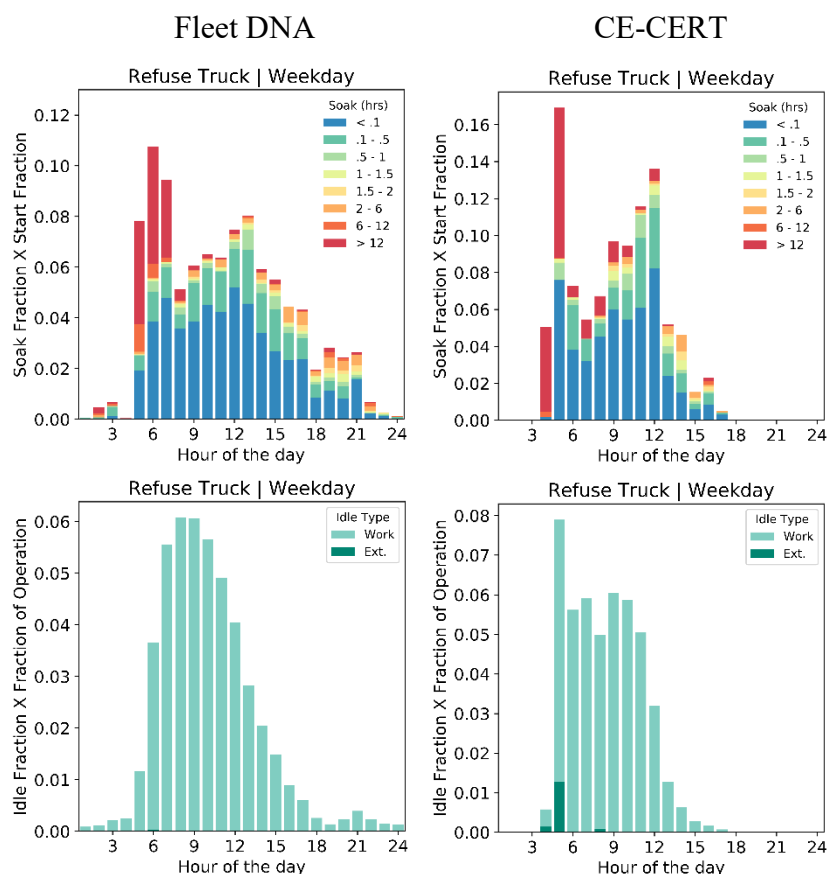


Figure 18. Comparisons of start, soak, and idle performance of refuse trucks on weekdays

The analytical results for refuse trucks are shown in Figure 18. It is apparent that the driving behaviors of refuse trucks are similar between these two databases, especially the idle performance. From the start and soak distributions, the refuse trucks from Fleet DNA have a start peak around 6 a.m., whereas the CE-CERT data have two start peaks around 5 a.m. and noon. However, the longer soak events (>12 hours) are mainly in the early hour starts for both databases. In addition, there is an almost identical normal distribution of idle operation for refuse trucks from both databases. However, trucks from CE-CERT data have a limited extended idle operation around 4–5 a.m., whereas trucks from Fleet DNA never operate in this idle mode.

3.3.4 Single-Unit Short Haul

The start, soak, and idle performance of the single-unit short haul on weekdays from both databases are shown in Figure 19. The start distributions from these two are clearly close, but the peak in the CE-CERT data is slightly later compared to Fleet DNA. However, the soak fraction distributions are distinct. In the Fleet DNA data, the short soak events that last less than 6 minutes dominate, whereas in the CE-CERT data, the fraction of soak events within 1 hour is much higher. A thorough investigation on the dominance of short soak periods in the Fleet DNA data revealed that this phenomenon is mainly caused by the specific driving behaviors of parcel delivery trucks. Such trucks conduct frequent engine-off events and engine starts (can be over 100 times per day) while delivering packages to customers, and each stop may only last about 1–

2 minutes. This result also implies that because multiple vocations are included in this vehicle type, a vocation-based investigation may be necessary to obtain more accurate insights.

The idle distributions are also similar, although the CE-CERT vehicles have a more apparent idle operation peak during normal business hours. In addition, in each hour of the day, the Fleet DNA vehicles may operate in extended idle mode. However, such an idle mode can only be seen clearly during normal business hours in the CE-CERT data.

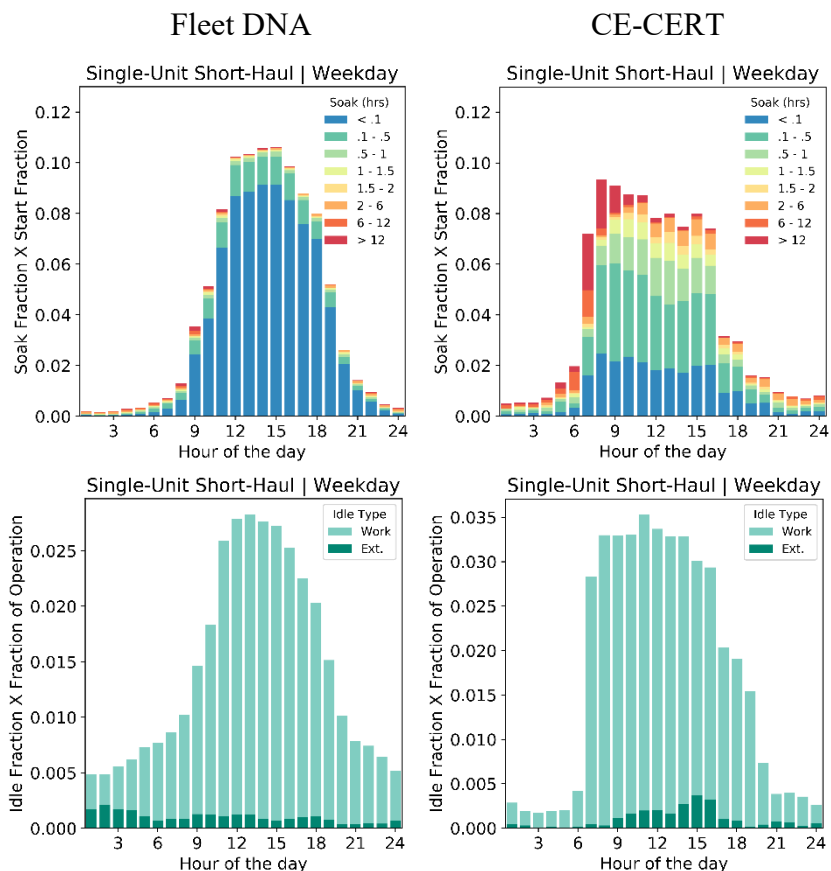


Figure 19. Comparisons of start, soak, and idle performance of single-unit short haul on weekdays

3.3.5 Combination-Unit Short Haul

The comparisons of the start, soak, and idle performance from the combination-unit short hauls are presented in this subsection (Figure 20). In general, the driving behaviors are comparable between these two databases. During normal business hours, the trucks in Fleet DNA have an even start distribution, whereas the trucks in CE-CERT have two minor peaks around 9 a.m. and 3 p.m. Furthermore, both the soak and idle distributions are similar from the two databases. These results indicate that the driving patterns of this vehicle type are fairly identical, and the variation in the data sets are not significant enough to see large differences between the two data sets.

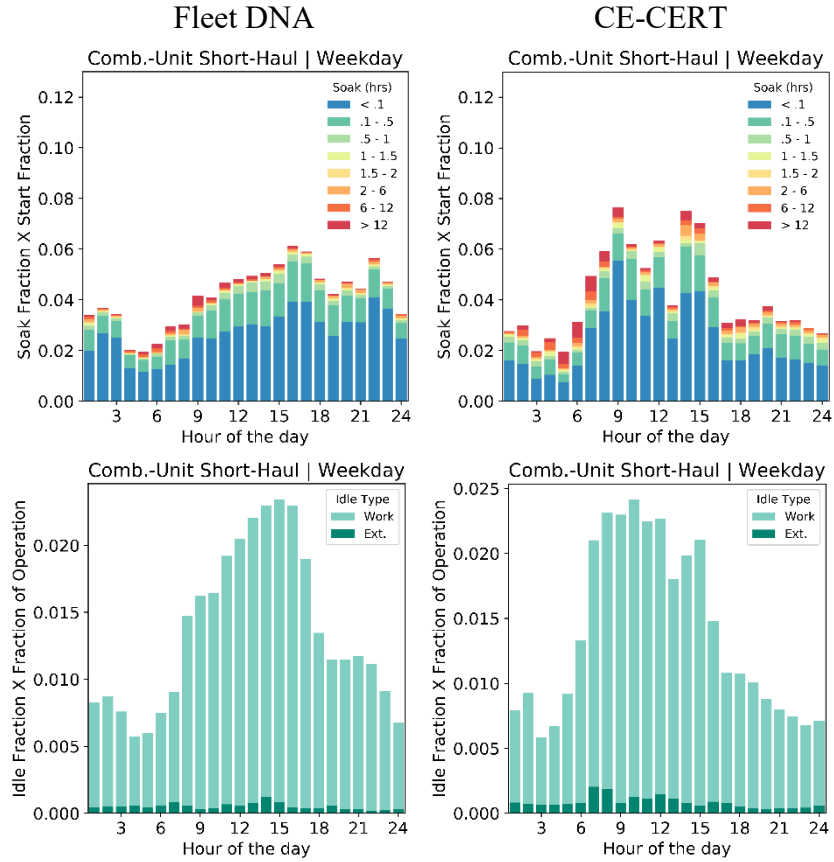


Figure 20. Comparisons of start, soak, and idle performance of combination-unit short haul on weekdays

3.4 Results of Combined Fleet DNA and CE-CERT Data

This section presents the related results from the combined Fleet DNA and CE-CERT data. Table 12 summarizes the averaged results across all seven vehicle types in the combined data set, which includes daily operation time, starts per day, fraction of workday idle and fraction of extended idle.

Table 12. Summary Statistics: Weekday Averages by Vehicle Type in Combined Data Set

Vehicle Type	Daily Operation	Starts per Day	Workday Idle	Extended Idle
Other Bus	8.73 hours	10.07	50.52%	0.83%
Transit Bus	9.06 hours	9.13	35.54%	4.85%
School Bus	2.45 hours	13.03	31.26%	0.18%
Refuse	5.68 hours	5.66	47.01%	0.22%
Single-Unit Short-Haul	3.42 hours	30.68	33.27%	2.42%
Combination-Unit Short-Haul	6.50 hours	17.80	31.29%	1.40%
Combination-Unit Long-Haul	9.77 hours	9.81	12.81%	8.05%

It should be noted that the “other bus” category is only within the CE-CERT data and the school bus and combination-unit long-haul categories are only within the Fleet DNA data. The combination-unit long-haul category also includes the additional 64 vehicles from the new Fleet DNA projects.

Similar to the Fleet DNA data set, single-unit short-haul vehicles showed the largest number of starts per day, whereas the refuse truck and combination-unit long-haul vehicles showed the fewest. Furthermore, the combination-unit long-haul, other bus, and transit bus types had the longest daily operation hours—over 8 hours—whereas the refuse and combination-unit short-haul types had 6 hours daily operation and single-unit short-haul types only averaged around 3–4 hours per day. School buses showed the shortest operation time with only about 2.45 hours. Almost all the vocations had 30%–50% working idle and less than 5% extended idle, except combination-unit long hauls, which had 12.81% working idle and 8.05% extended idle.



Figure 21. Soak fraction multiplied by start fraction vs. hour of the day for weekdays (combined data)

The detailed analyses start with the examination of start, idle, and soak fractions of each vehicle type. Figure 21 shows the similar vehicle type-specific start fraction multiplied by the soak bin fraction as a function of hour of the day for weekdays in the combined data set. Because the “other bus” category is only included in the CE-CERT data set, the related result is already shown in Figure 2.

It is clear that the results from the combined data set are fairly close to the original Fleet DNA data set (see Appendix G), which indicates that the combined results are dominated by the Fleet

DNA data set due to its larger number of vehicles sampled for each source type. For most MOVES source and day types, the distribution of the start fraction from all vocations is almost identical to Fleet DNA results, whereas the soak fraction in each hour bin may be marginally affected. These results are intuitive because the number of vehicles across all vocations in Fleet DNA are much larger compared to the CE-CERT data. The averaging method we used (Method 3 in Appendix C) calculates the start and soak fractions by weighting each vehicle according to its daily average start activity. If we had start and soak fractions by weighting each vehicle according to the total measured start activity (Method 2 described in Appendix C), we would expect a larger effect of the CE-CERT data on the combined results because on average the CE-CERT vehicles were instrumented for almost three times as many days as the vehicles in the Fleet DNA database.

Figure 22 shows the workday and extended idle fractions by vehicle and day types from the combined data. The definition of extended idle and workday idle are fixed, as shown in Figure 3. It is clear from Figure 22 that both “other” bus and refuse pickup trucks have the longest idle fraction from weekend and weekday. The combination-unit long haul has the largest extended idle fraction on weekdays but the shortest idle fraction if we looked at the combined extended and workday idle fractions together. Another observation is that all the transit bus, refuse pickup, and single-unit short-haul types have much longer extended idle fractions on weekends compared to their weekday counterparts. These results reflect clearly different driving behaviors on weekends compared to weekdays in these vocations.

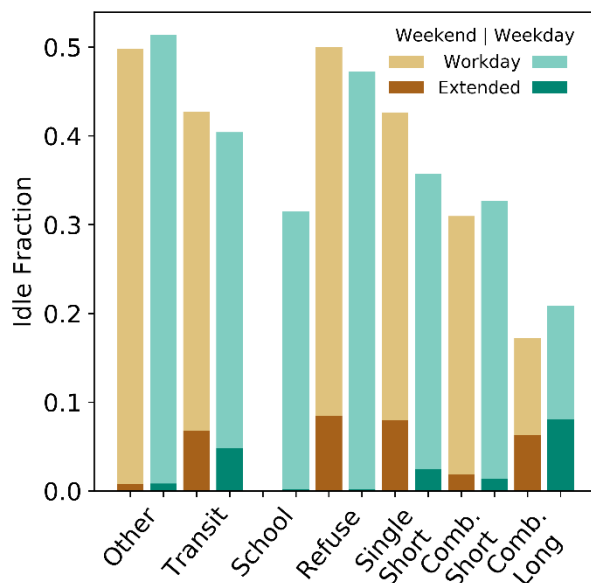


Figure 22. Extended and workday idle fractions vs. day type and vehicle type (combined data)

To gain a better understanding of idle fraction, Figure 23 examines weekday idle fraction multiplied by the fraction of operation as a function of hour and vehicle type, similar to Figure 4. Again, the result for “other bus” is not shown here because this category only exists in the CE-CERT data and can be found in Figure 4. Compared to the Fleet DNA data set, these results have some variation caused by adding the results from CE-CERT data. One clear observation occurs in transit bus—although the extended idle are fairly small in Fleet DNA, the combined data

shows a high fraction of extended idle fraction from 9 p.m. to midnight. Another observation is that both single-unit short-haul and combination-unit short-haul categories have an increased fraction of operation between 9 a.m. and 4 p.m. in the combined data set. The rest of results are similar between the Fleet DNA and combined data set. Similar plots showing the hourly extended and workday idle fractions of each vehicle type on weekends from the combined data set are provided in Appendix K.

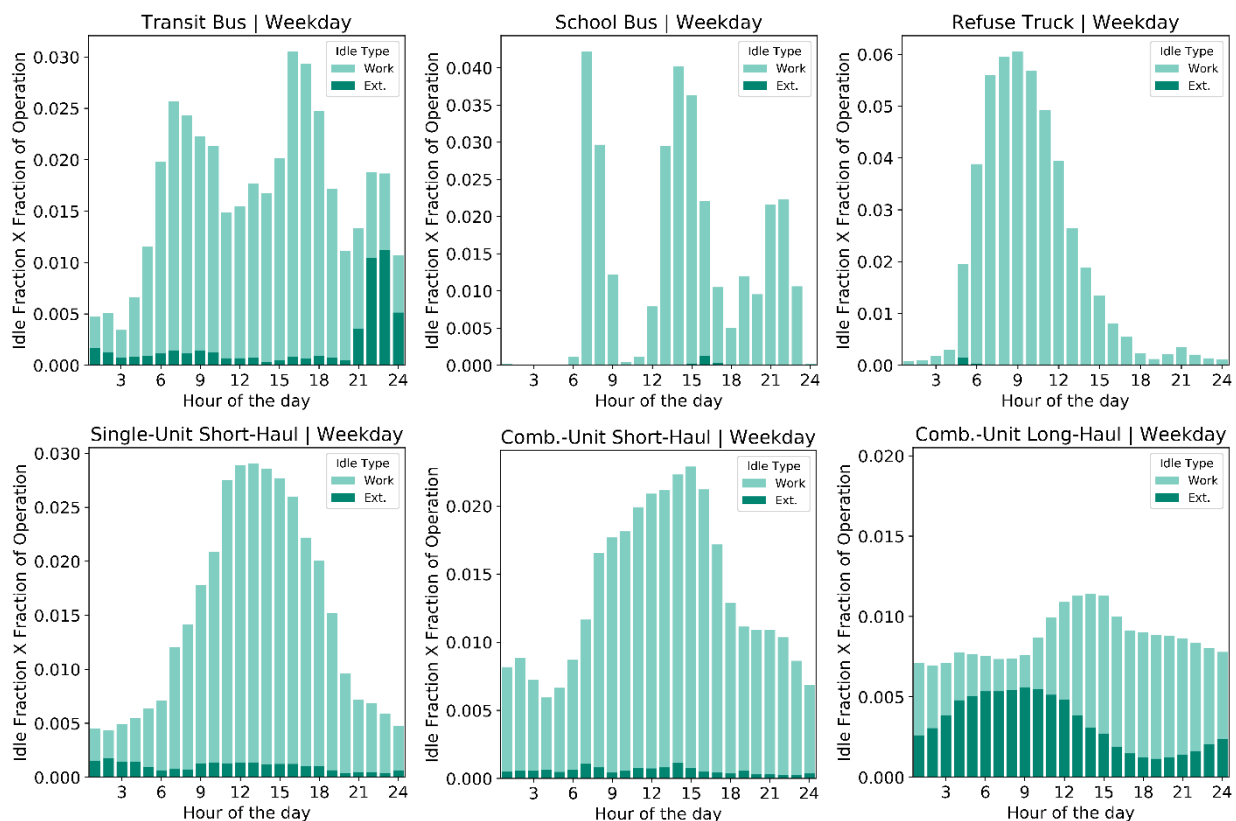


Figure 23. Extended and workday idle fractions vs. vehicle type for weekdays

We believe that integrating more fleet data, like CE-CERT, into Fleet DNA would be beneficial for characterizing each vocation’s driving behavior. In general, including additional data should make the average activity statistics more representative of the national fleet, but this may not always be the case. For example, the CE-CERT transit buses had a high amount of activity between 9 p.m. and midnight, which may not be representative of the national transit fleet. However, by providing these combined data, users can intentionally exclude individual vehicles (e.g., based on vocation, geographic location) and select the vehicles that are most representative of the vocation or area they are most interested in representing.

4 Conclusion

This analysis used heavy-duty activity data collected from CE-CERT to provide additional heavy-duty fleet information (complemented with information from NREL’s Fleet DNA database) as inputs informing EPA’s MOVES model. Five of the nine MOVES heavy-duty vehicle types were available in the CE-CERT database, providing data from 84 heavy-duty vehicles with over 76,000 days of operation. Start fraction, soak fraction, and idle fraction by

hour of the day were derived for each vehicle type. Vocation-based investigations were also specifically conducted with the single- and combination-unit short-haul vehicles.

In addition, this analysis from the CE-CERT database is also compared with the corresponding results from conventional heavy-duty vehicles analyzed from the Fleet DNA database, which added activity from 64 combination-unit long-haul vehicles. The comparison between these two databases reflects that the driving behaviors of each vehicle type are comparable, which validate, to some extent, the fidelity of the inputs from both databases. The related analytical results of the combined data (including both Fleet DNA and CE-CERT data) were also documented in this report for reference.

Despite the large number of vehicles sampled, substantial variability of activity is still measured across vocations within the MOVES source types. For example, parcel delivery trucks within the MOVES single-unit short-haul truck source type have much higher starts per day than the other vocations (see Appendix L). Vehicle population data of truck vocations are needed to better develop representative national activity estimates for MOVES source types (see discussion in Appendix C). In addition, this information would help prioritize future vehicle instrumentation studies to target truck vocations that are underrepresented in current activity estimates.

References

Boriboonsomsin, Kanok, Kent Johnson, George Scora, Daniel Sandez, Alexander Vu, Tom Durbin, Yu (Jade) Jiang, and Andrew Burnette. 2017. *Collection of Activity Data from On-Road Heavy-Duty Diesel Vehicles*. Riverside, CA: University of California at Riverside, College of Engineering, Center for Environmental Research & Technology (CE-CERT).

<http://ww3.arb.ca.gov/research/apr/past/13-301.pdf>.

California Air Resources Board. 2008. "California's Heavy-Duty Diesel Vehicle Idling Regulations." <https://www.ncsl.org/print/energy/dchenidling07.pdf>.

Kotz, Andrew and Kenneth Kelly. 2019. *MOVES Activity Updates Using Fleet DNA Data: Interim Report*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-70671. <https://www.nrel.gov/docs/fy19osti/70671.pdf>.

National Renewable Energy Laboratory (NREL). 2019. "Fleet DNA Project Data." <http://www.nrel.gov/fleetdna>.

SAE International. 2010. *Recommended Practice for a Serial Control and Communications Vehicle Network*. Warrendale, PA: SAE International. Ground Vehicle Standard J1939_201002. https://saemobilus.sae.org/content/J1939_201002/.

U.S. Environmental Protection Agency (EPA). 2003. A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information. EPA/100/B-03/001. Prepared for the U.S. Environmental Protection Agency by members of the Assessment Factors Workgroup, a group of the EPA's Science Policy Council Washington, D.C. June 2003. <https://www.epa.gov/risk/summary-general-assessment-factors-evaluating-quality-scientific-and-technical-information>.

———. 2016. *Population and Activity of On-road Vehicles in MOVES2014*. Washington, D.C.: EPA Office of Transportation and Air Quality, Assessment and Standards Division. EPA-420-R-16-003a. <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O7PS.pdf>.

———. 2020a. "MOtor Vehicle Emission Simulator (MOVES)." Washington, D.C.: EPA. <https://www.epa.gov/moves>.

———. 2020b. *Population and Activity of Onroad Vehicles in MOVES3*. Washington, D.C.: EPA Office of Transportation and Air Quality, Assessment and Standards Division. EPA-420-R-20-023. <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1010MSS.pdf>.

Appendix A: MOVES Definitions

Table A1. MOVES Road Types

MOVES Road ID	Road Type	FHWA Functional Types
1	Off Network	Off Network
2	Rural Restricted Access	Rural Interstate
3	Rural Unrestricted Access	Rural Principal Arterial, Minor Arterial, Major Collector, Minor Collector, and Local
4	Urban Restricted Access	Urban Interstate and Urban Freeway/Expressway
5	Urban Unrestricted Access	Urban Principal Arterial, Minor Arterial, Collector, and Local

Table A2. Heavy-Duty Vehicle MOVES Vehicle Types

MOVES Vehicle ID	Vehicle Type
41	Intercity Buses (non-school, non-transit)
42	Transit Buses
43	School Buses
51	Refuse Trucks
52	Single-Unit Short-Haul Trucks
53	Single-Unit Long-Haul Trucks
54	Motor Homes
61	Combination Short-Haul Trucks
62	Combination Long-Haul Trucks

Table A3. MOVES Day Types

MOVES Day ID	Day Type
2	Weekend Days: Saturday and Sunday
5	Weekdays: Monday through Friday

Table A4. MOVES Hour Types

MOVES Hour ID	Hour
1	Hour beginning at 12:00 midnight
2	Hour beginning at 1:00 a.m.
3	Hour beginning at 2:00 a.m.
4	Hour beginning at 3:00 a.m.
5	Hour beginning at 4:00 a.m.
6	Hour beginning at 5:00 a.m.
7	Hour beginning at 6:00 a.m.
8	Hour beginning at 7:00 a.m.
9	Hour beginning at 8:00 a.m.
10	Hour beginning at 9:00 a.m.
11	Hour beginning at 10:00 a.m.
12	Hour beginning at 11:00 a.m.
13	Hour beginning at 12:00 noon
14	Hour beginning at 1:00 p.m.
15	Hour beginning at 2:00 p.m.
16	Hour beginning at 3:00 p.m.
17	Hour beginning at 4:00 p.m.
18	Hour beginning at 5:00 p.m.
19	Hour beginning at 6:00 p.m.
20	Hour beginning at 7:00 p.m.
21	Hour beginning at 8:00 p.m.
22	Hour beginning at 9:00 p.m.
23	Hour beginning at 10:00 p.m.
24	Hour beginning at 11:00 p.m.

Table A5. MOVES Soak Time Operation Modes

MOVES Bin ID	Soak Length Bin Description
101	Soak Time < 6 minutes
102	6 minutes ≤ Soak Time < 30 minutes
103	30 minutes ≤ Soak Time < 60 minutes
104	60 minutes ≤ Soak Time < 90 minutes
105	90 minutes ≤ Soak Time < 120 minutes
106	120 minutes ≤ Soak Time < 360 minutes
107	360 minutes ≤ Soak Time < 720 minutes
108	720 minutes ≤ Soak Time

Appendix B: Gap Length Analysis

As mentioned in Section 2.2.2, when a gap occurred in the time stamp of the recorded vehicle activity without a corresponding engine start (the engine speed did not fall to 0 rpm), we implemented an algorithm that would add an engine start (by setting the engine speed to 0 rpm) depending on the length of the gap in the time stamp (referred to as the gap length). Previously, the assumed the gap length is set as 6 hours. However, in this revision, we have revisited this assumption to assume that vehicles turned off if the gap is greater than 2 seconds. We believe this revision more accurately measures the real-world activity.

The following table lists the starts per day of the original long haul fleet in Fleet DNA and the additional long haul fleet derived from the two time gap assumptions. As can be seen, using the 6 hour time gap assumption, the original long haul fleet possess much less starts per day in both weekday and weekends, compared to the additional long haul data via the same method. When we change the time gap assumption to 2 seconds, the corresponding starts per day in original long haul truck is still lower than the additional long haul fleet, but the average starts are much more comparable.

Table B1. Starts per Day Comparison Across Different Fleets and Different Time Gaps Assumption

Case	Start per day [weekday]	Start per day [weekend]
Original long haul with 6 hour time gap	0.81	0.60
Original long haul with 2 second time gap	8.98	6.12
Additional long haul with 6 hour time gap	15.52	17.27
Additional long haul with 2 second time gap	17.40	19.27

We also evaluated the impact of the time gap assumption on the resulting the start and soak distributions across the four cases above, as shown in Figure B1 and Figure B2. Figure B1 shows that the start and soak distributions from these two fleets are completely distinct if we use the 6 hour time gap assumption: the original long haul fleet possesses dominated long soak (over 12 hours) start events across the entire day. However, the start and soak distributions are comparable between the two datasets if we revise the time gap assumption from 6 hours to 2 seconds as shown in Figure B2. Because using the 2 second time gap gives us start data that is more comparable between the two datasets, we believe it is more reflective of the actual start activity behavior for the measured vehicles. We have updated the results in this report using the 2 second gap for all vehicles.

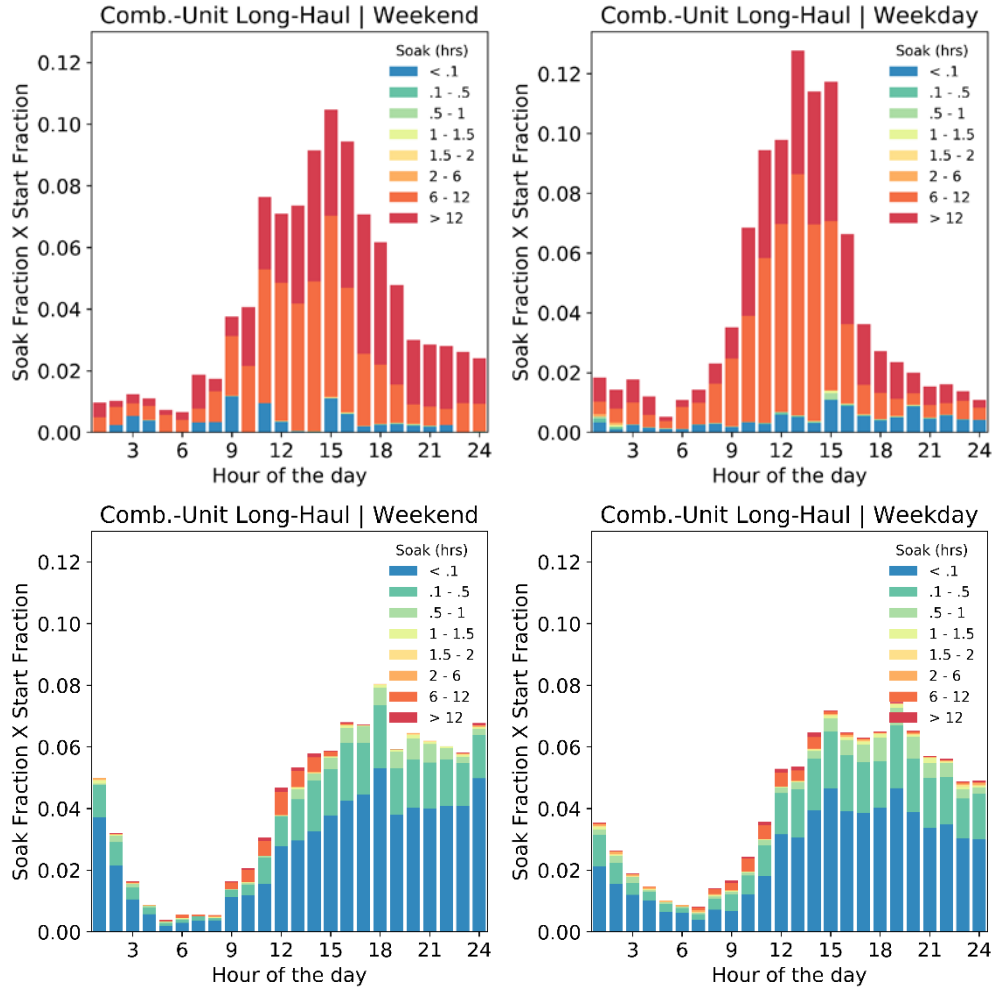


Figure B1. Comparison of start fraction for original (top) and additional (bottom) long haul fleet under 6 hours' time gap assumption

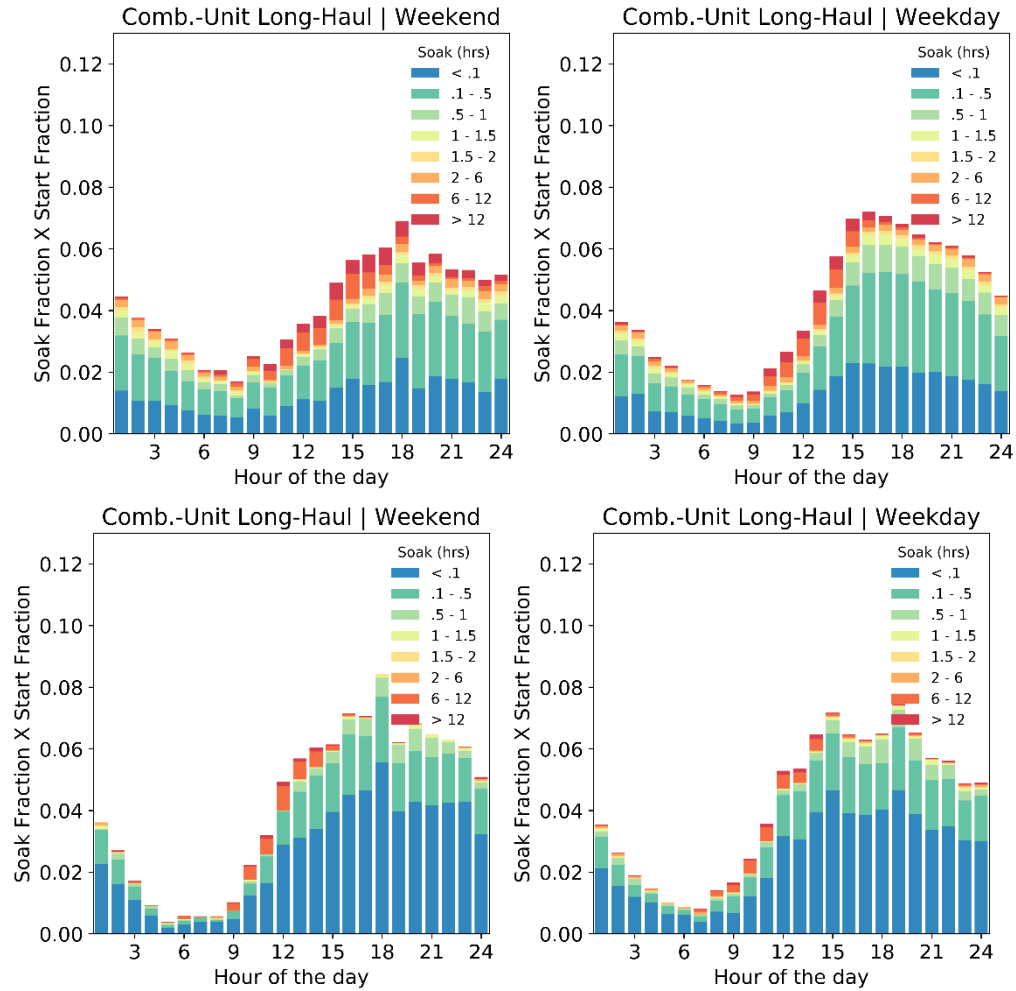


Figure B2. Comparison of start fraction for original (top) and additional (bottom) long haul fleet under 2 seconds' time gap assumption

Appendix C: Averaging Methods Evaluation

The instrumented truck data provide great detail on individual vehicle activity, but to calculate representative national MOVES inputs for heavy-duty starts, soaks, and idle fractions, we need to compute averages across the available data. Because different averaging methods lead to different results, we evaluated several different approaches to calculating these averages. The following discussion uses the calculation of the idle fraction by source type ID and day ID (weekend and weekday) to illustrate the strengths and weaknesses of each method.

Averaging Methods

Initially, we used Method 1 (Equation C1) to average the idle fractions across all vehicles within the same source type ID and day ID (weekday vs. weekend). Method 1 could also be referred to as an average of ratios. We initially chose Method 1 because it is simple to implement and equally weights each vehicle in the sample.

$$\text{Idle fraction}_{s,d} = \frac{\sum \text{Idle fraction}_i}{n} \quad (\text{C1})$$

Method 1 –
“Average
of Ratios”
 $i = \text{individual vehicle ID}$
 $n = \text{vehicles sampled within each source type}$
 $s = \text{source type ID}$
 $d = \text{day type ID}$

However, to estimate a representative idle fraction, the vehicle should be weighted by its contribution to real-world activity. By weighting each individual vehicle idle fraction equally, Method 1 overrepresents the vehicles with little real-world activity (with possibly unrealistic idle fractions) and underrepresents the idle fractions from the vehicles with the most activity.

We then considered Method 2, shown in Equation C2, which is referred to as the “Sum over Sum” method. In Method 2, the average is weighted according to vehicle activity. Vehicles that are operated for long workdays will have more operating hours and idle hours than vehicles that are only operated intermittently. Multiplying the idle fraction estimated from Method 2 by the total operating hours, $\sum \text{operating hours}_i$, will yield the total idle hours, $\sum \text{idle hours}_i$, measured in our sample. This property ensures that the relationship between idle hours and operating time is consistent between our model estimates and the source data.

$$\text{Idle fraction}_{s,d} = \frac{\sum \text{idle hours}_i}{\sum \text{operating hours}_i} \quad (\text{C2})$$

Method 2 –
“Sum over
Sum”
 $i = \text{individual vehicle ID}$
 $s = \text{source type ID}$
 $d = \text{day type ID}$

One disadvantage of Method 2 is that the idle fraction is dependent on the instrumentation time. For example, a vehicle that is instrumented for 2 months will be weighted twice as much in the idle fraction calculation as a vehicle with the same duty cycle that is only measured for 1 month. In some cases, using more information from vehicles that are instrumented longer would be a desirable property; however, if instrumentation times are not random, this can skew the average

to overrepresent certain groups of vehicles. For example, the Fleet DNA data set had an average instrumentation time of 33 days/vehicle and the HD SCR (CE-CERT) data set had a 91-day/vehicle average. Using Method 2 to combine data from these two data sets, the HD SCR vehicle data would be weighted almost three times as much as the vehicles in the Fleet DNA sample. This is undesirable because we have no reason to assume that the HD SCR sample vehicles are more representative of the national fleet than the Fleet DNA sample vehicles.

In Method 3, we propose using a “Normalized Sum over Sum” approach as shown in Equation C3. Method 3 is similar to Method 2, except that the sum of idle hours and the operating hours from each vehicle is divided (or normalized) by the number of days each sample vehicle was instrumented. Method 3 controls for the different lengths of time each vehicle is instrumented, and the idle fraction is weighted most heavily by the vehicles with the most daily average activity, rather than the most measured activity. Method 3 (Equation C3) is the current approach we are using for developing MOVES inputs as presented in Section 2.2.3.

$$\text{Method 3 – “Normalized Sum over Sum”} \quad \text{Idle fraction}_{s,d} = \frac{\sum (\text{idle hours}_i / \text{days}_i)}{\sum (\text{operating hours}_i / \text{days}_i)} \quad (\text{C3})$$

i = individual vehicle ID
days_i = number of days vehicle *i* is instrumented
s = source type ID
d = day type ID

These methods are also applicable to estimating start fractions. The start fraction determines what fraction of total daily starts occur at each hour of the day. The equations for the start fractions for each of the three methods follow:

$$\text{Method 1 – “Average of Ratios”} \quad \text{Start fraction}_{h,s,d} = \frac{\sum \text{Start fraction}_{h,i}}{n} \quad (\text{C4})$$

h = hour of the day
i = individual vehicle ID
n = number of sampled vehicles
s = source type ID
d = day type ID

$$\text{Method 2 – “Sum over Sum”} \quad \text{Start fraction}_{h,s,d} = \frac{\sum \text{starts}_{h,i}}{\sum \text{starts}_i} \quad (\text{C5})$$

h = hour of the day
i = individual vehicle ID
s = source type ID
d = day type ID

$$\text{Method 3 – “Normalized Sum over Sum”} \quad \text{Start fraction}_{h,s,d} = \frac{\sum (\text{starts}_{h,i} / \text{days}_i)}{\sum (\text{starts}_i / \text{days}_i)} \quad (\text{C6})$$

h = hour of the day
i = individual vehicle ID
days_i = days vehicle_{*i*} is instrumented
s = source type ID
d = day type ID

The three different averaging methods were also applied for calculating the soak fractions. The soak fraction determines the distribution of starts occurring for the eight different start operating modes in MOVES (or soak lengths) as defined in Table A5.

$$Soak\ fraction_{h,o,s,d} = \frac{\sum Soak\ fraction_{h,i,o}}{n}$$

Method 1 – *h* = hour of the day
 “Average of *i* = Vehicle ID
 Ratios” *n* = # of sampled vehicles
s = source type ID
d = day type ID

(C7)

$$Soak\ fraction_{h,o,s,d} = \frac{\sum starts_{h,i,o}}{\sum starts_{h,i}}$$

Method 2 – *h* = hour of the day
 “Sum over *i* = Vehicle ID
 Sum” *o* = operating mode (soak length)
s = source type ID
d = day type ID

(C8)

$$Soak\ fraction_{h,o,s,d} = \frac{\sum (starts_{h,i,o} / days_i)}{\sum (starts_{h,i} / days_i)}$$

Method 3 – *h* = hour of the day
 “Normalized *i* = Vehicle ID
 Sum over *o* = operating mode (soak length)
 Sum” *days_i* = days vehicle_{*i*} is instrumented
s = source type ID
d = day type ID

(C9)

Comparison of Evaluated Methods

Figure C1 graphically compares the idle fractions calculated using Method 1 and Method 3 using the data for single-unit short-haul trucks. In the graph, the darker colors represent idling that is over 1 hour in duration, classified as extended idle. The height of the bars represents the total idle fraction. For refuse trucks and single-unit short-haul trucks, there is a significantly higher idle fraction on the weekends when using Method 3. This implies that the refuse and single-unit trucks that operate most on the weekend also have higher idle fractions. Method 3 appropriately weights the idle fractions from each vehicle according to its average daily activity.

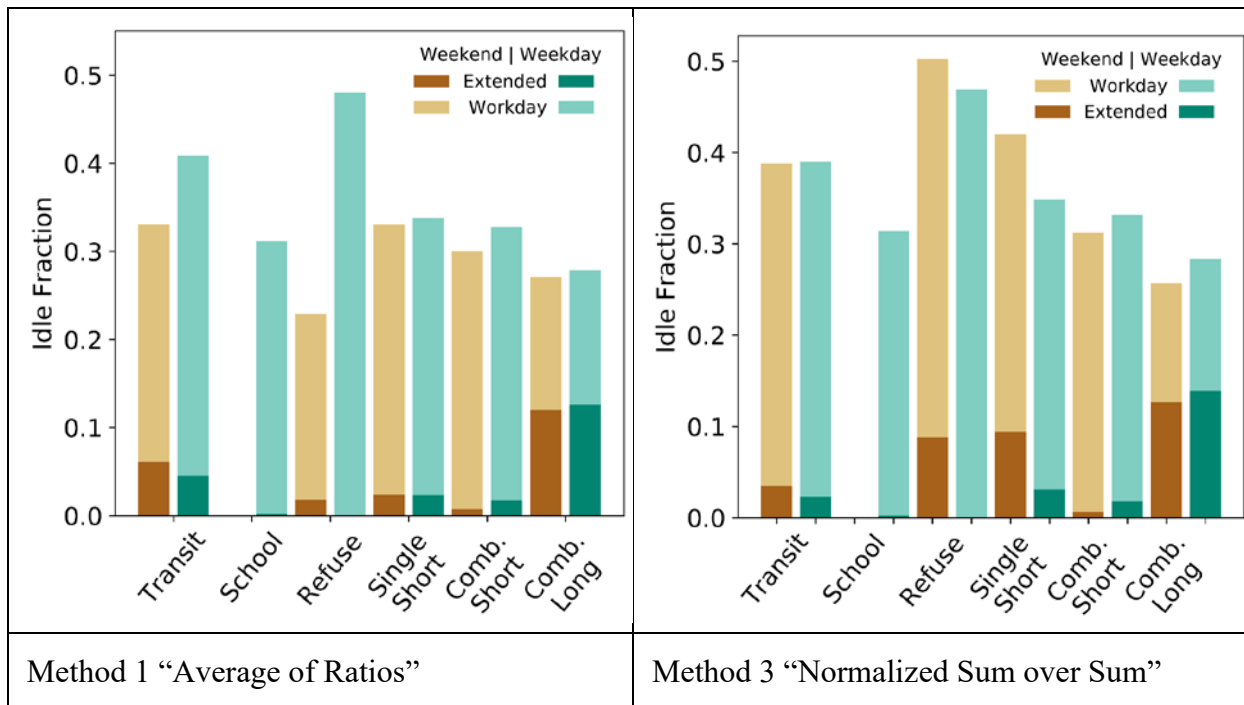


Figure C1. Idle fraction calculated using Method 1 and Method 3

Figure C2 graphically compares the start fractions and soak fractions calculated using Method 1 and Method 3, using the data for single-unit short-haul trucks on weekdays. The start distribution calculated with Method 1 weights all vehicles the same and thus overrepresents the start and soak times of vehicles with fewer starts (and long soak periods). With Method 3, the start and soak distributions more accurately characterize all the starts. The start distribution with Method 3 is dominated by vehicles that have many starts per day. The starts occur more evenly across the workday and have shorter soak periods. Because emission rates increase with longer soak periods, the differences in averaging methods can have significant impacts on both the total emissions and the temporal allocation of the emissions.

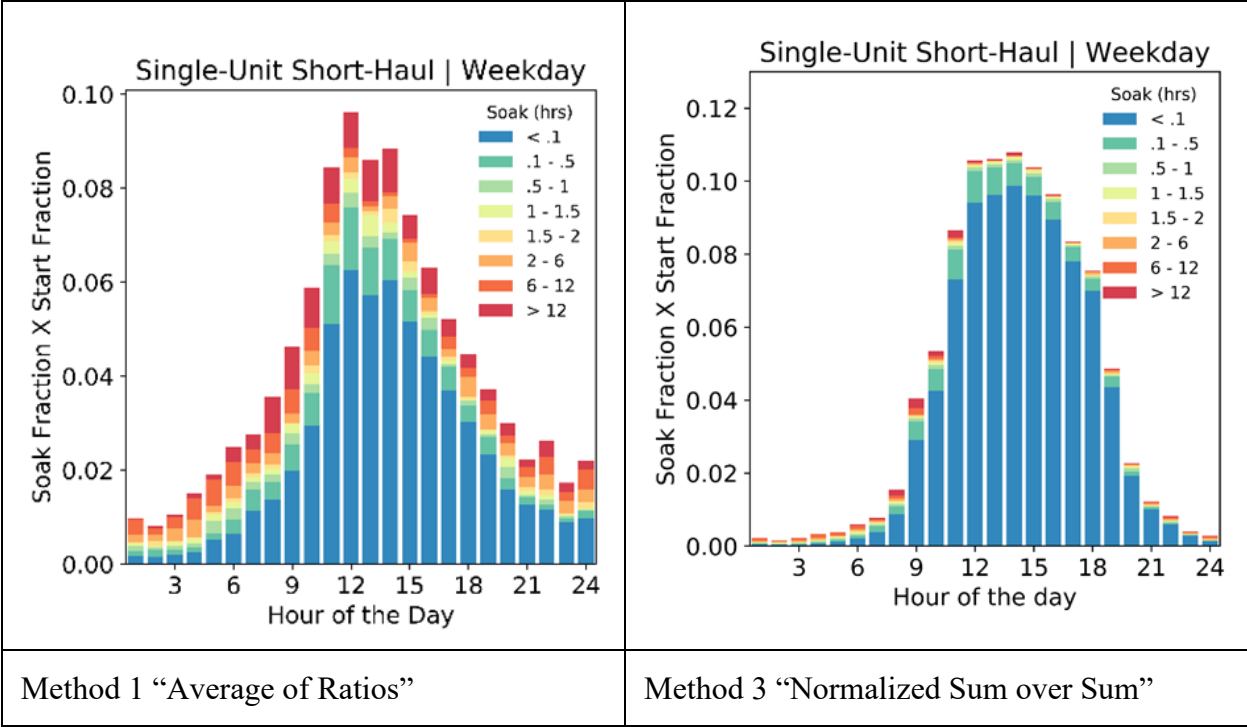


Figure C2. Start and soak fraction calculated using Method 1 and Method 3

Appendix D: Start and Soak Plots – CE-CERT Data

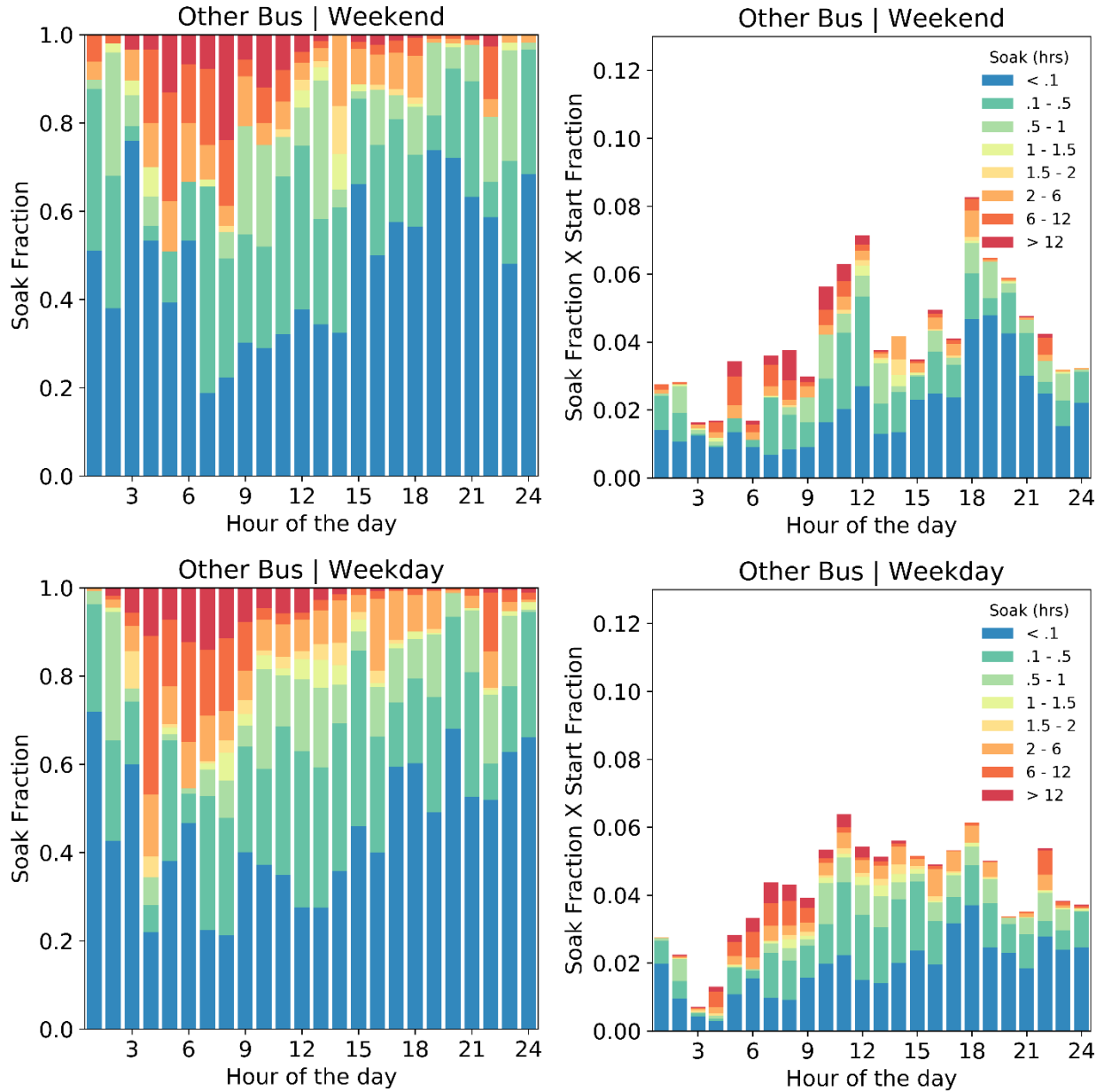


Figure D1. Soak fraction and start fraction vs. hour of the day for “other bus”

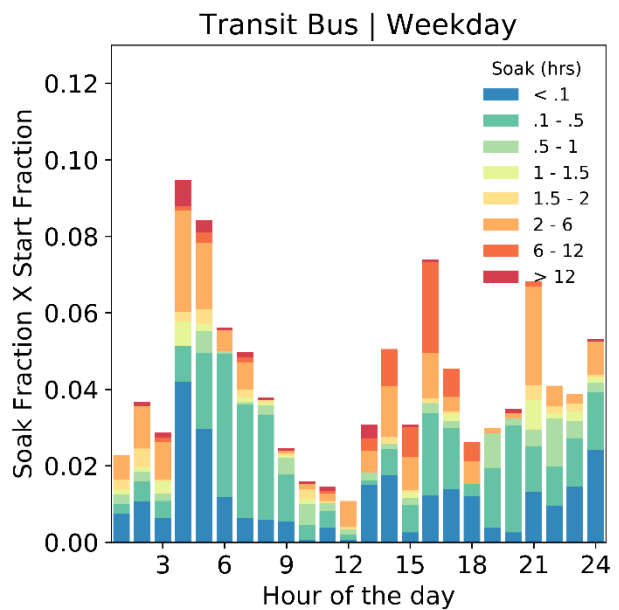
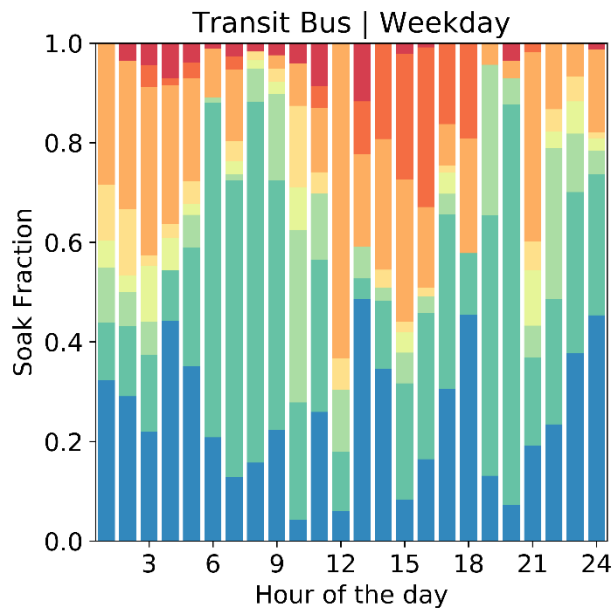
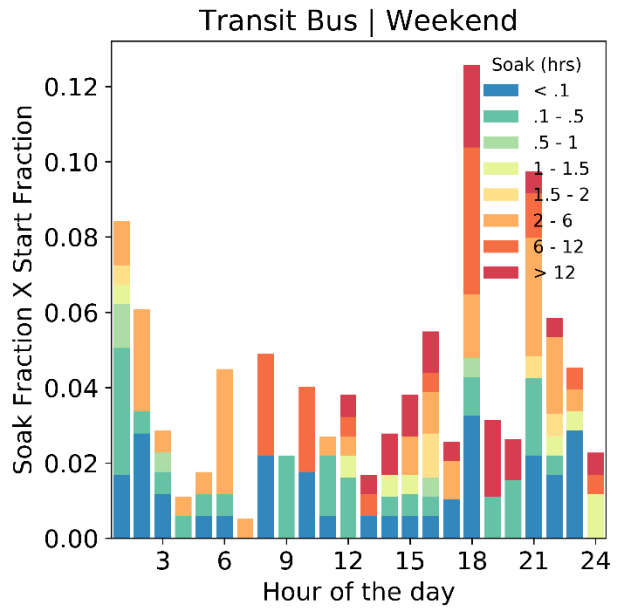
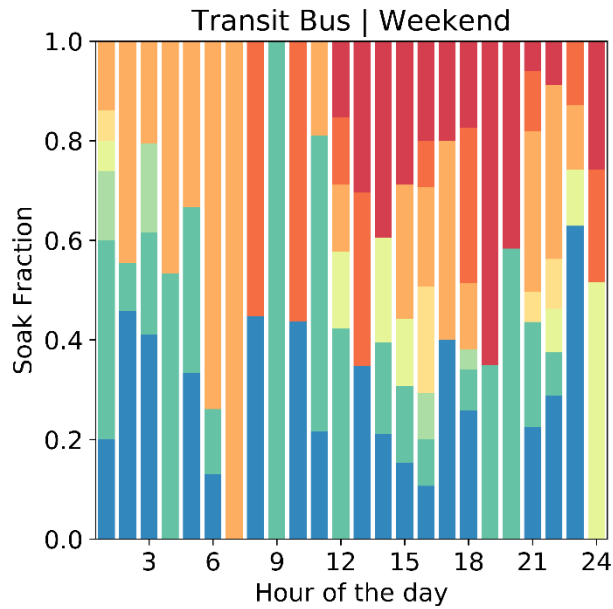


Figure D2. Soak fraction and start fraction vs. hour of the day for transit bus

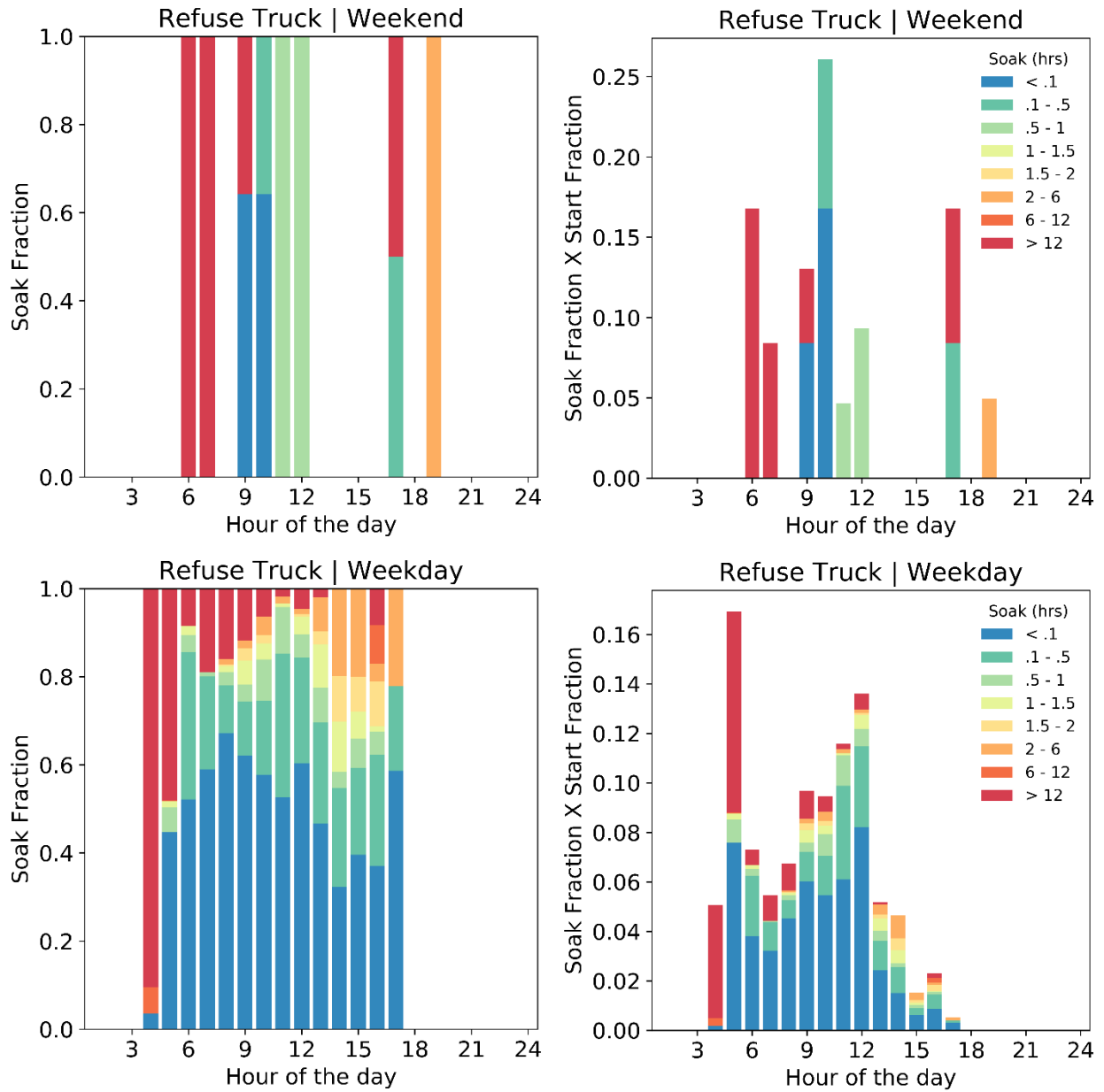


Figure D3. Soak fraction and start fraction vs. hour of the day for refuse truck

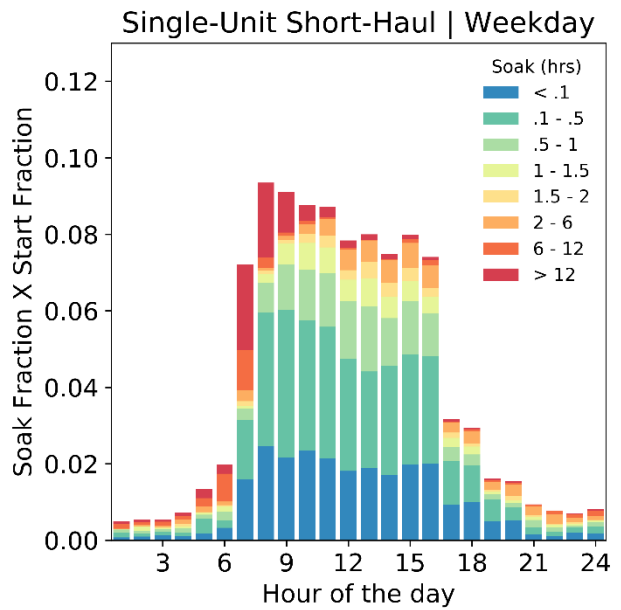
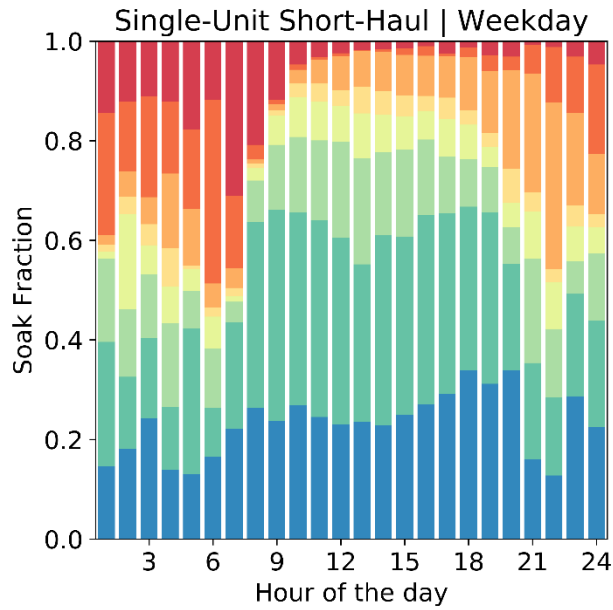
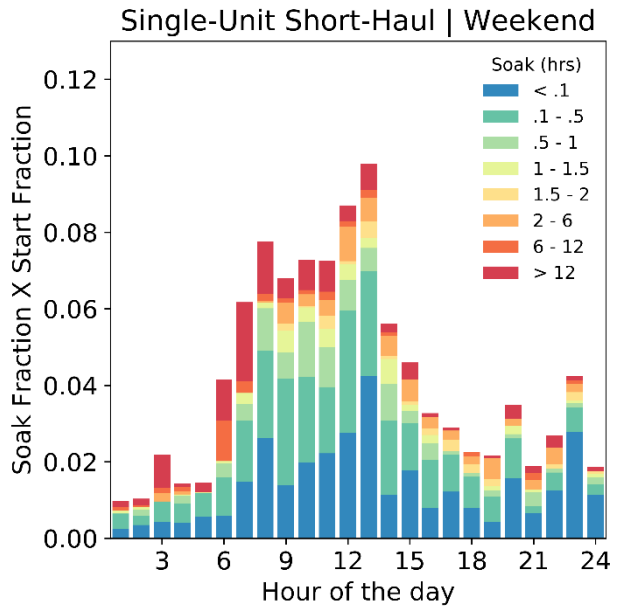
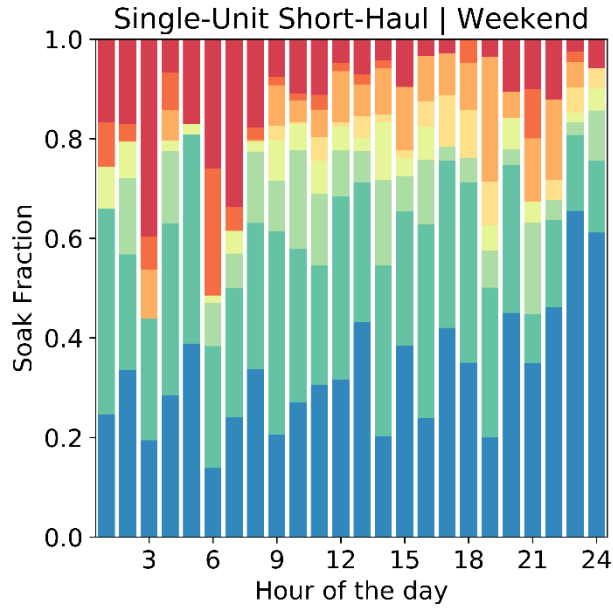


Figure D4. Soak fraction and start fraction vs. hour of the day for single-unit short haul

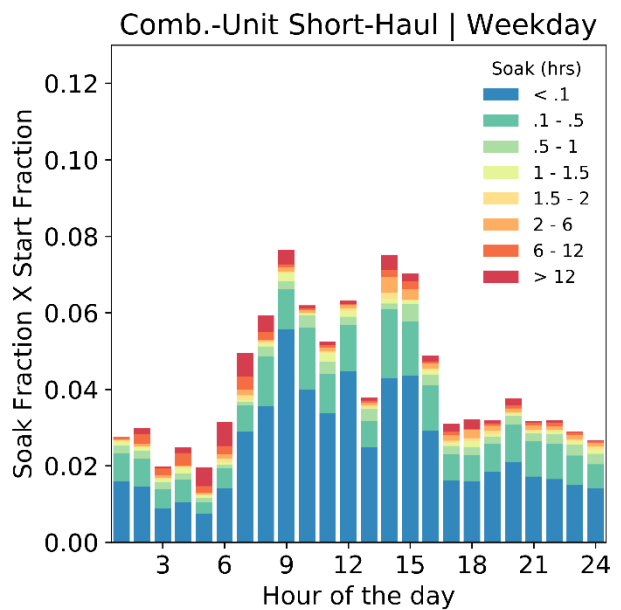
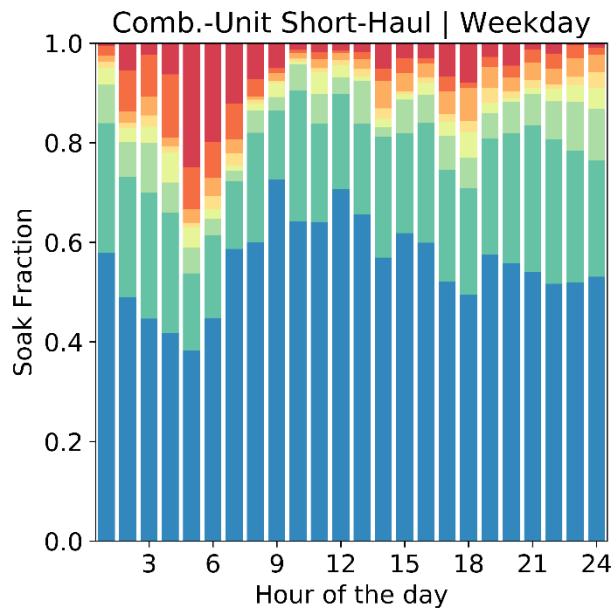
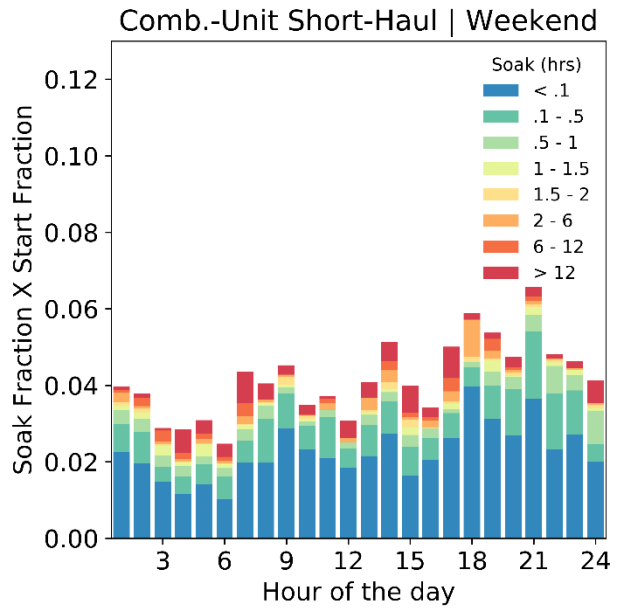
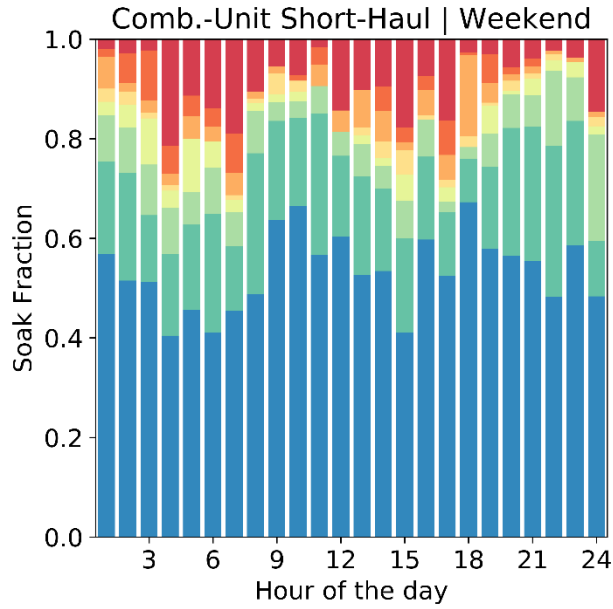


Figure D5. Soak fraction and start fraction vs. hour of the day for combination-unit short haul

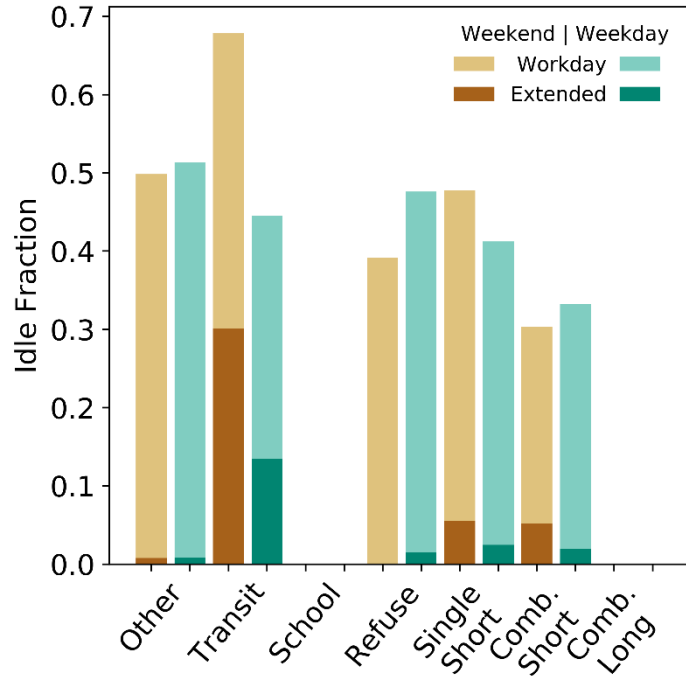


Figure D6. Extended and workday idle fractions vs. day type and vehicle type

Appendix E: Hourly Idle Plots – CE-CERT Data

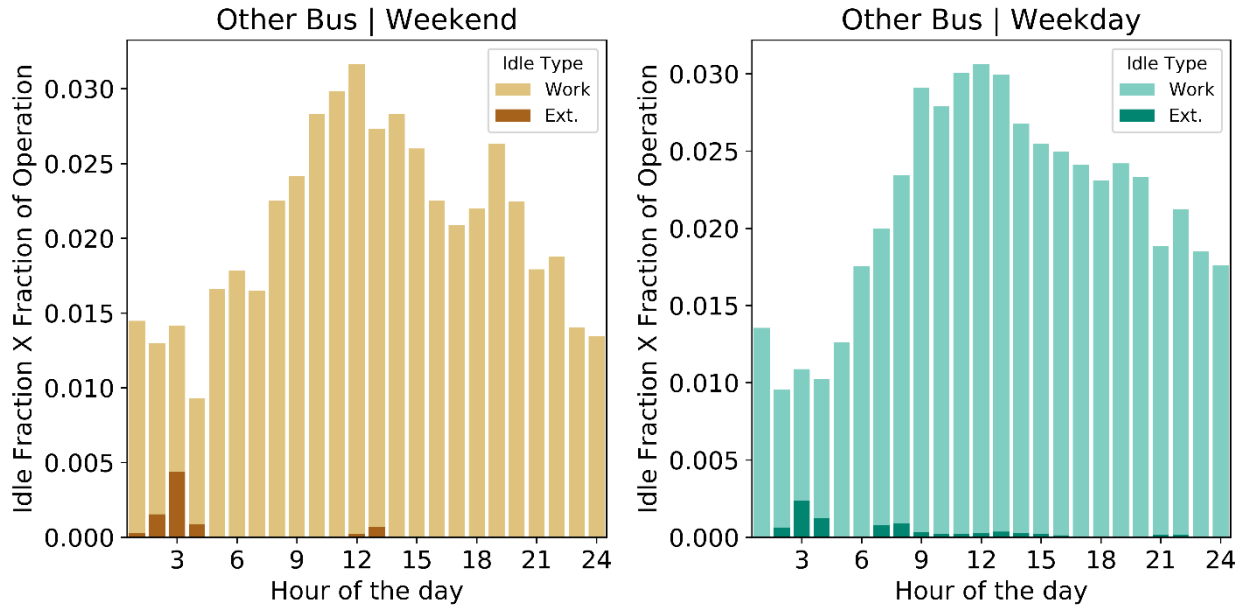


Figure E1. Hourly idle fraction vs. hour of the day for “other bus”

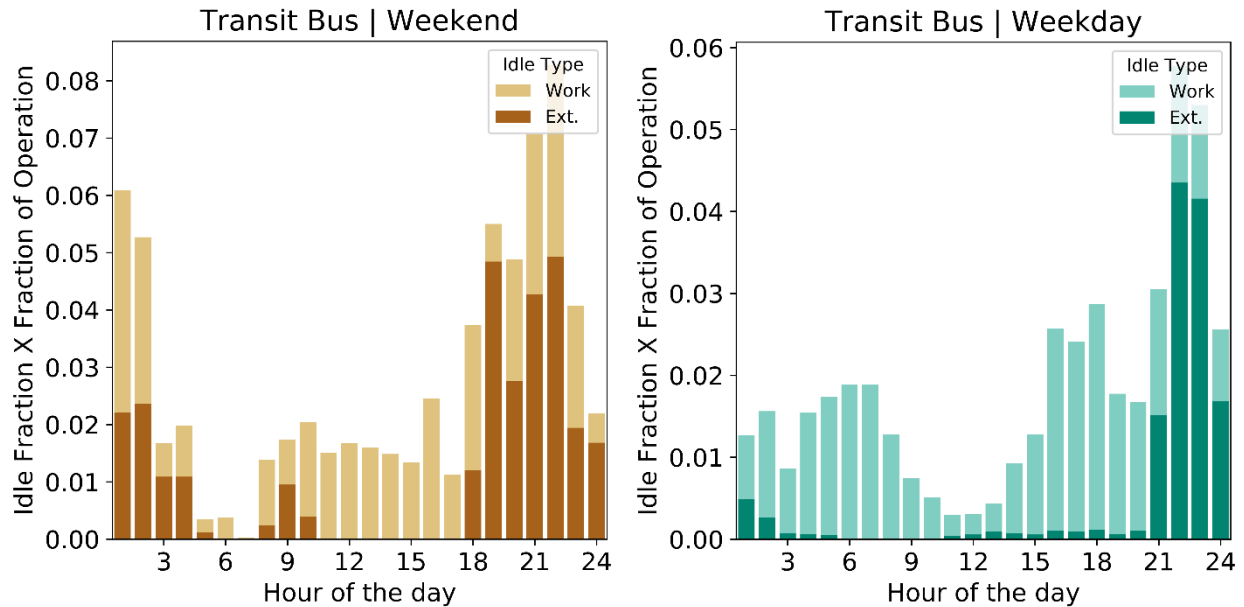


Figure E2. Hourly idle fraction vs. hour of the day for transit bus

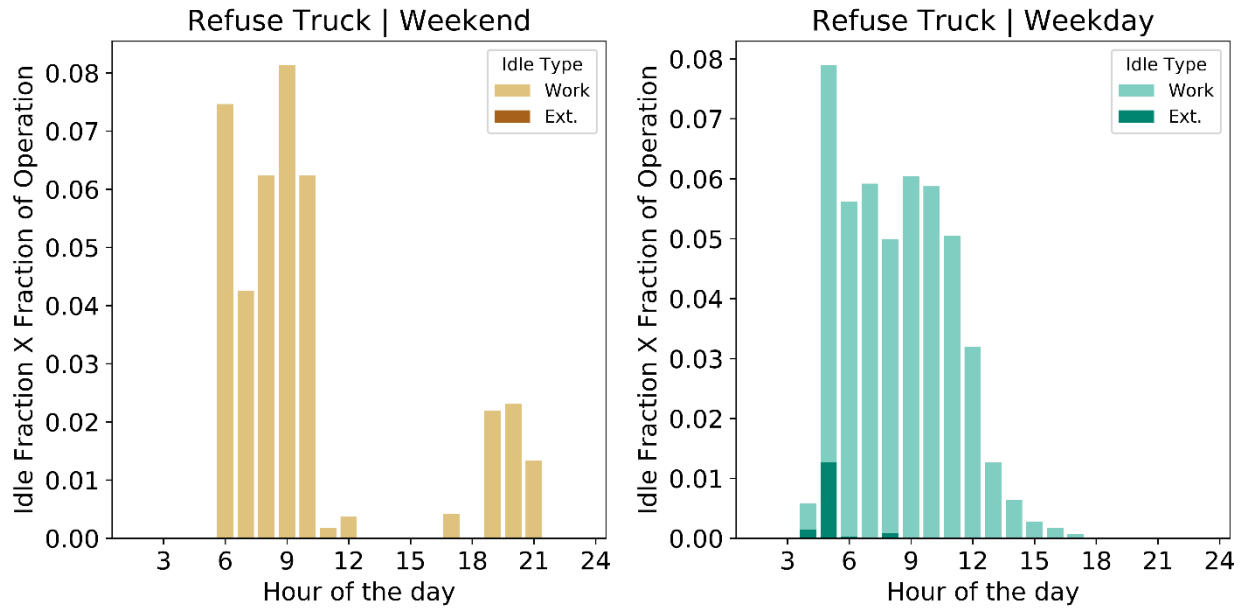


Figure E3. Hourly idle fraction vs. hour of the day for refuse truck

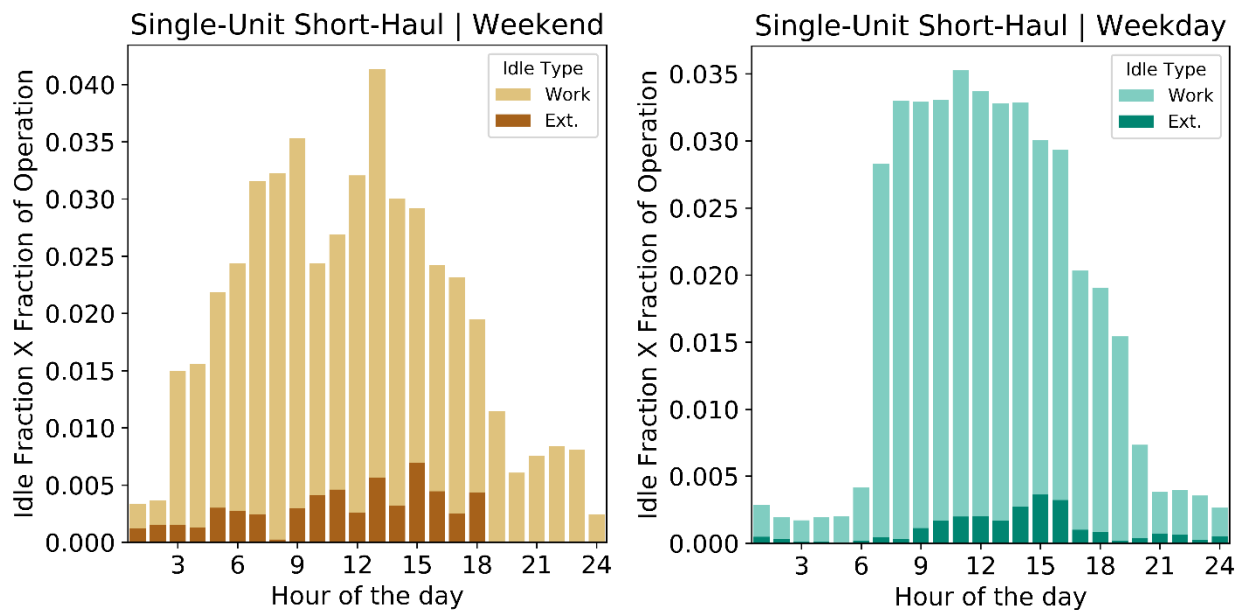


Figure E4. Hourly idle fraction vs. hour of the day for single-unit short haul

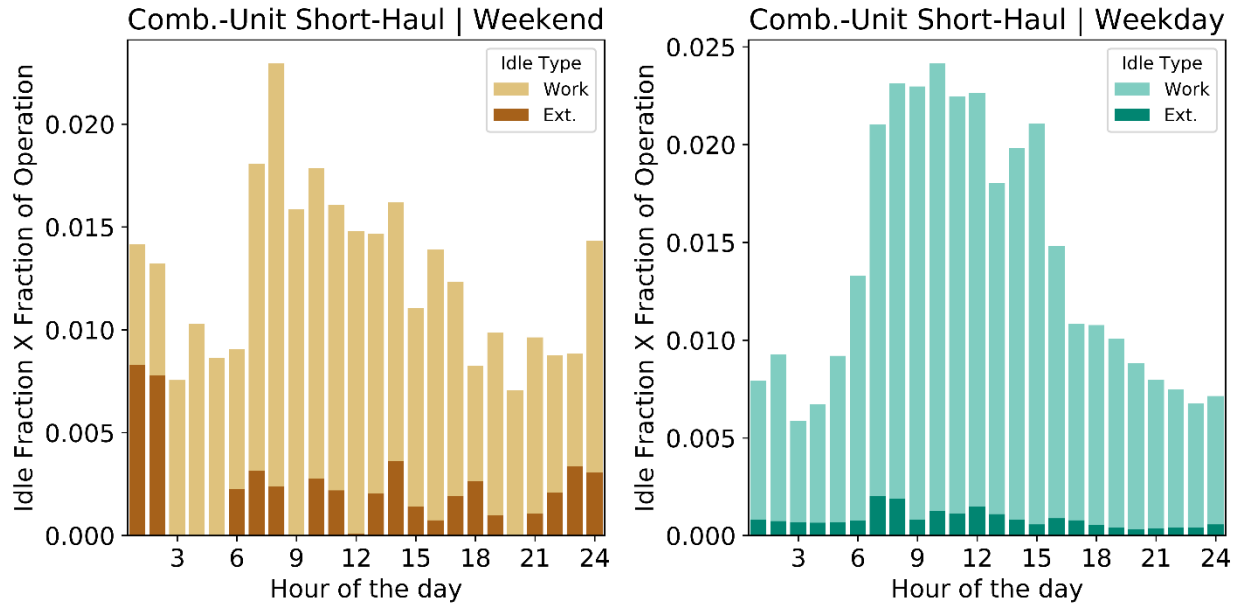


Figure E5. Hourly idle fraction vs. hour of the day for combination-unit short haul

Appendix F: Result by Vocation – CE-CERT Data

Note: CU indicates combination-unit and SU indicates single-unit for short-haul vehicles

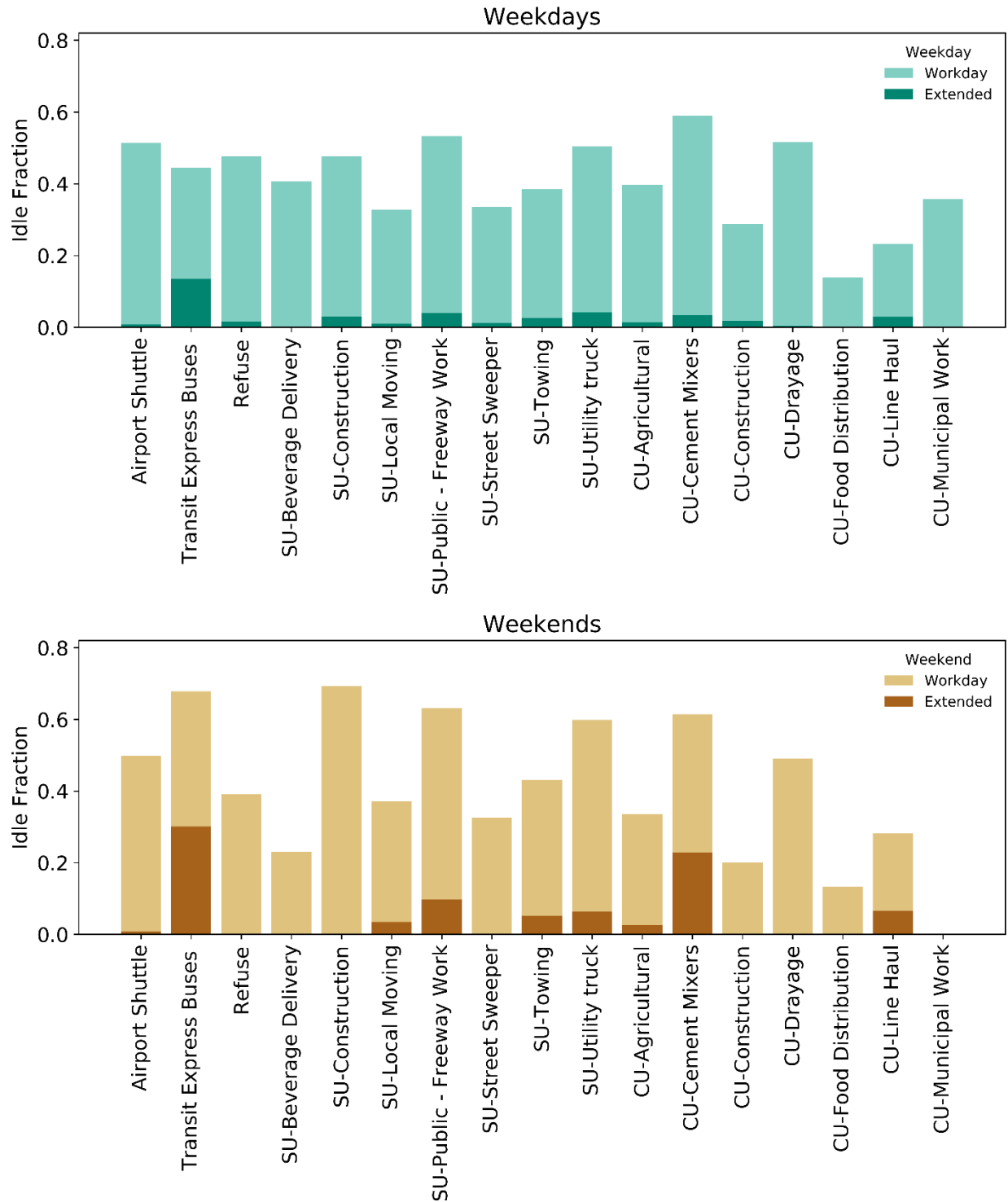


Figure F1. Vocation-based idle fraction distribution

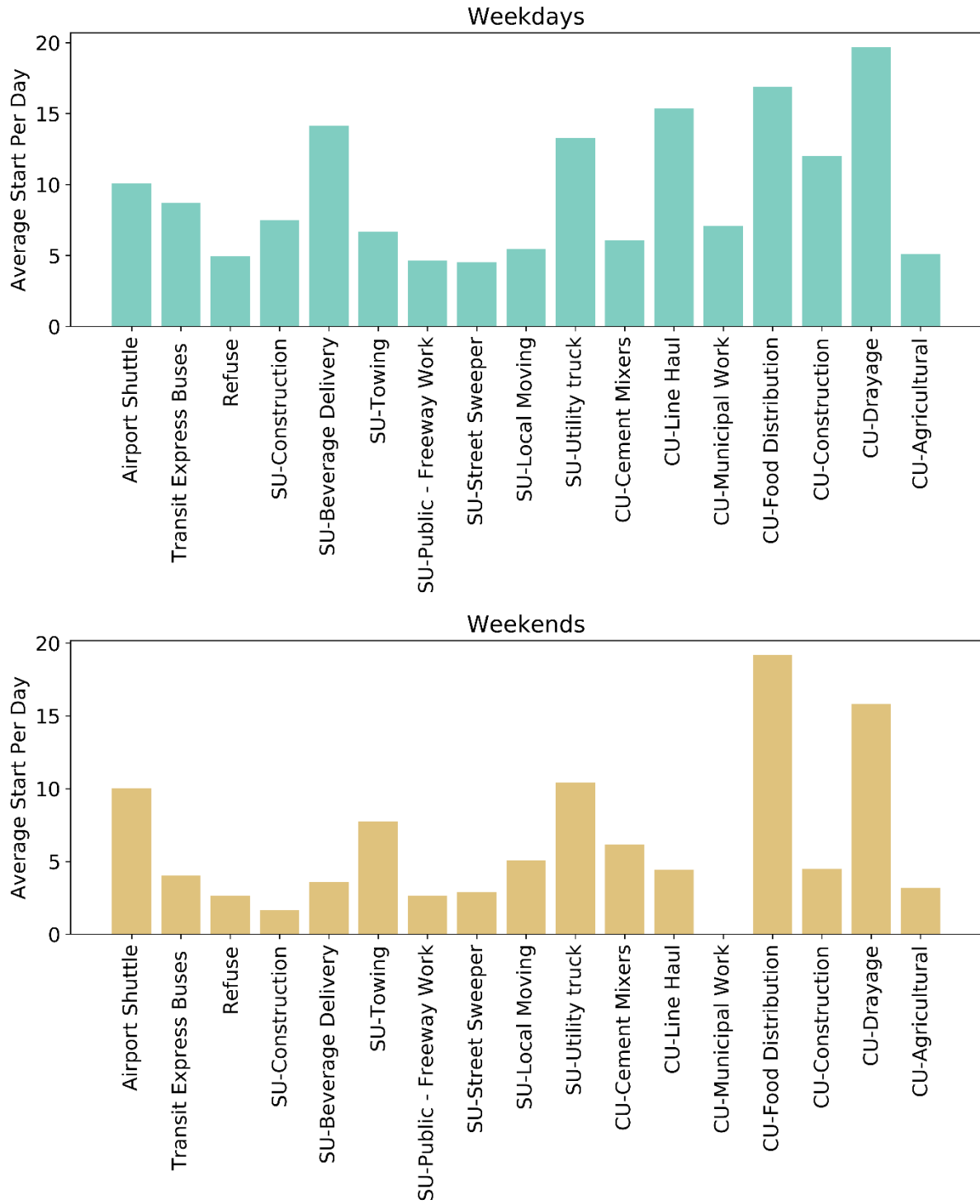


Figure F2. Vocation-based average start per day distribution

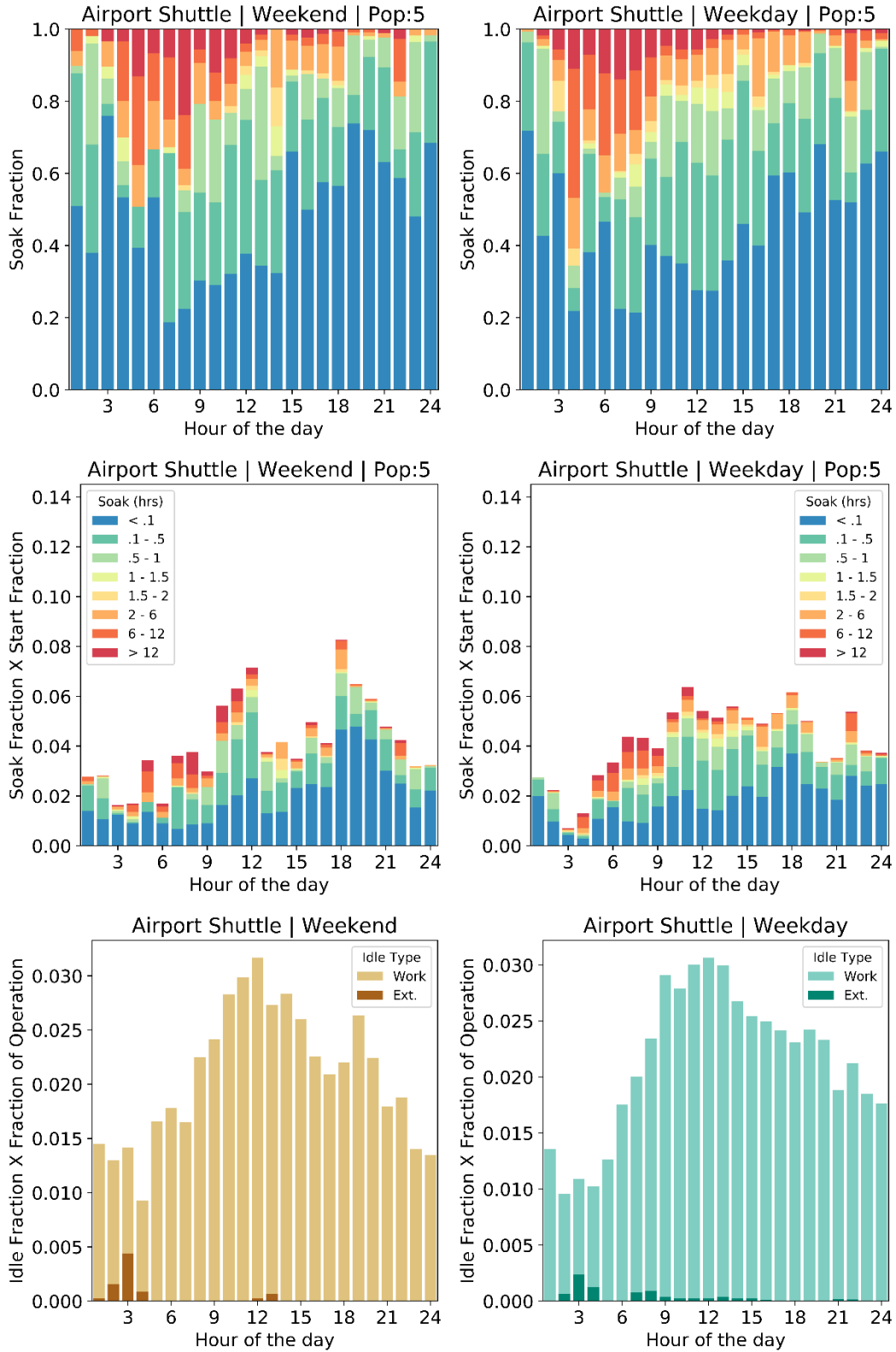


Figure F3. Start, soak, and idle performance of “other bus” (airport shuttle)

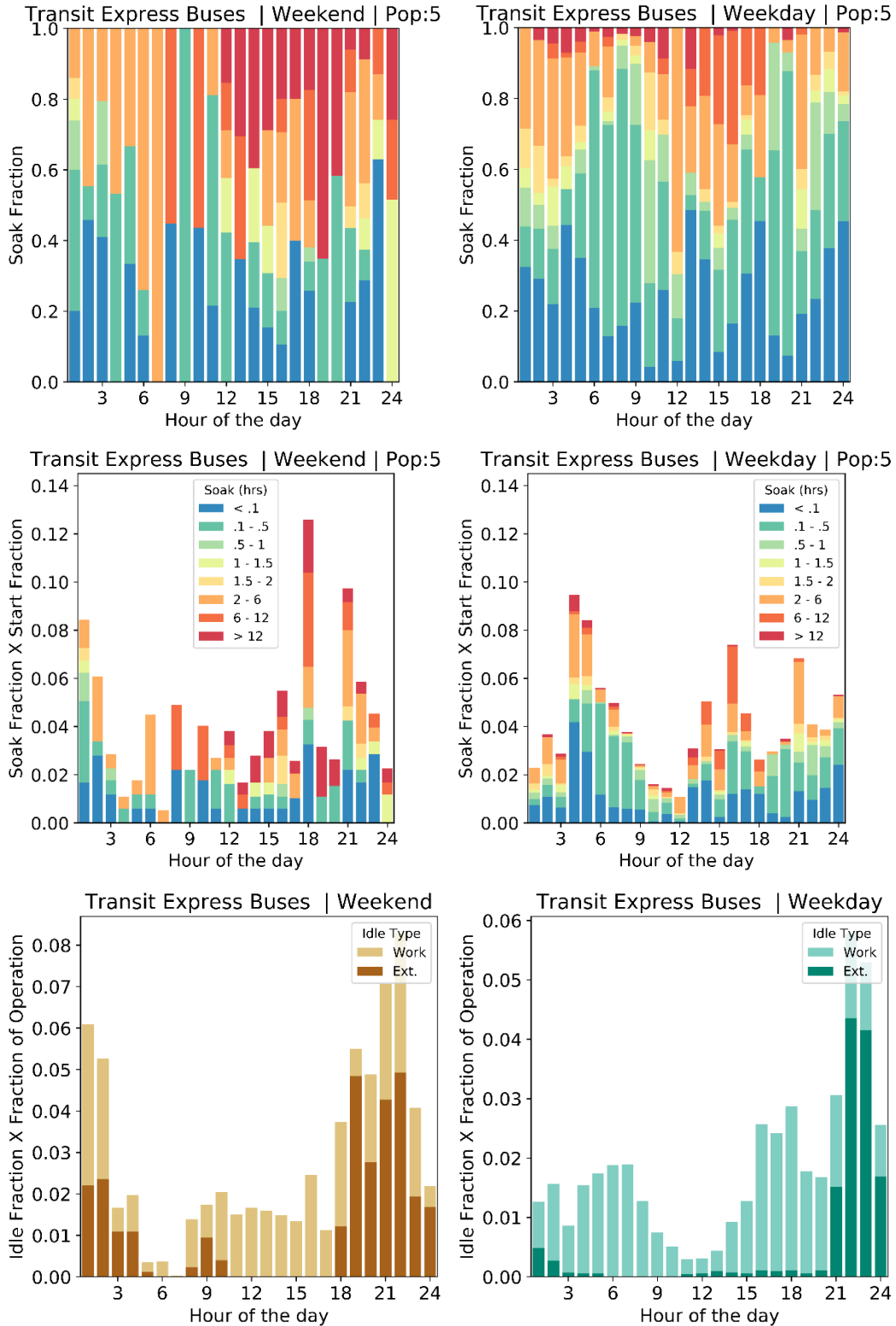


Figure F4. Start, soak, and idle performance of transit bus

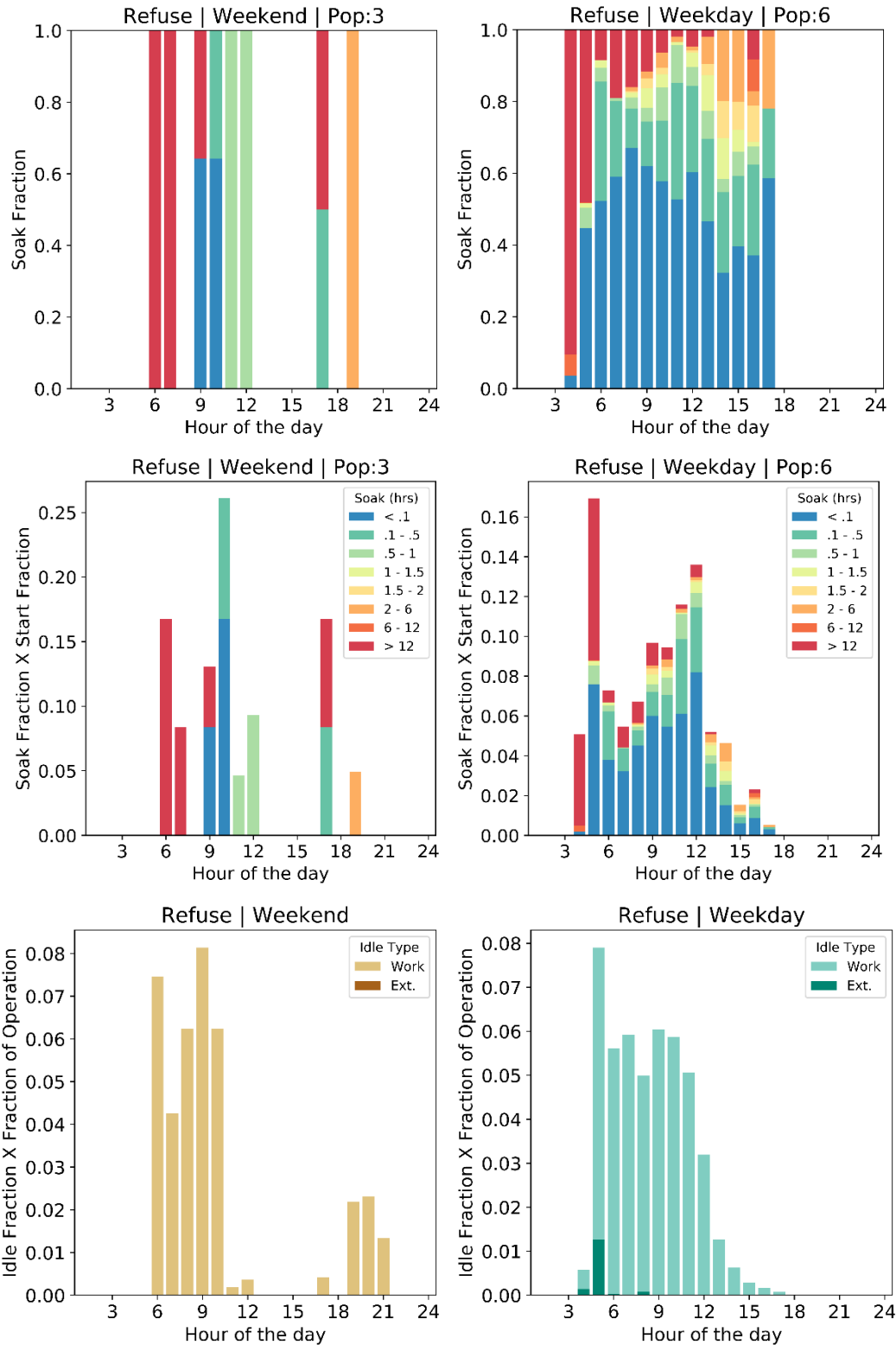


Figure F5. Start, soak, and idle performance of refuse

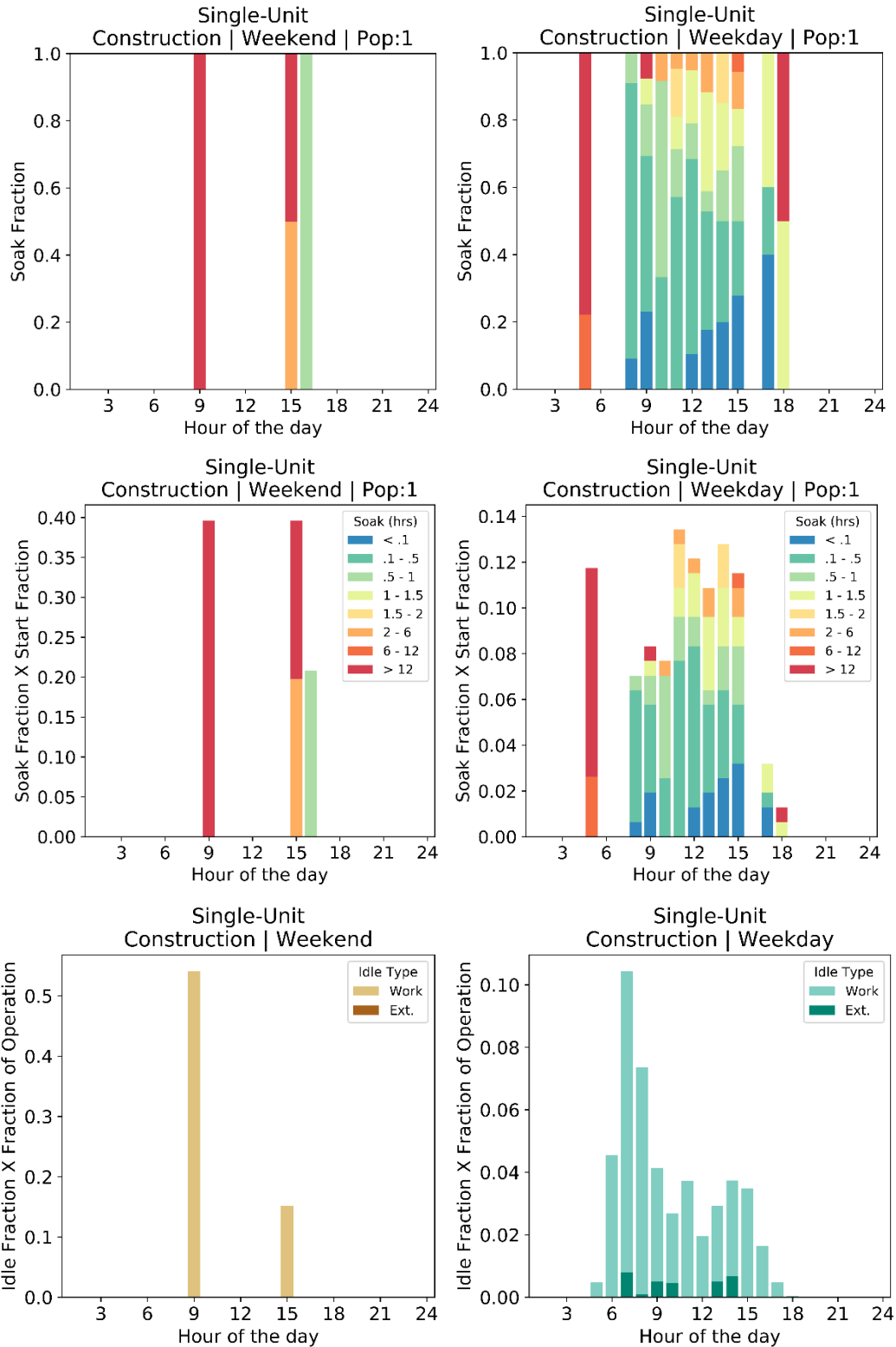


Figure F6. Start, soak, and idle performance of single-unit short haul – construction

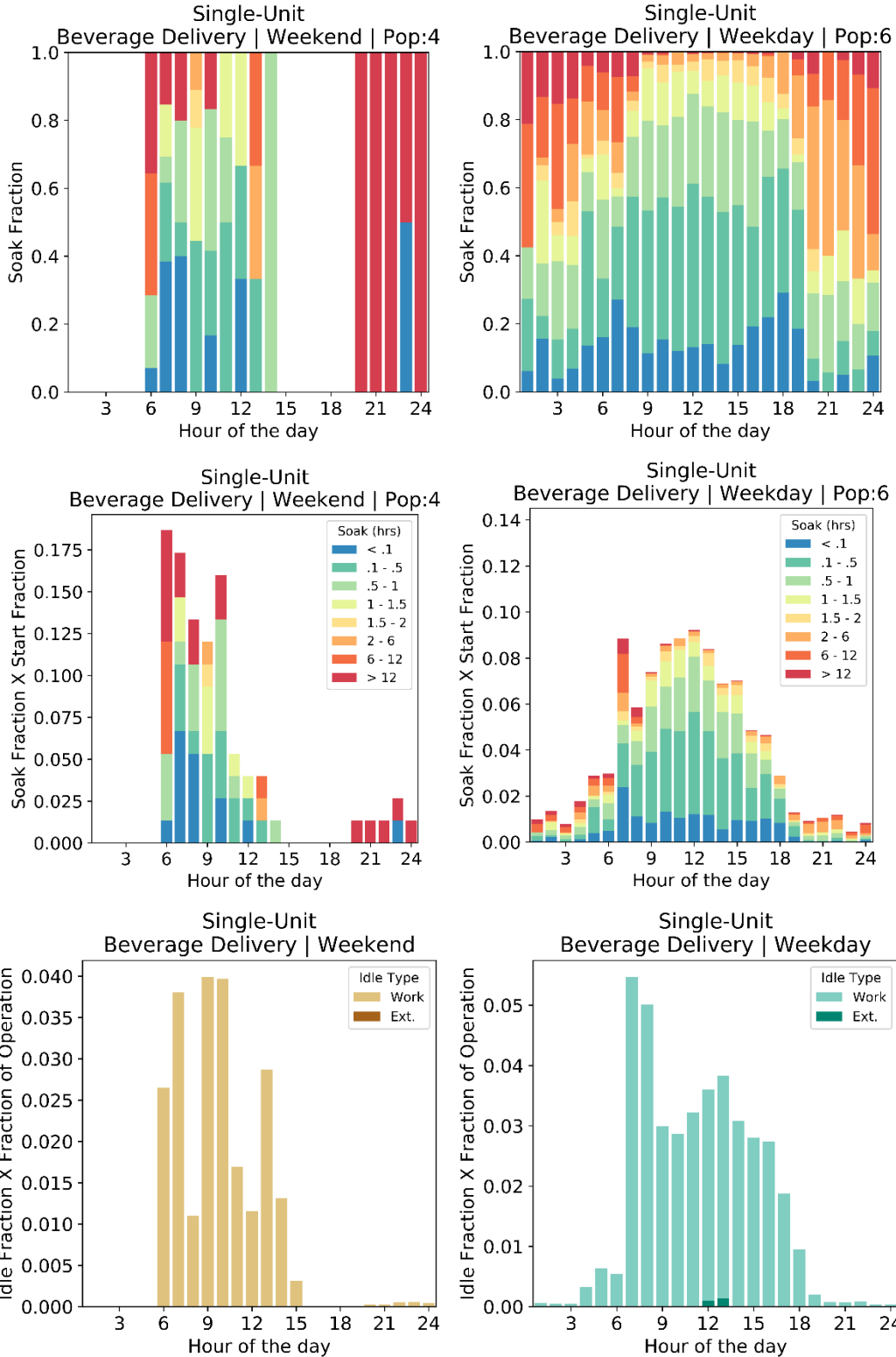


Figure F7. Start, soak, and idle performance of single-unit short haul – beverage delivery

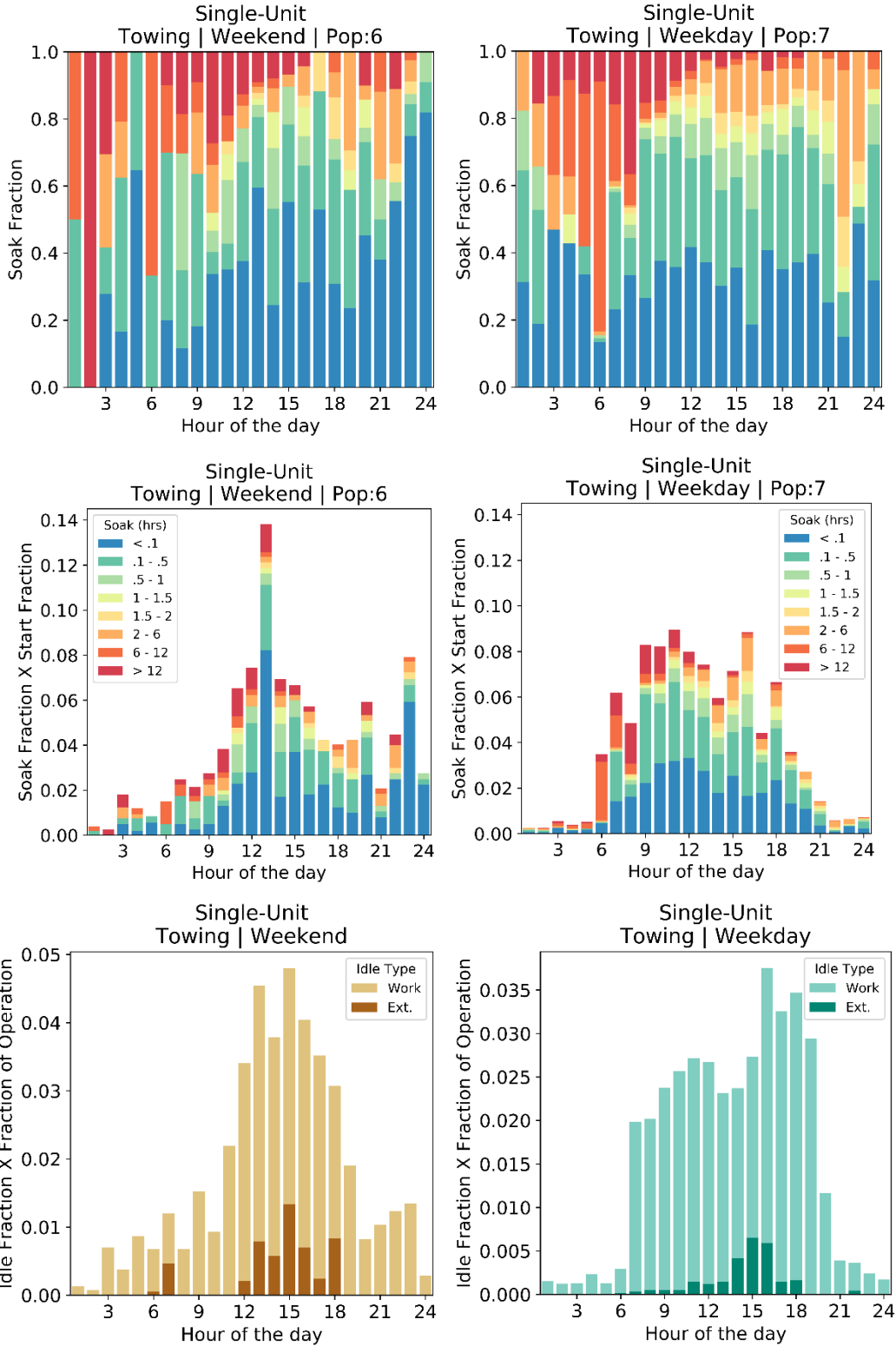


Figure F8. Start, soak, and idle performance of single-unit short haul – towing

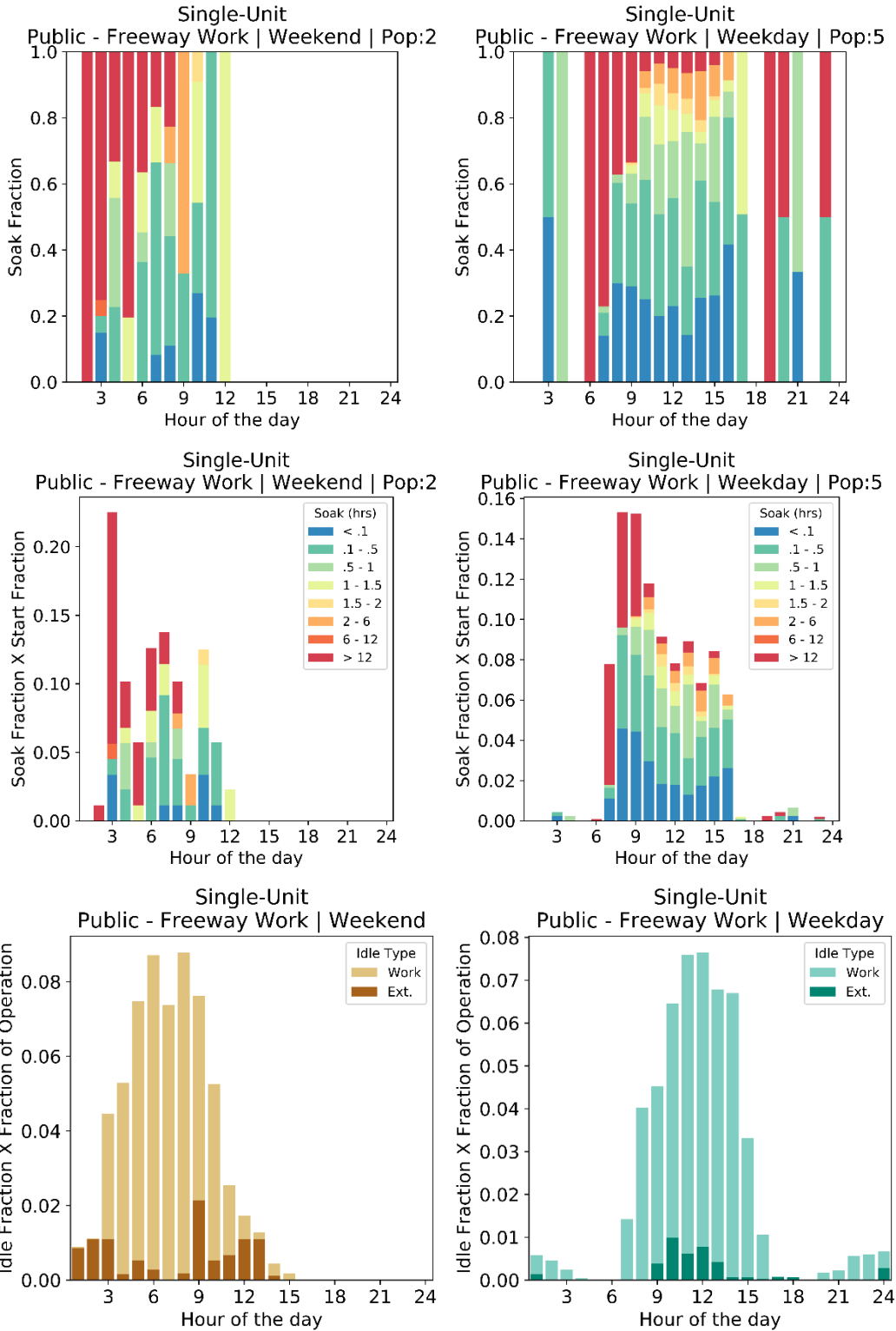


Figure F9. Start, soak, and idle performance of single-unit short haul – freeway work

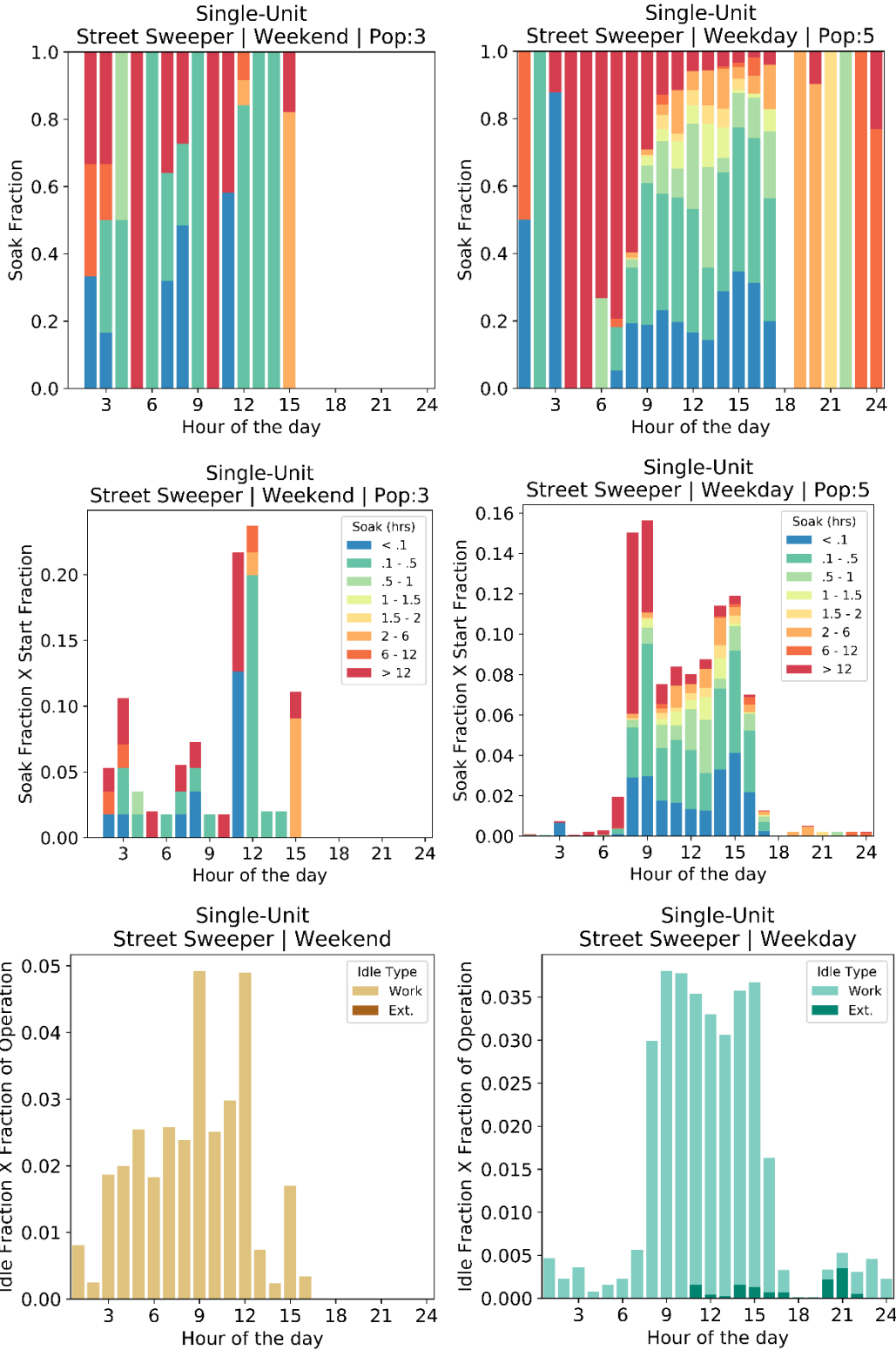


Figure F10. Start, soak, and idle performance of single-unit short haul – street sweeper

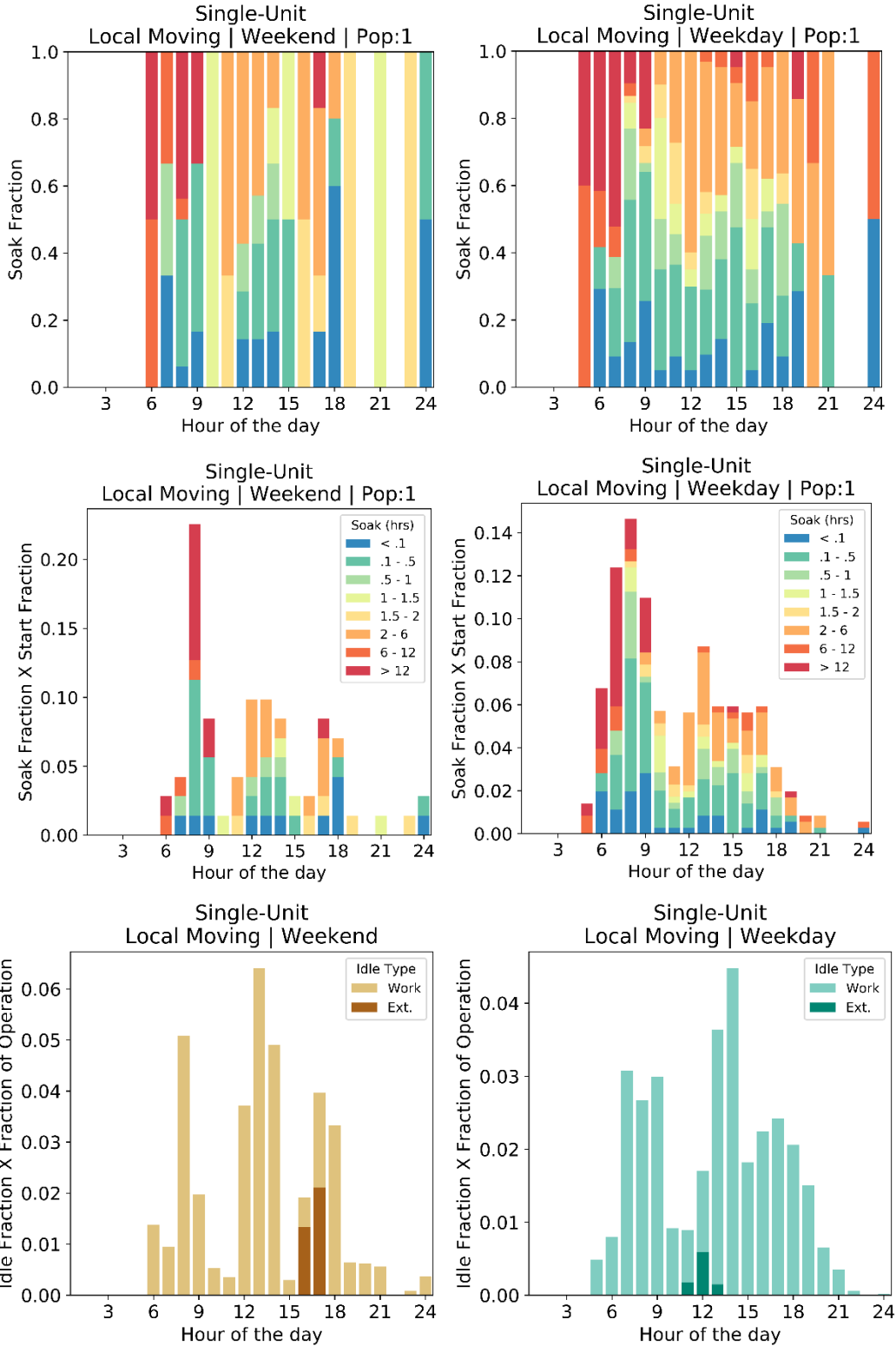


Figure F11. Start, soak, and idle performance of single-unit short haul – local moving

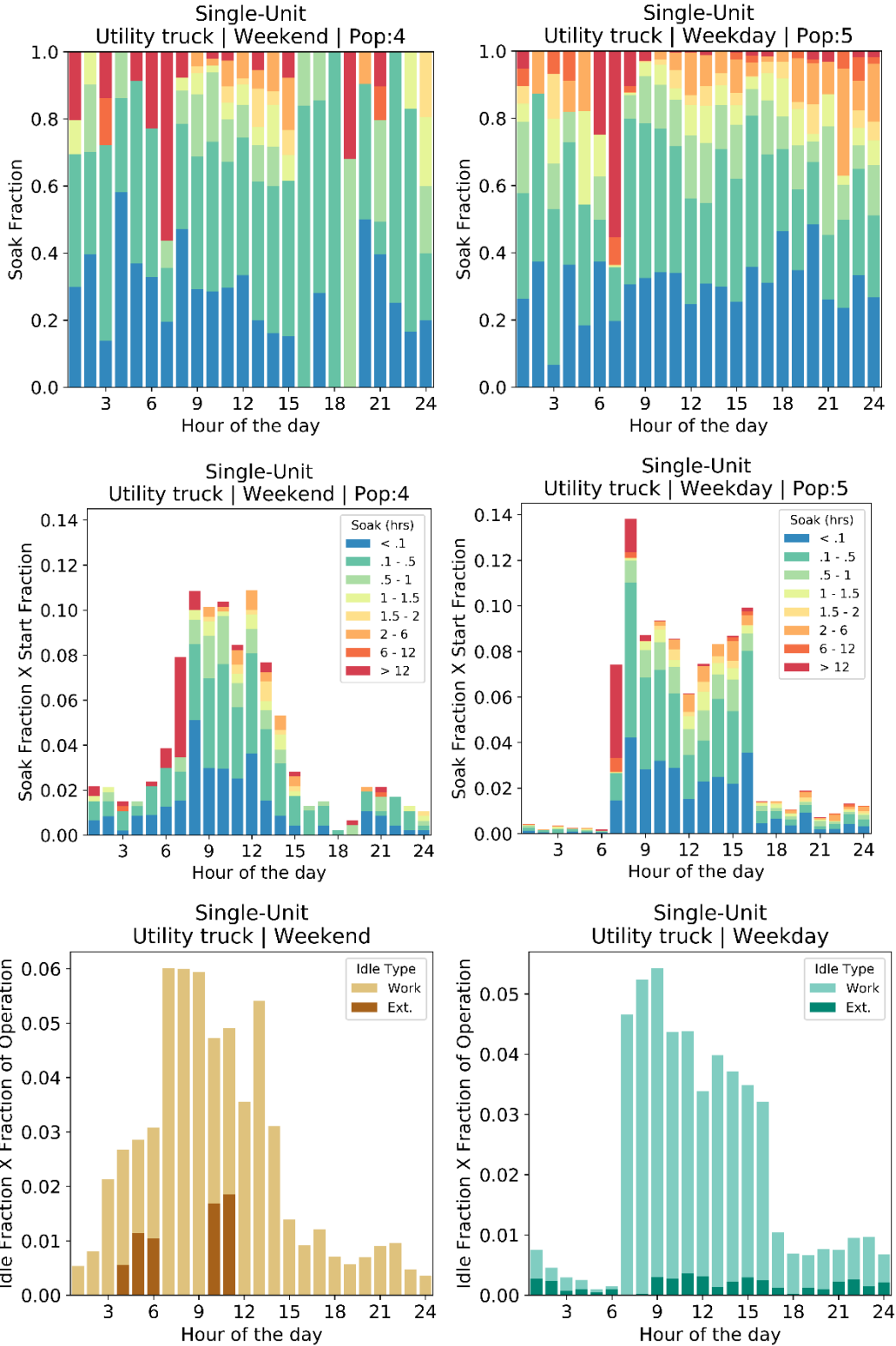


Figure F12. Start, soak, and idle performance of single-unit short haul – utility truck

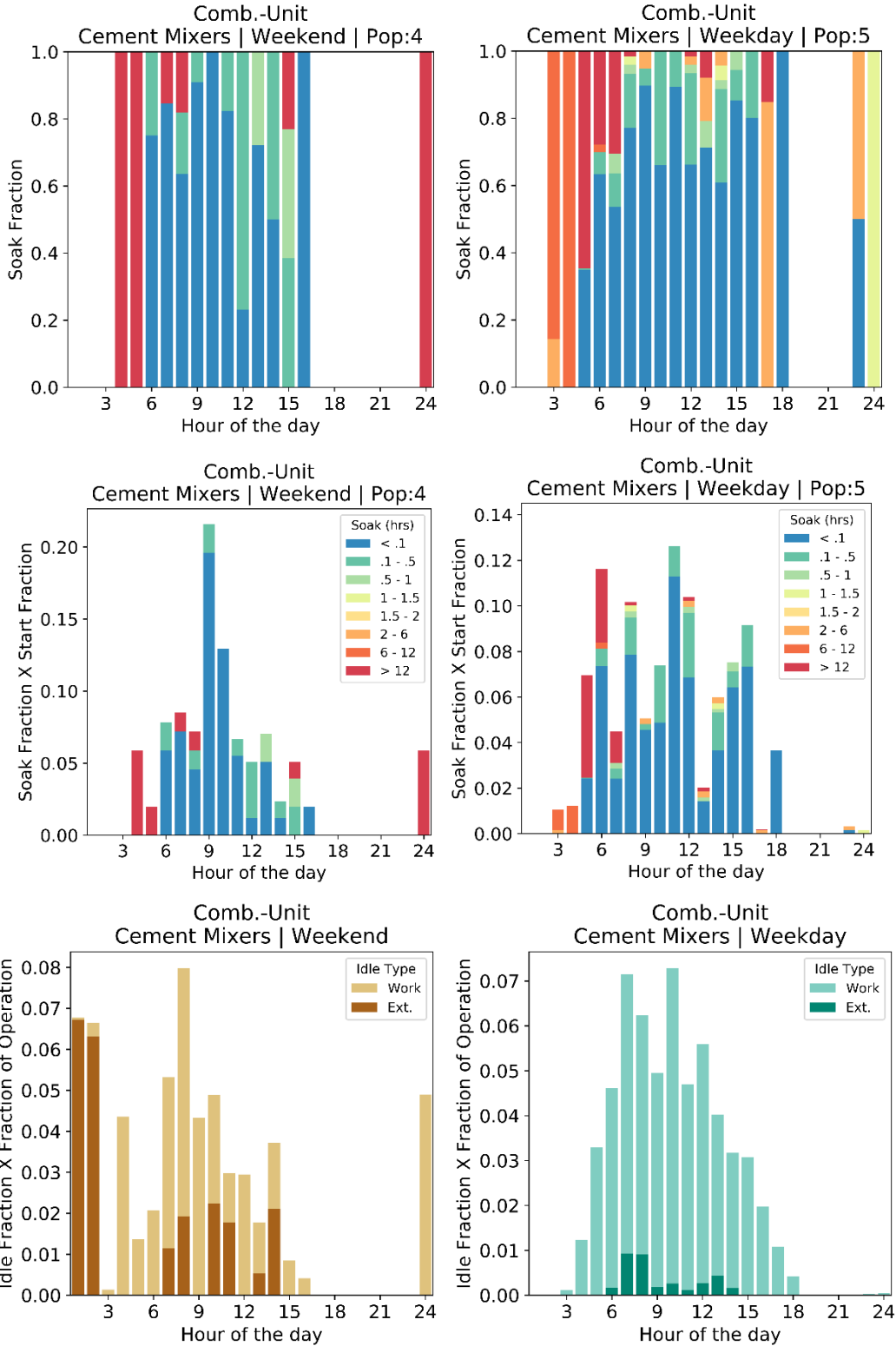


Figure F13. Start, soak, and idle performance of combination-unit short haul – cement mixers

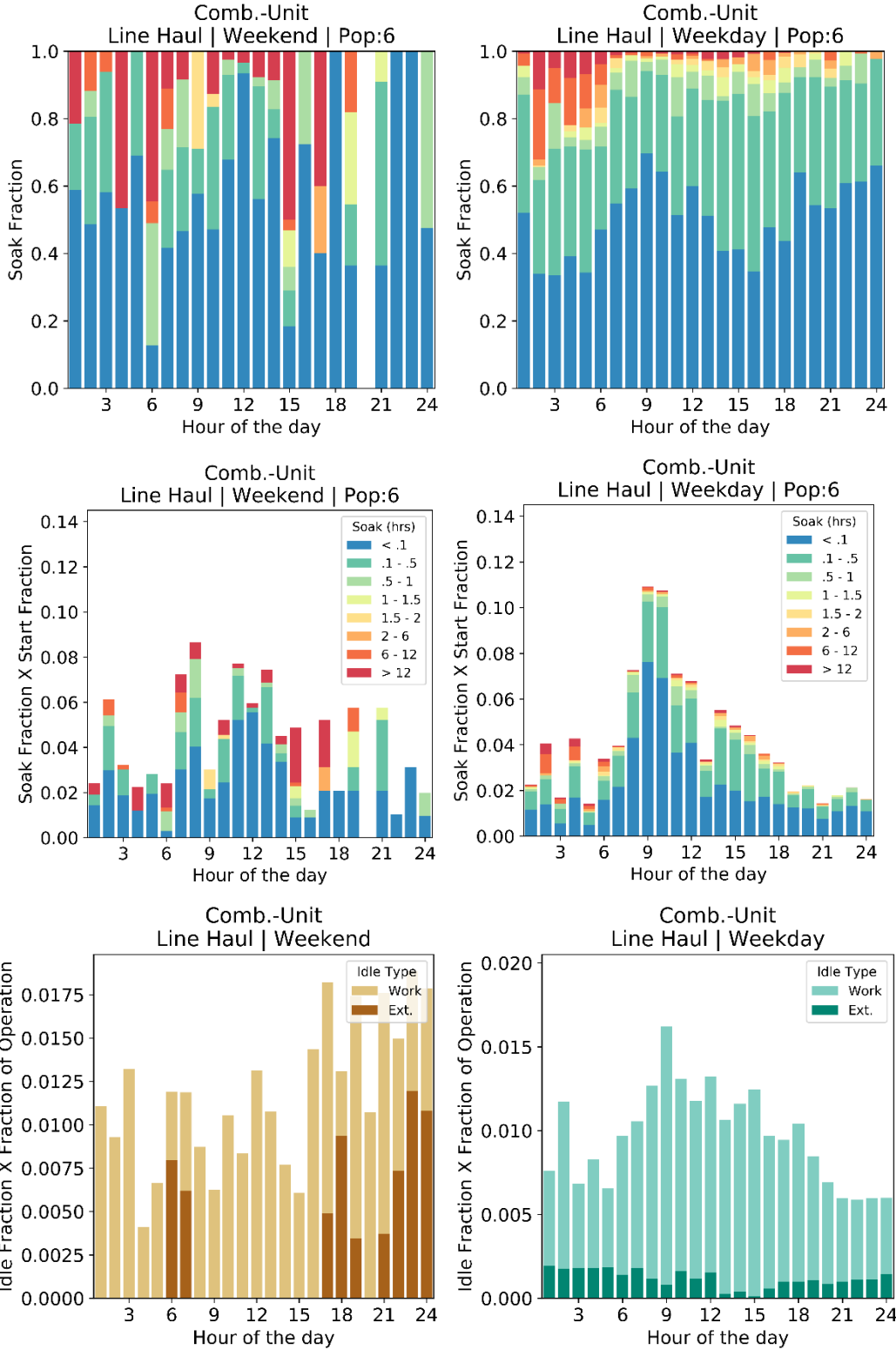


Figure F14. Start, soak, and idle performance of combination-unit short haul – line haul

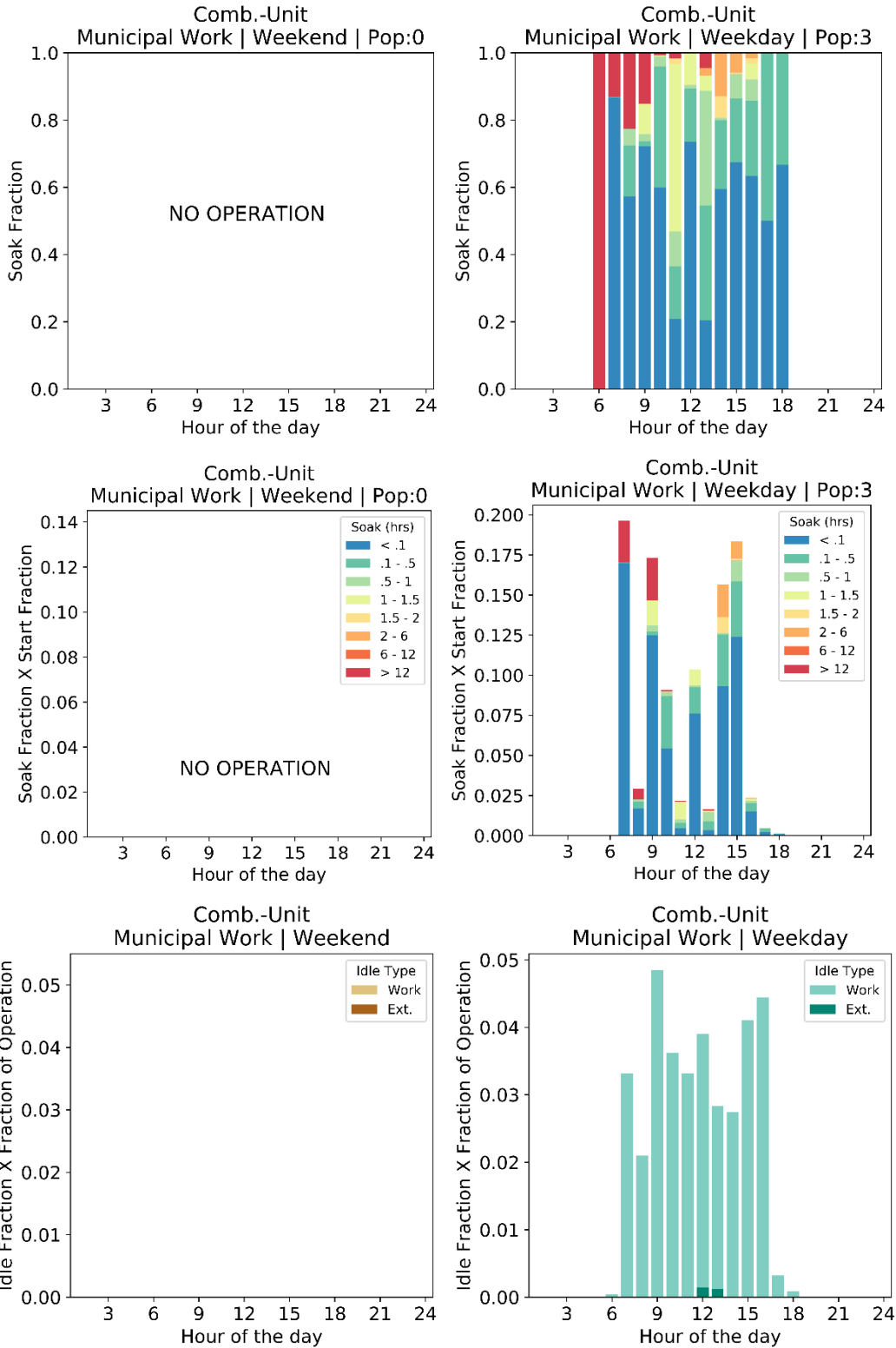


Figure F15. Start, soak, and idle performance of combination-unit short haul – municipal work

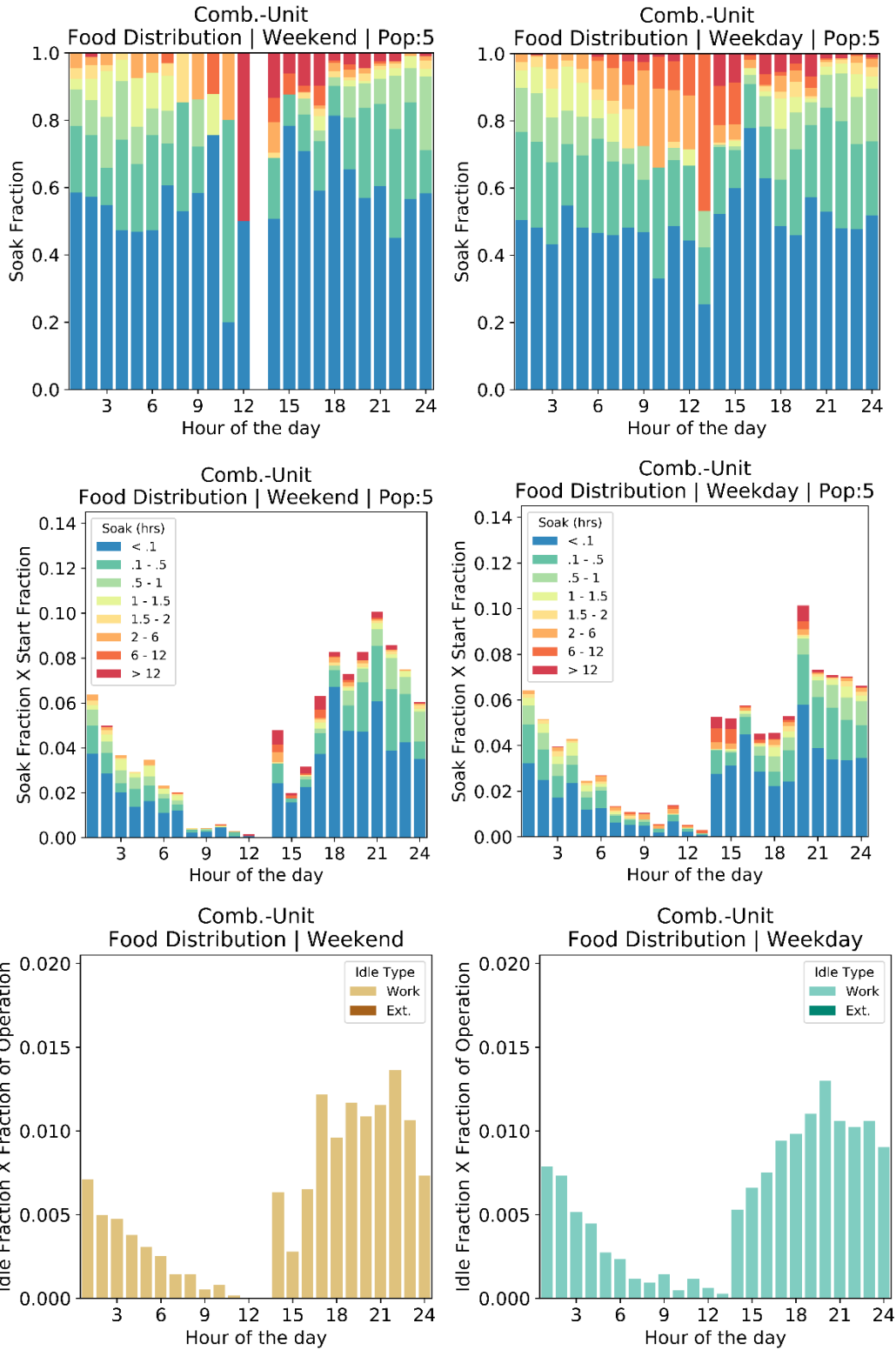


Figure F16. Start, soak, and idle performance of combination-unit short haul – food distribution

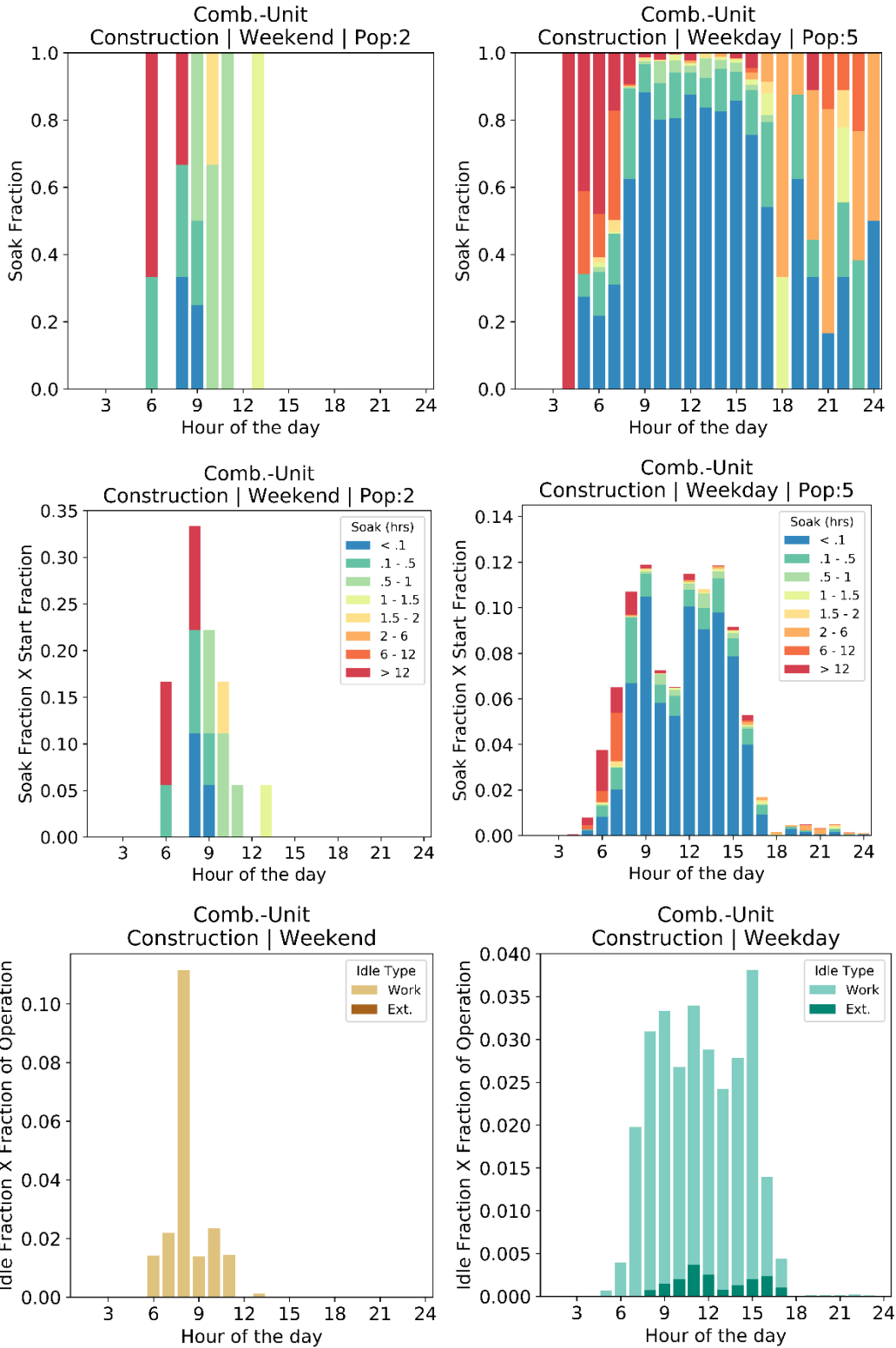


Figure F17. Start, soak, and idle performance of combination-unit short haul – construction

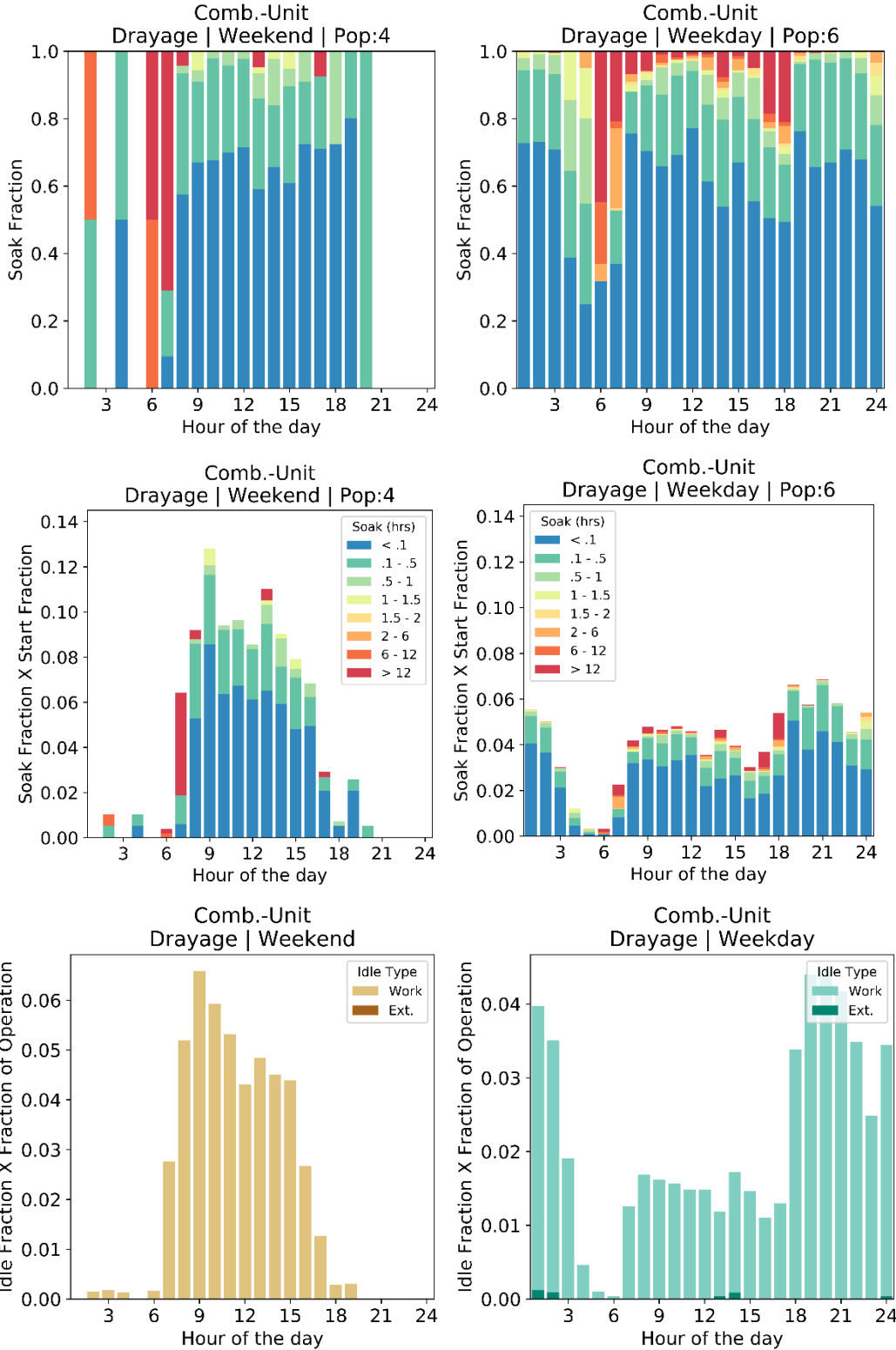


Figure F18. Start, soak, and idle performance of combination-unit short haul – drayage

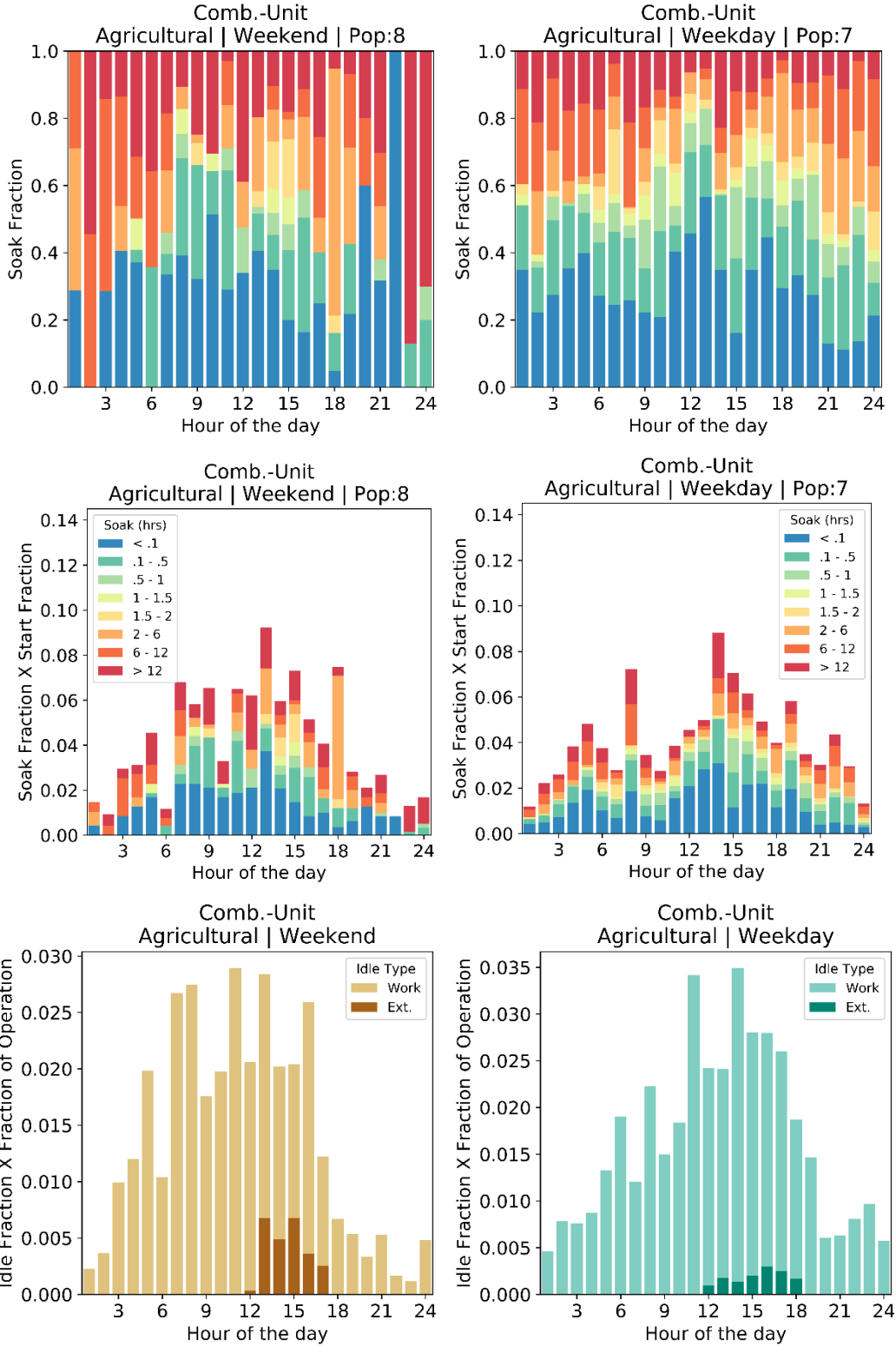


Figure F19. Start, soak, and idle performance of combination-unit short haul – agricultural

Appendix G: Start and Soak Plots – Original Fleet DNA Data

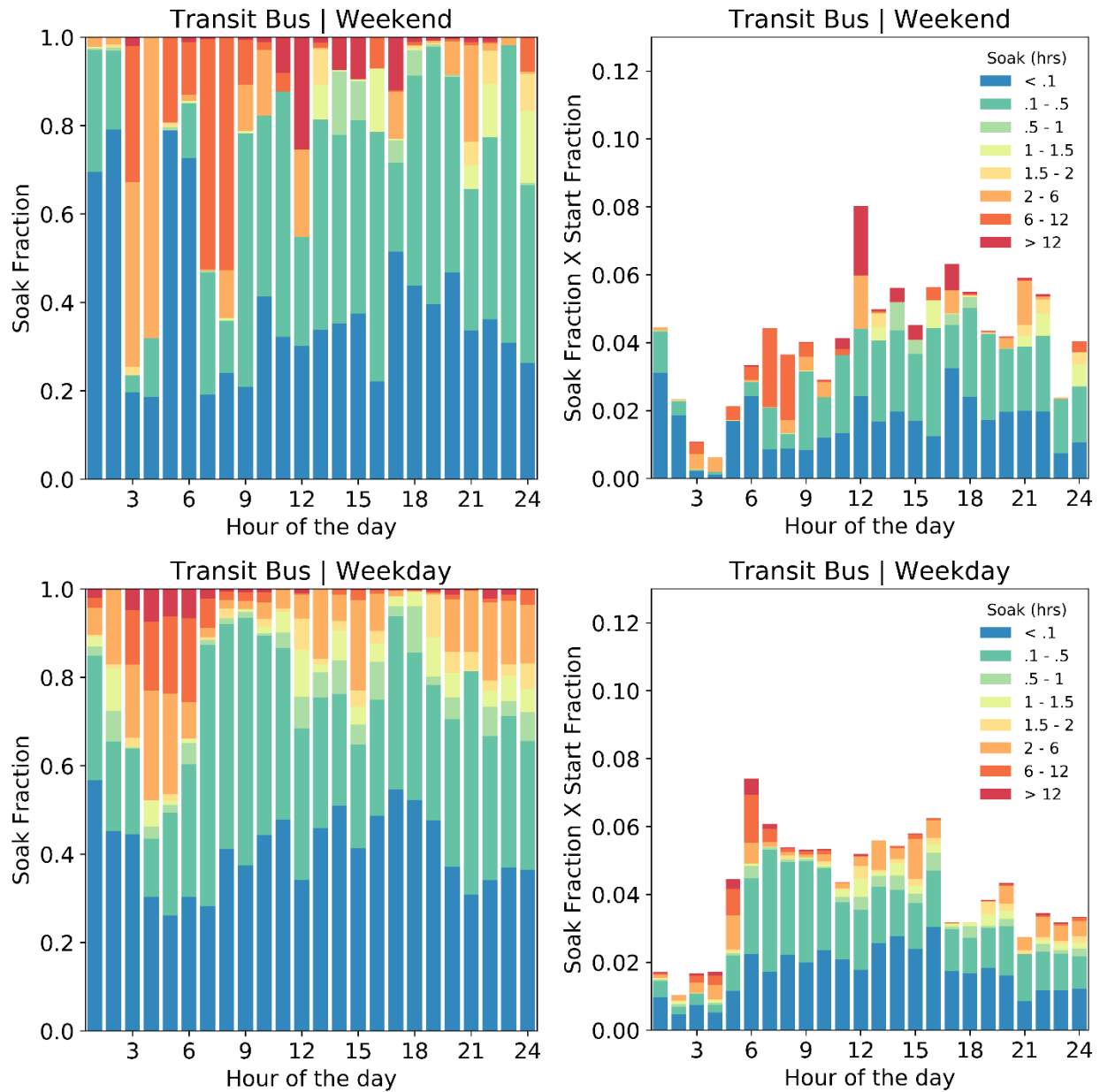


Figure G1. Soak fraction and start fraction vs. hour of the day for transit bus

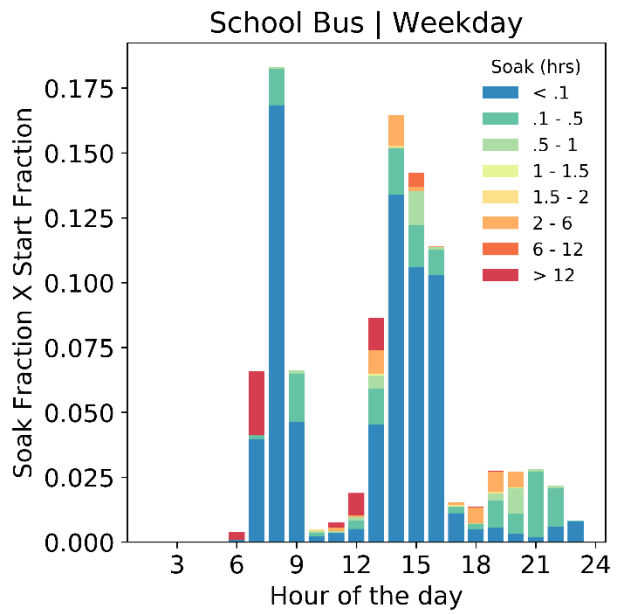
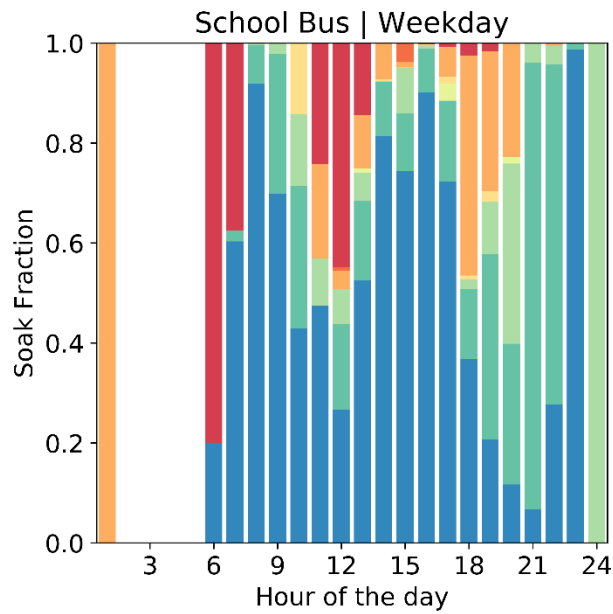
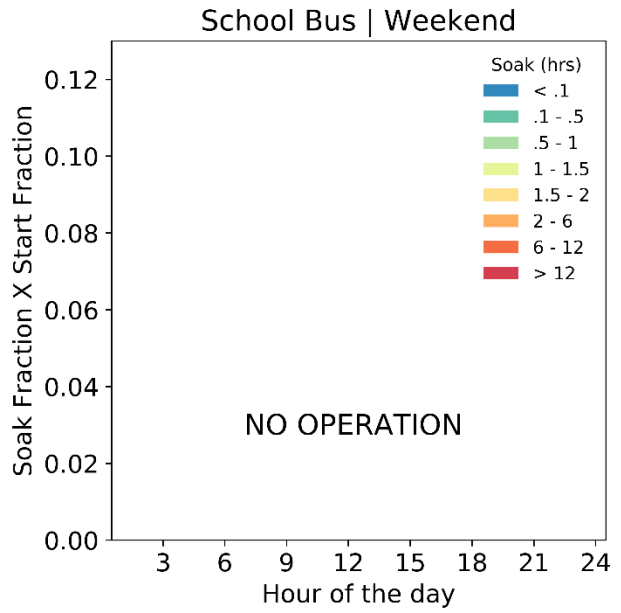
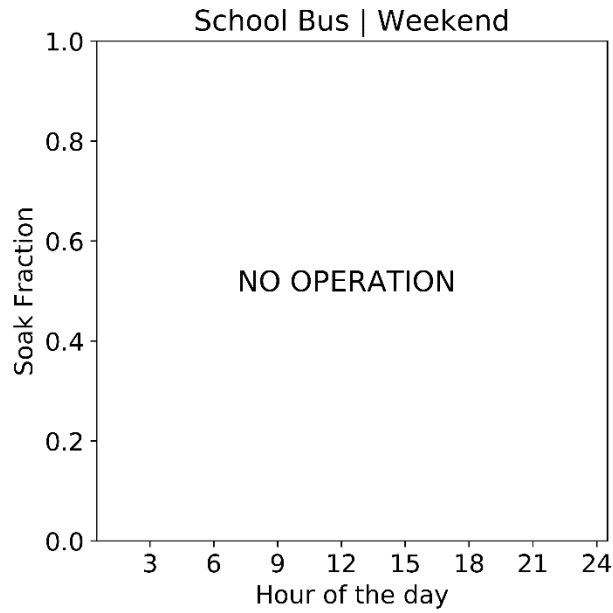


Figure G2. Soak fraction and start fraction vs. hour of the day for school bus

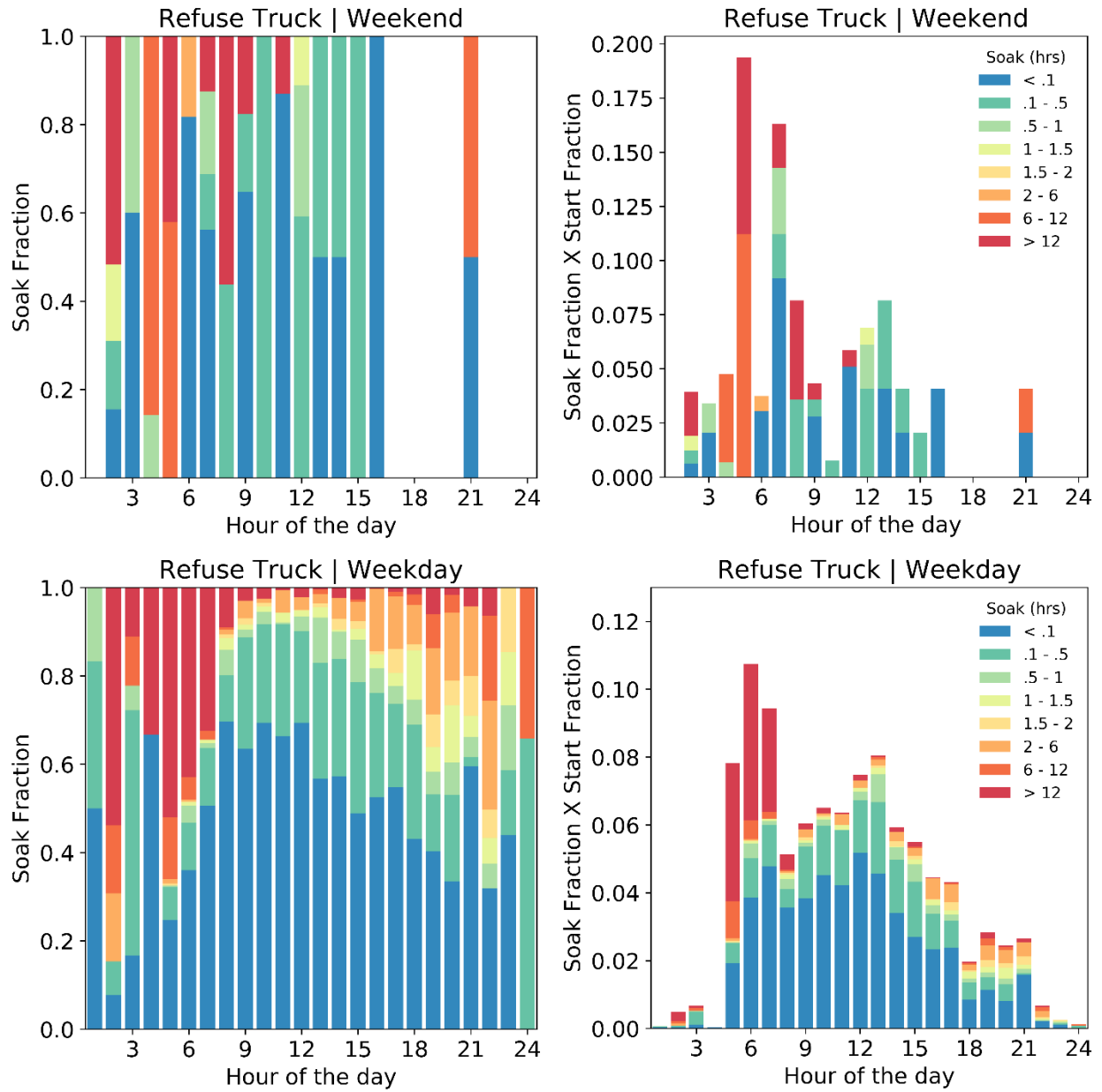


Figure G3. Soak fraction and start fraction vs. hour of the day for refuse truck

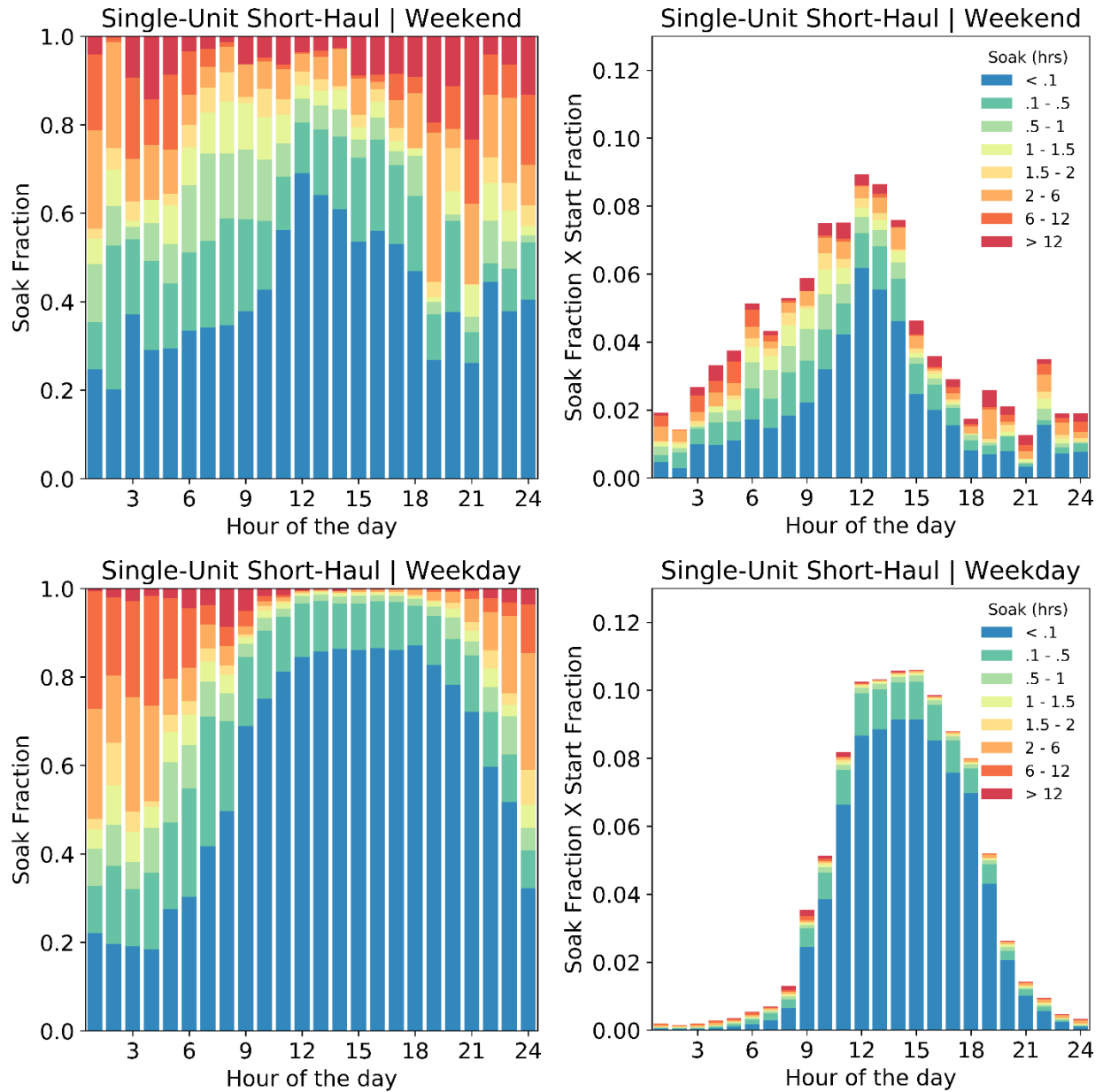


Figure G4. Soak fraction and start fraction vs. hour of the day for single-unit short haul

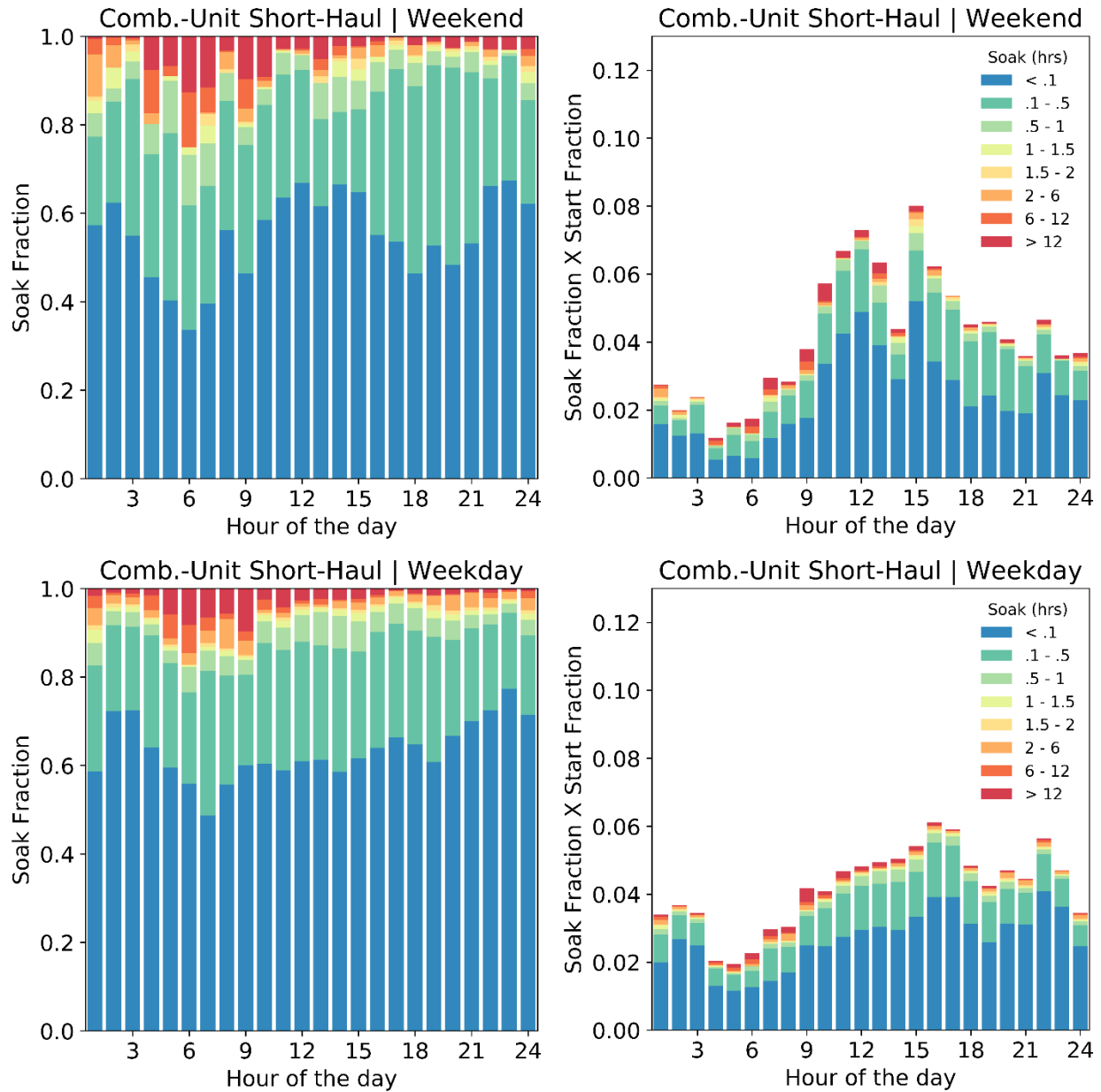


Figure G5. Soak fraction and start fraction vs. hour of the day for combination-unit short haul

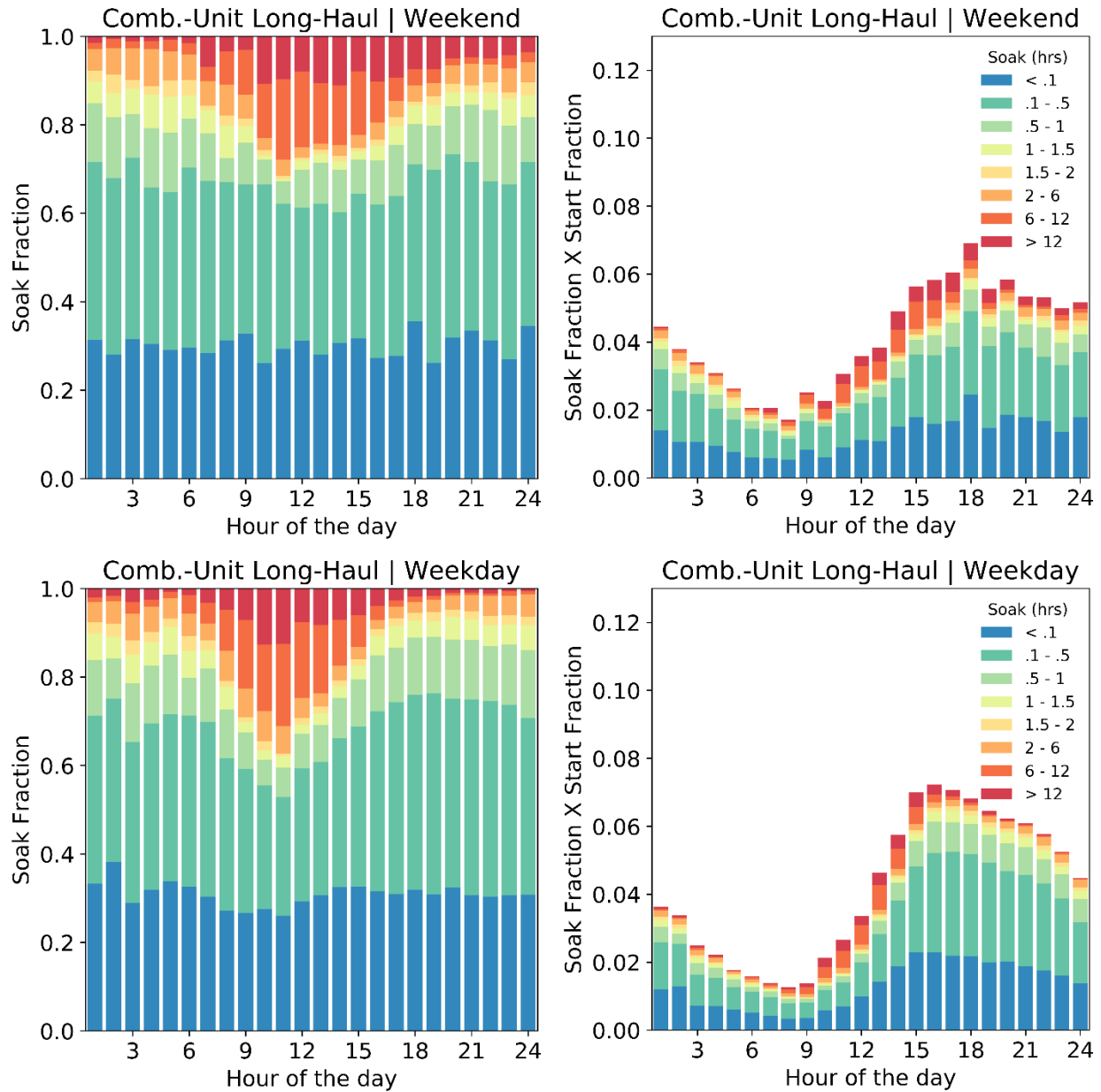


Figure G6. Soak fraction and start fraction vs. hour of the day for combination-unit long haul

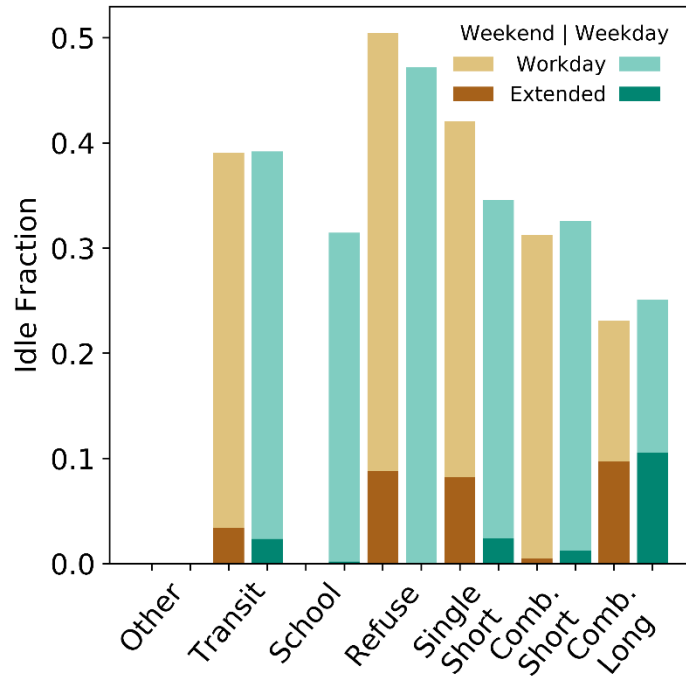


Figure G7. Extended and workday idle fractions vs. day type and vehicle type

Appendix H: Hourly Idle Plots – Original Fleet DNA Data

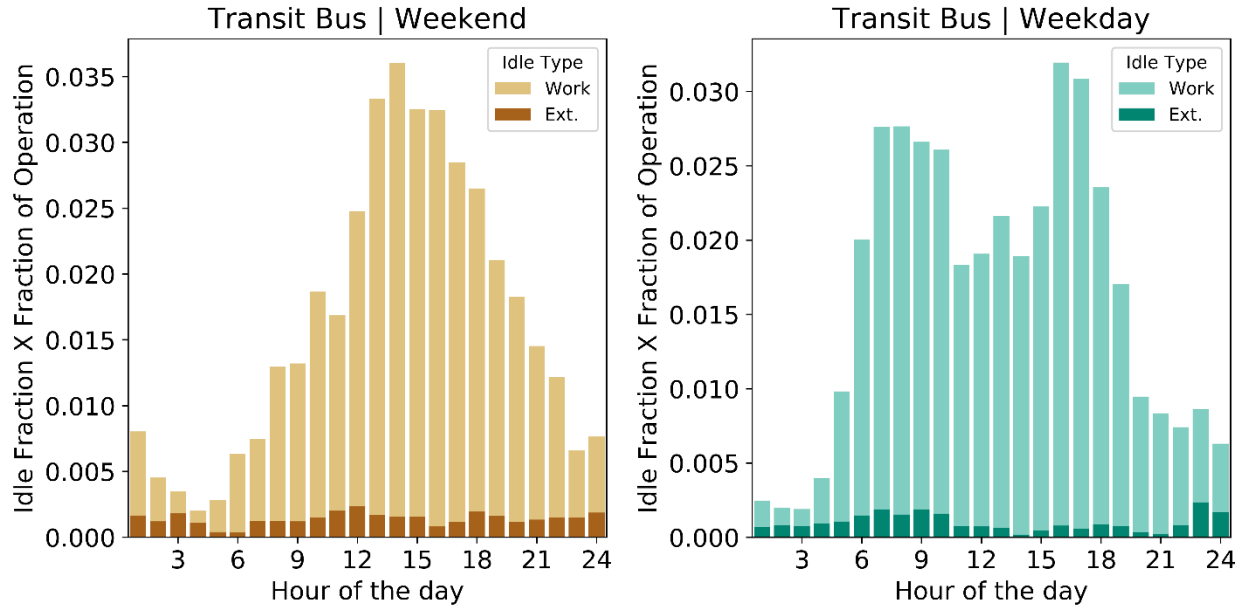


Figure H1. Hourly idle fraction vs. hour of the day for transit bus

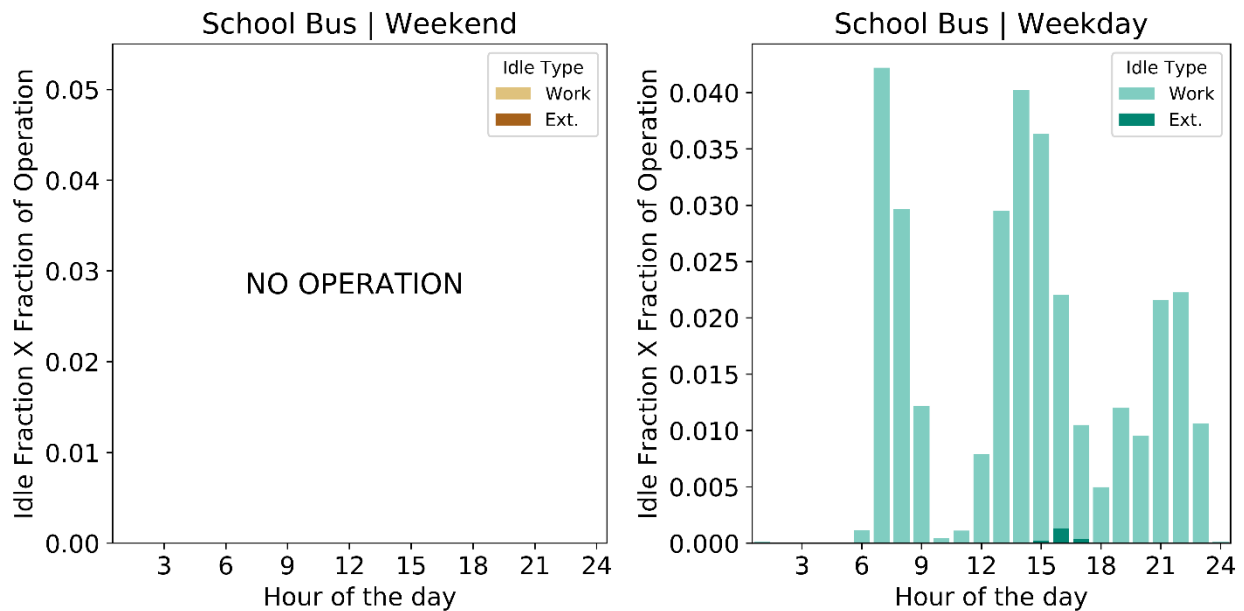


Figure H2. Hourly idle fraction vs. hour of the day for school bus

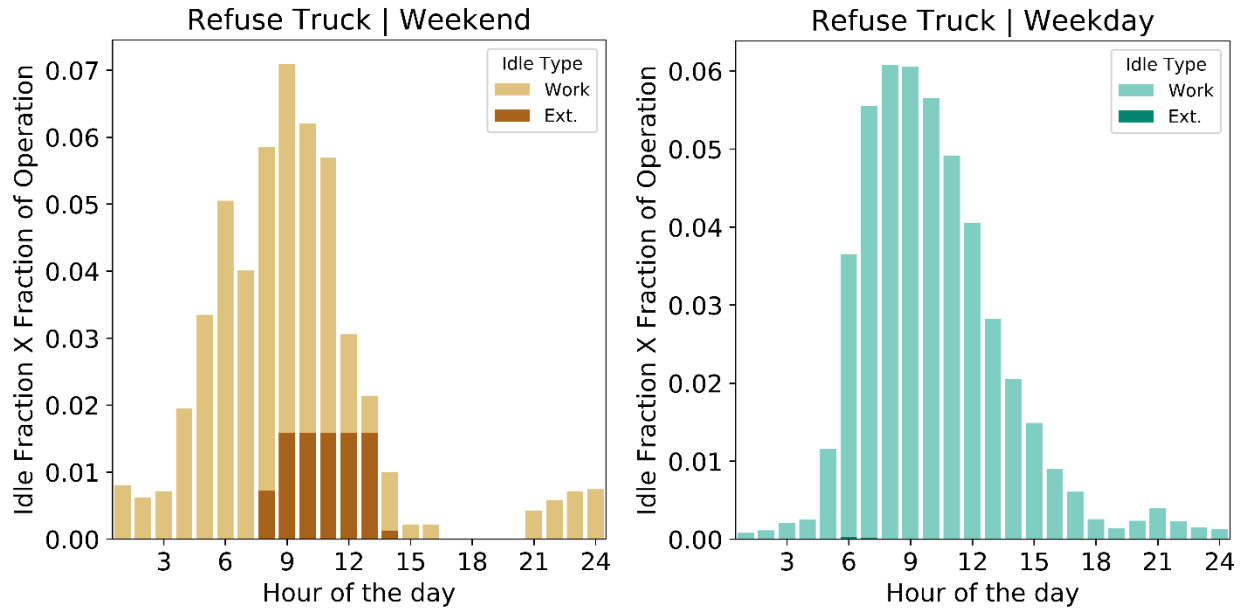


Figure H3. Hourly idle fraction vs. hour of the day for refuse truck

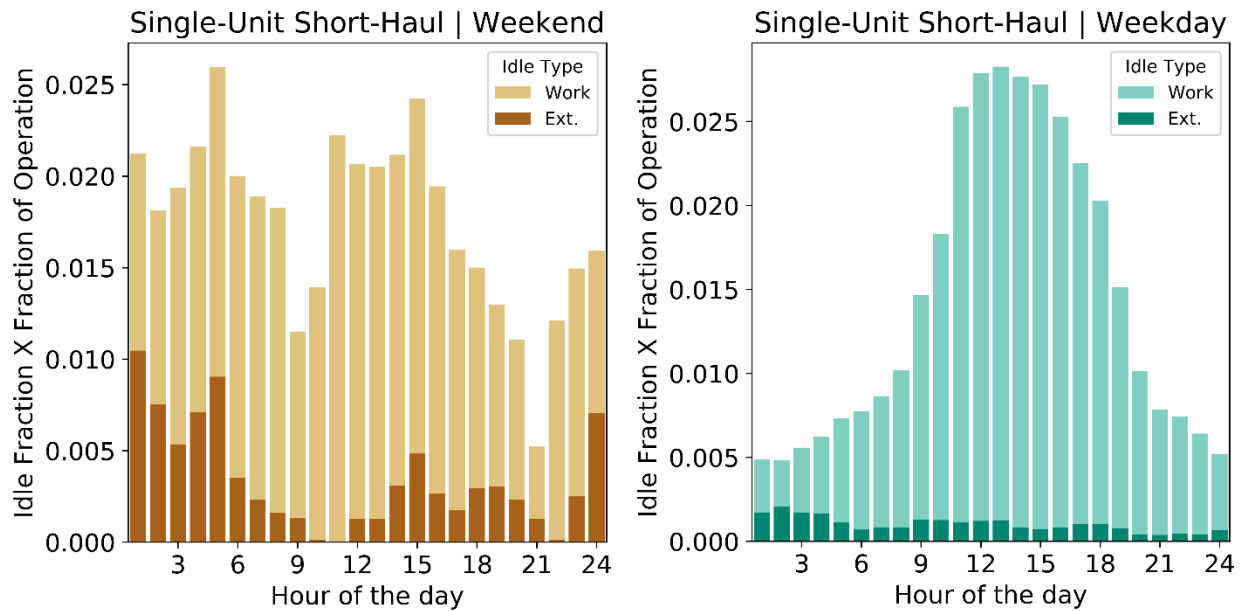


Figure H4. Hourly idle fraction vs. hour of the day for single-unit short haul

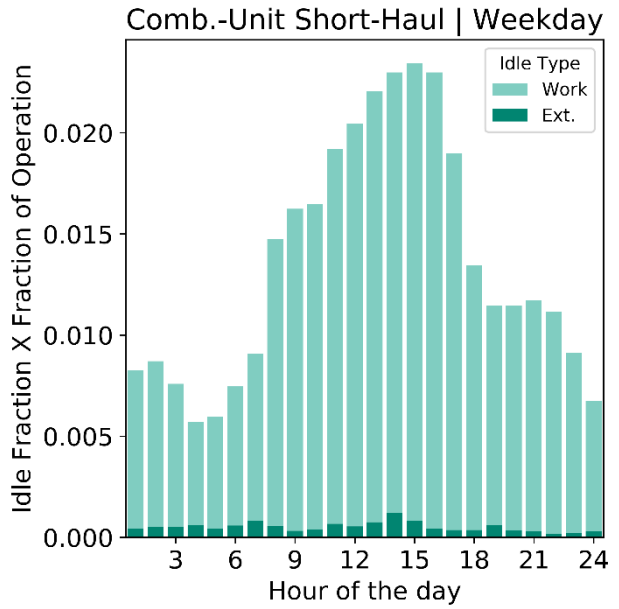
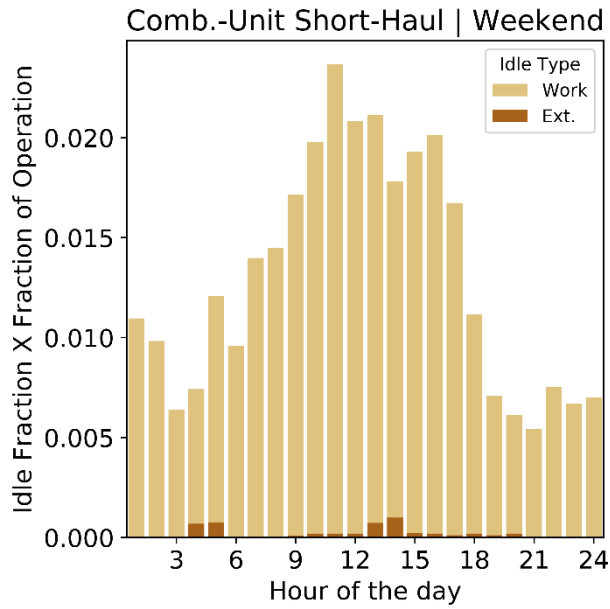


Figure H5. Hourly idle fraction vs. hour of the day for combination-unit short haul

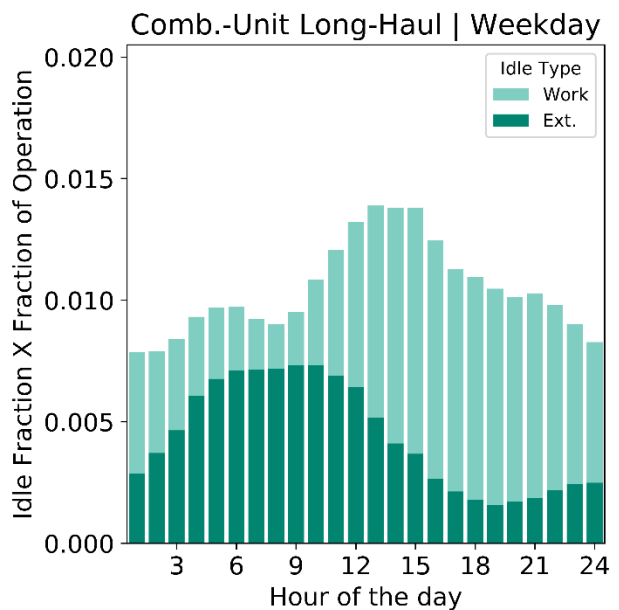
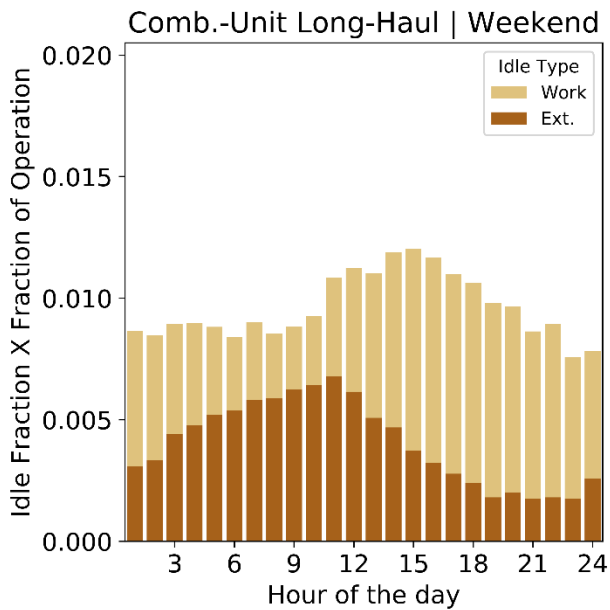


Figure H6. Hourly idle fraction vs. hour of the day for combination-unit long haul

Appendix I: Result by Vocation – Fleet DNA Data

Note: CU indicates combination-unit and SU indicates single-unit for short-haul vehicles

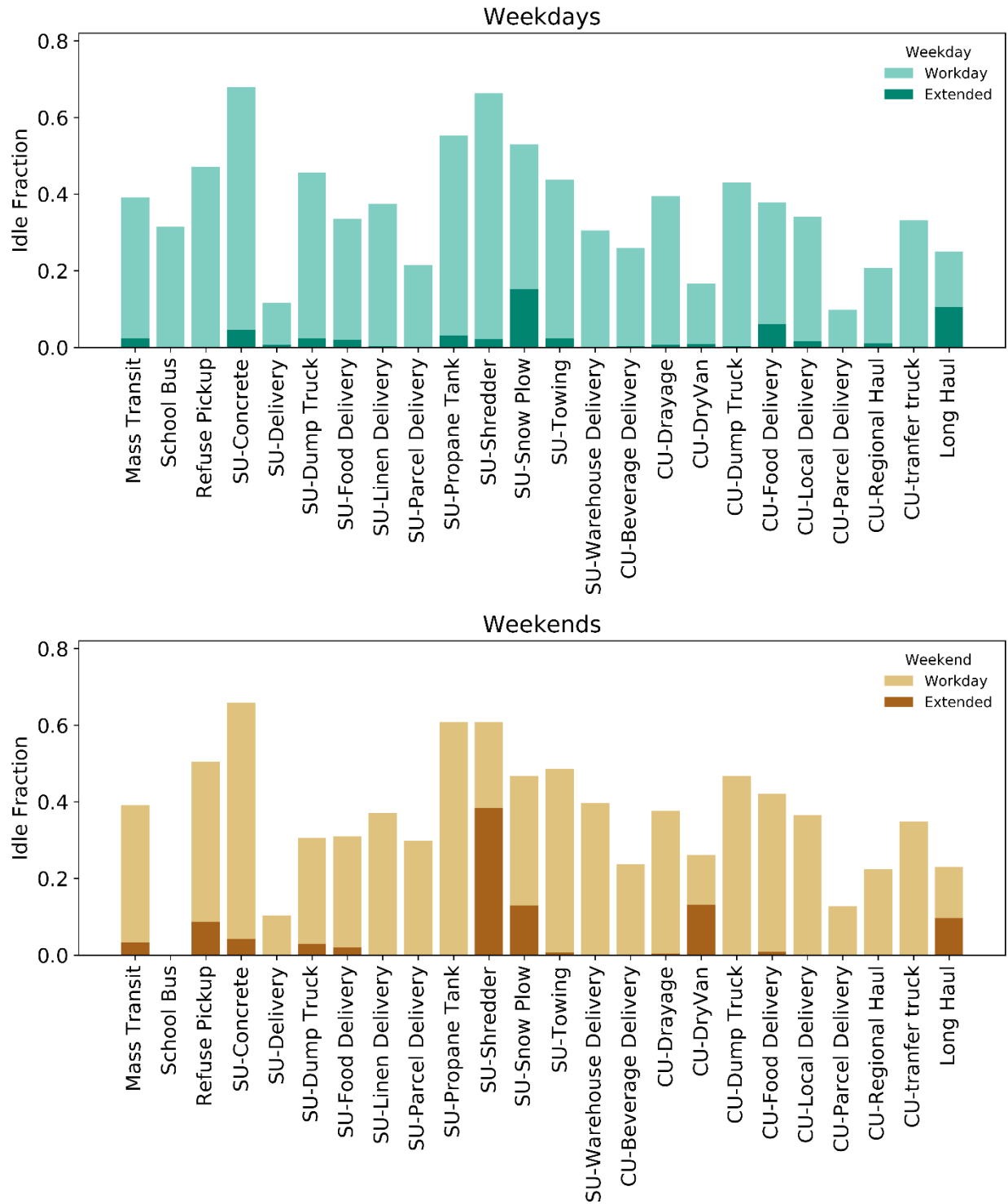


Figure I1. Vocation-based idle fraction distribution

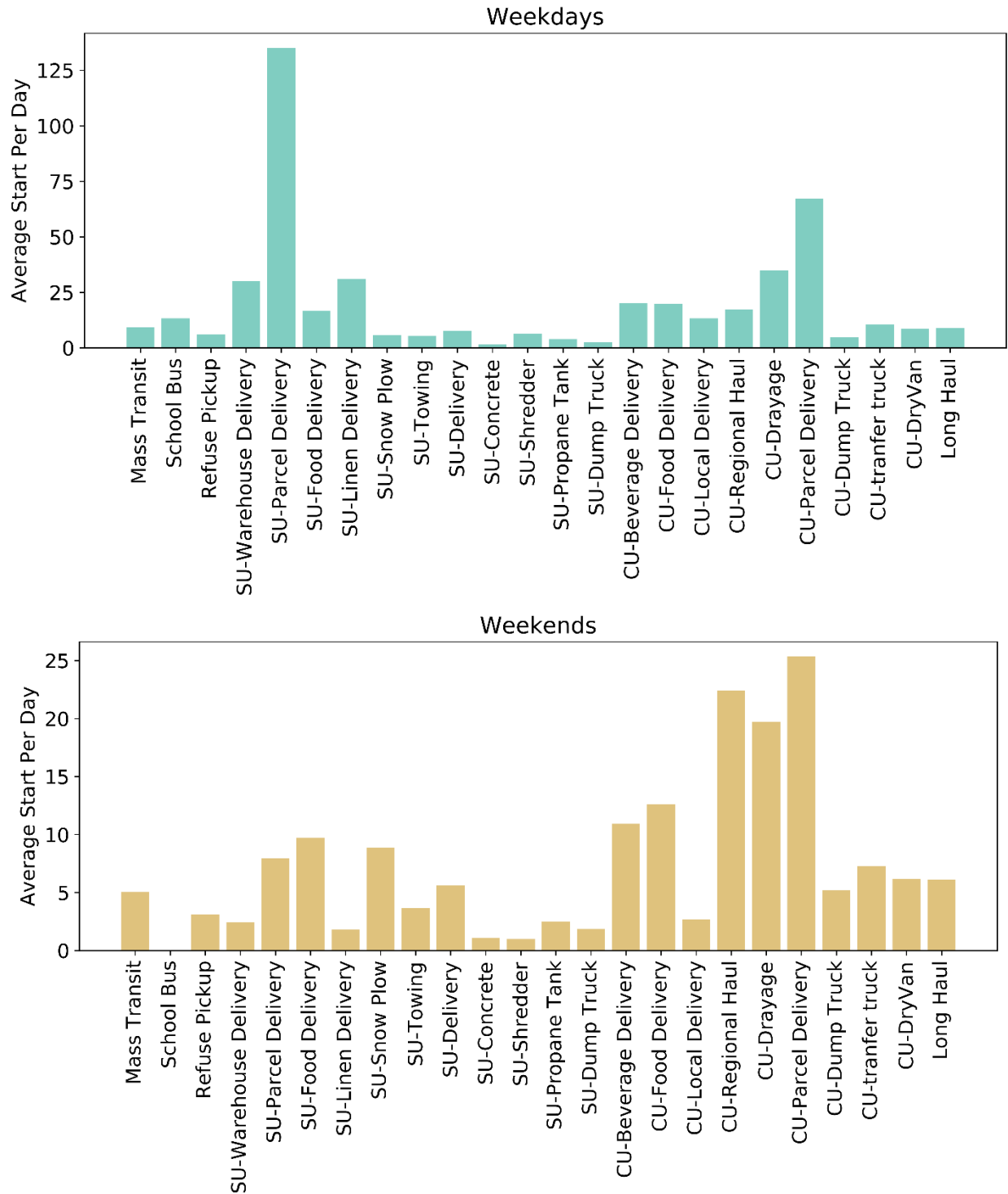


Figure I2. Vocation-based average start per day distribution

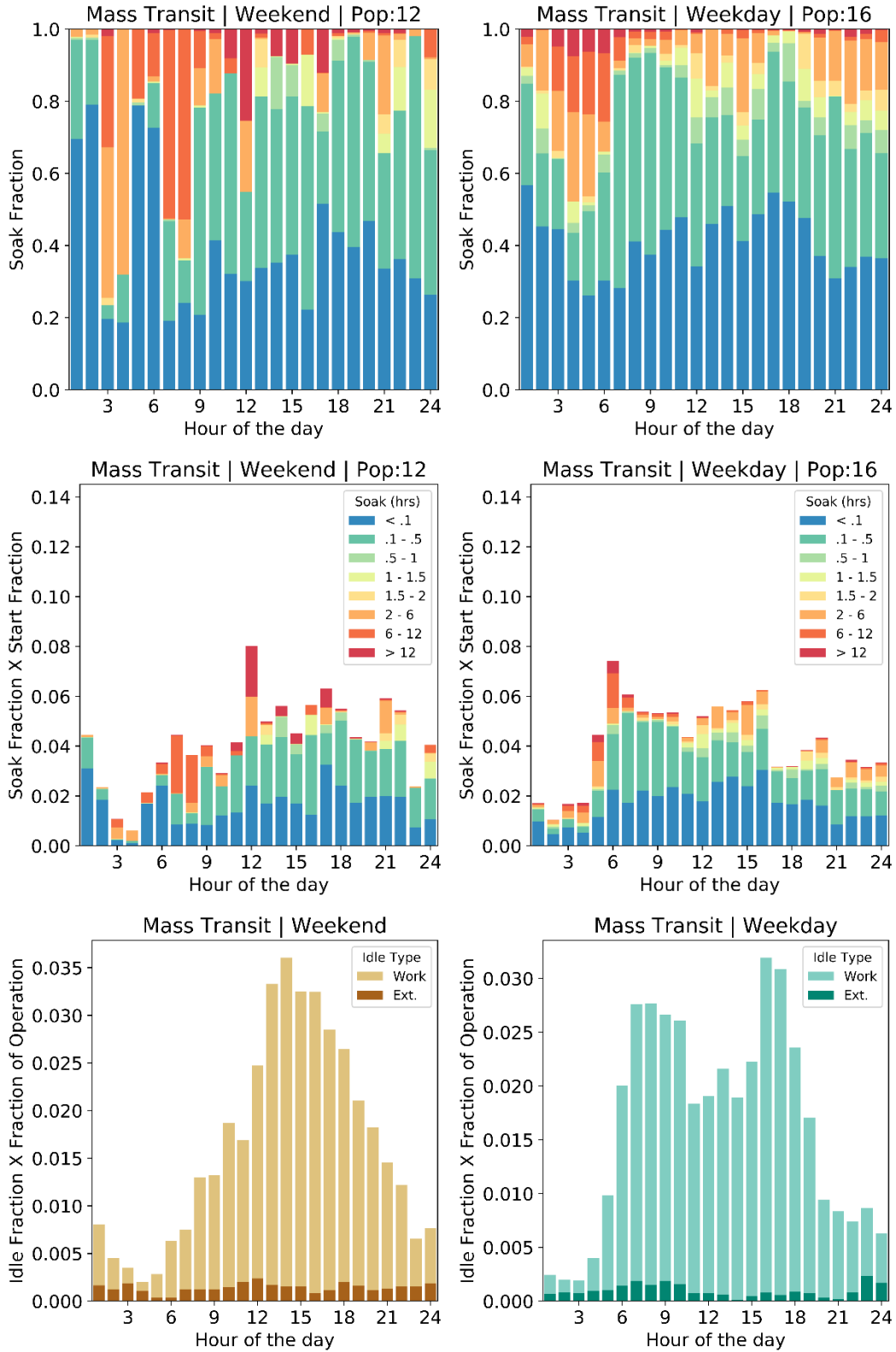


Figure I3. Start, soak, and idle performance of transit bus

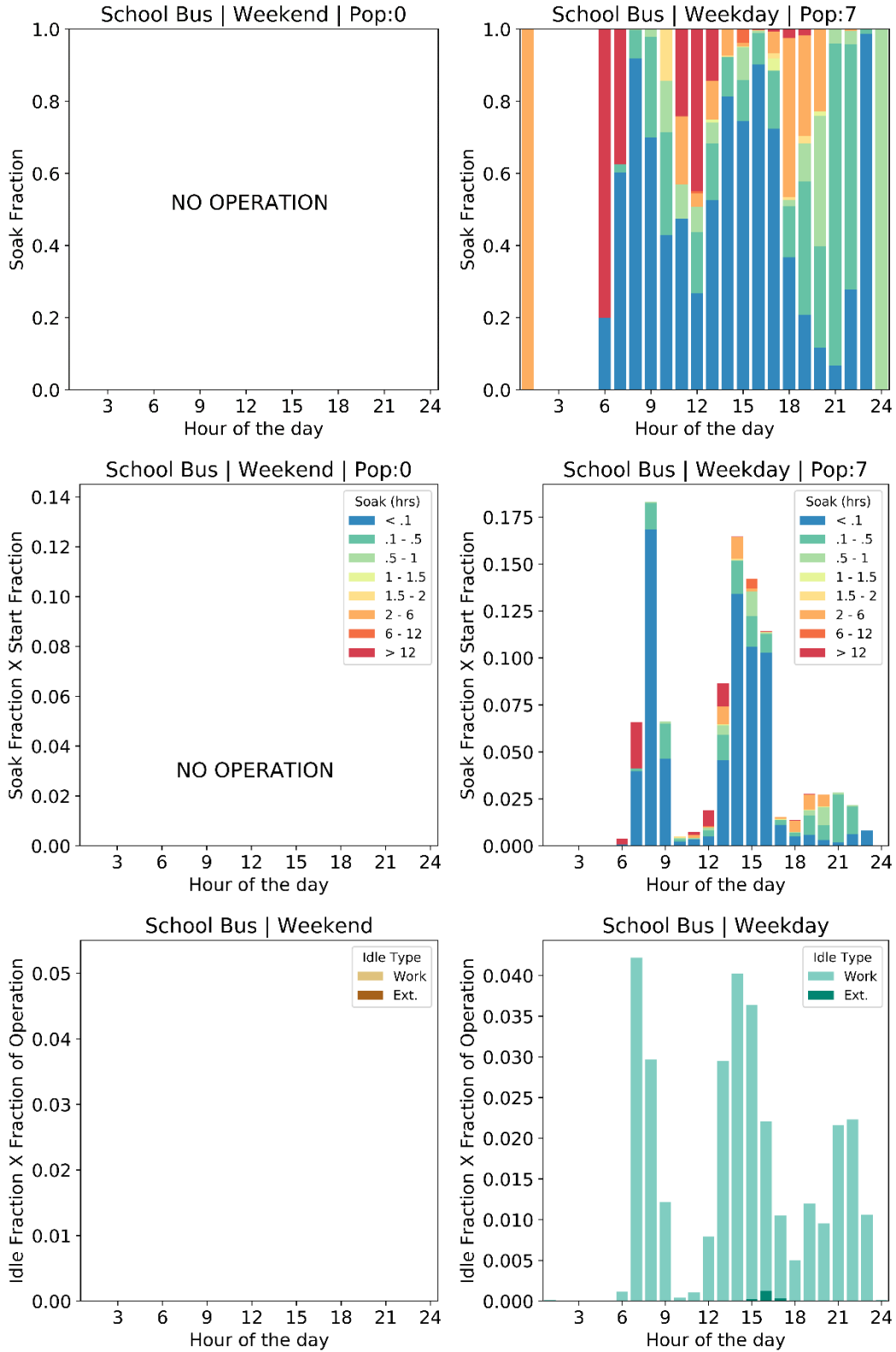


Figure I4. Start, soak, and idle performance of school bus

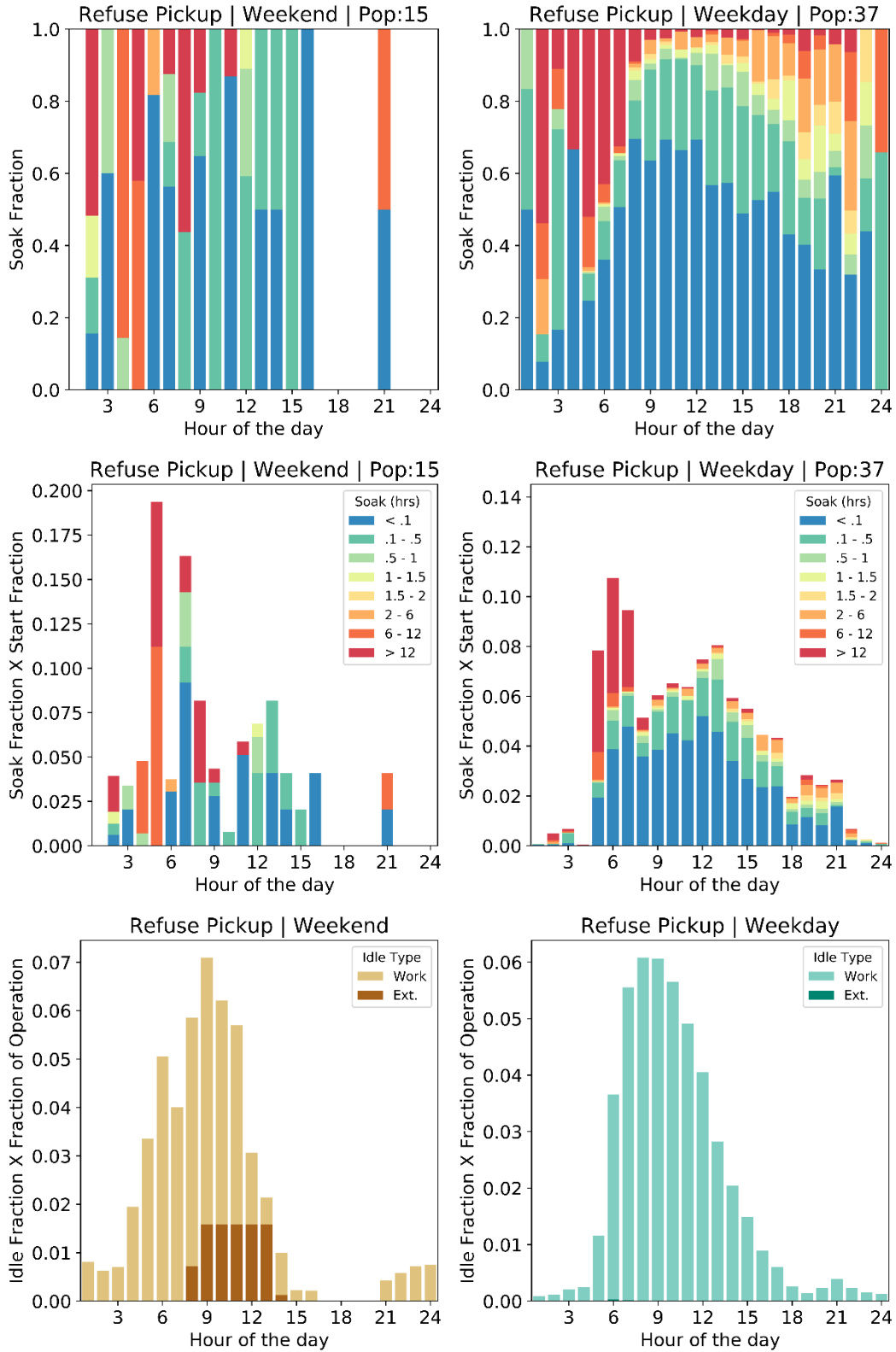


Figure 15. Start, soak, and idle performance of refuse pickup

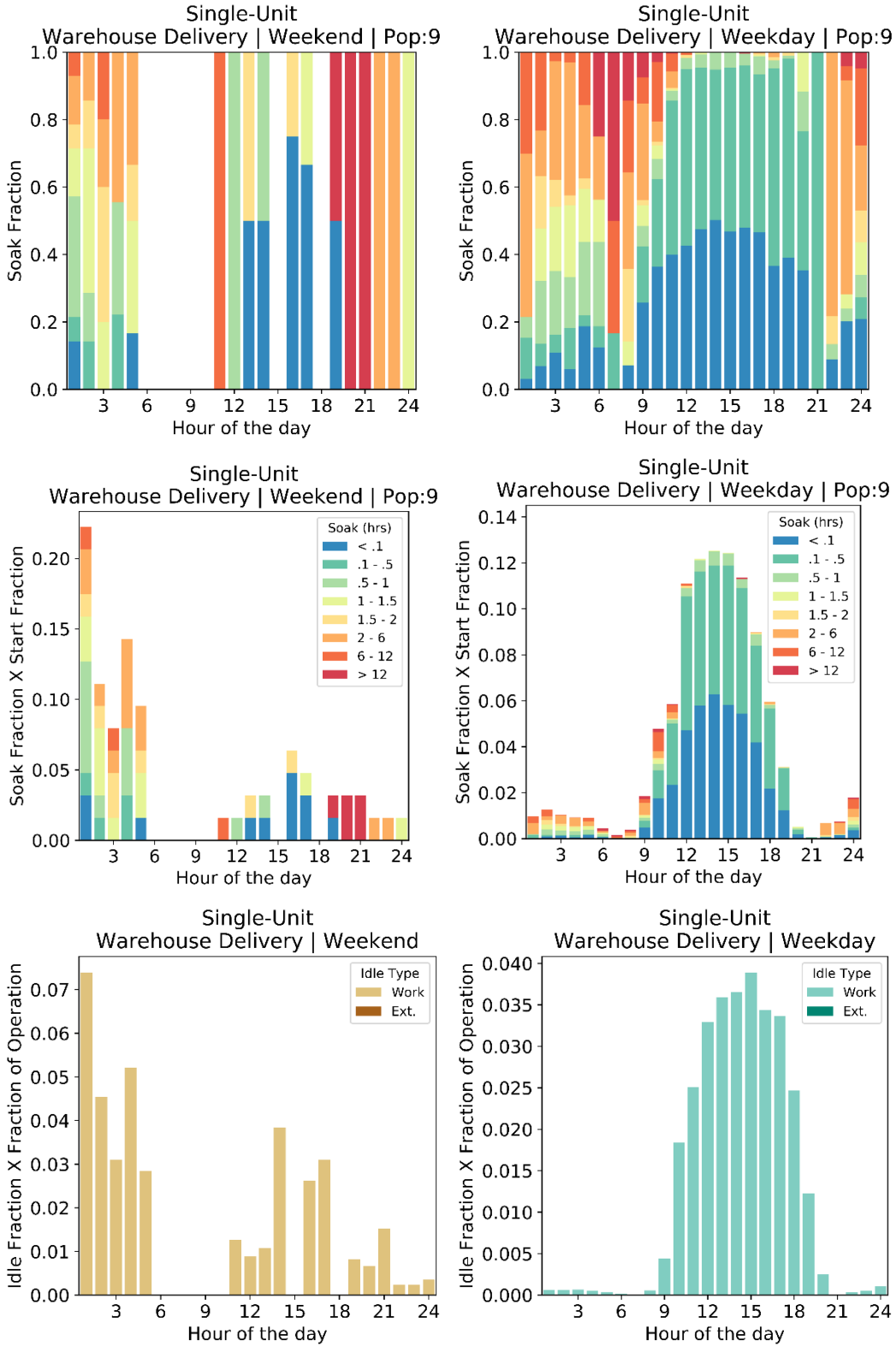


Figure I6. Start, soak, and idle performance of single-unit short haul – warehouse delivery

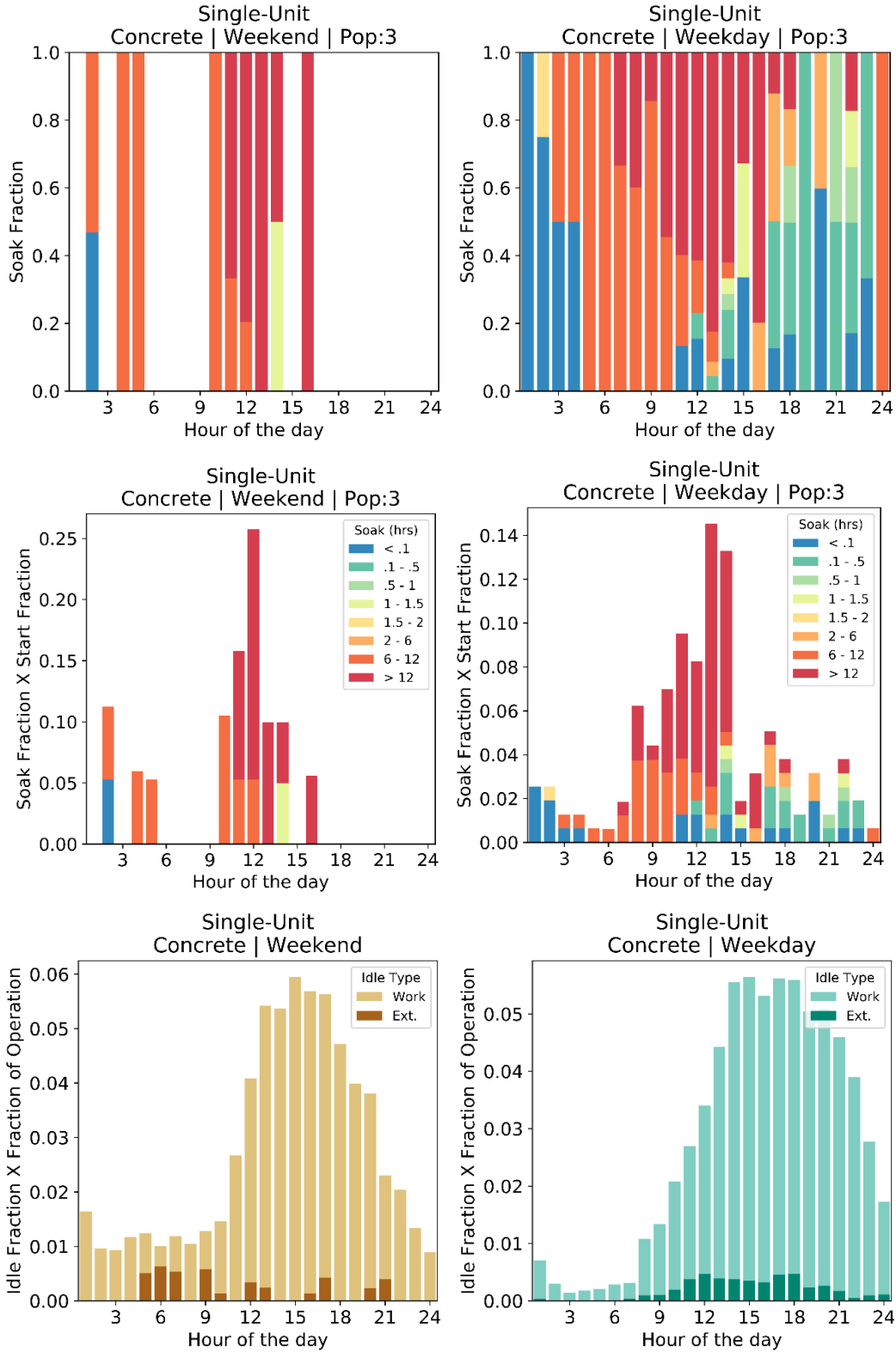


Figure I7. Start, soak, and idle performance of single-unit short haul – concrete

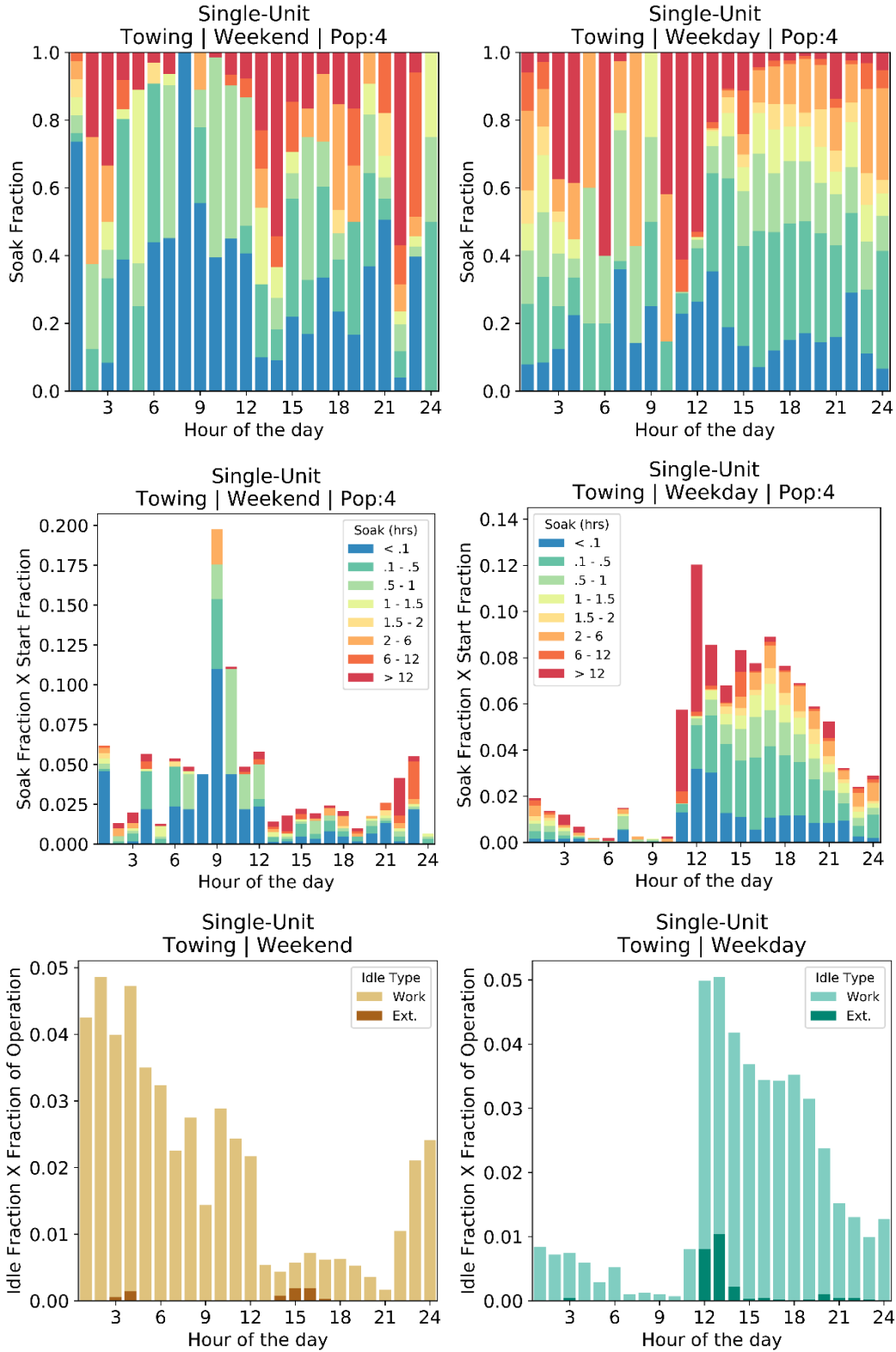


Figure I8. Start, soak, and idle performance of single-unit short haul – towing

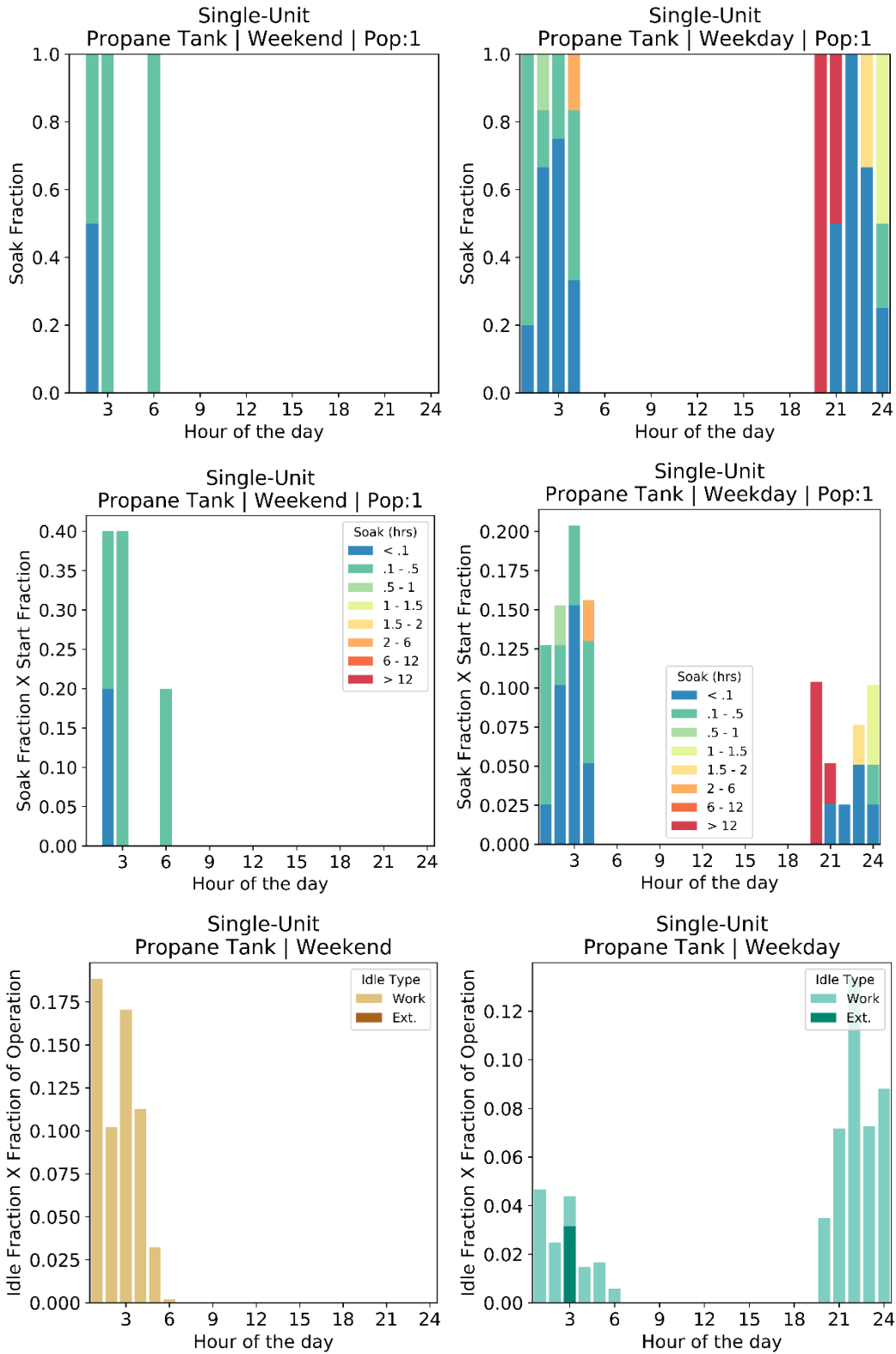


Figure I9. Start, soak, and idle performance of single-unit short haul – propane tank

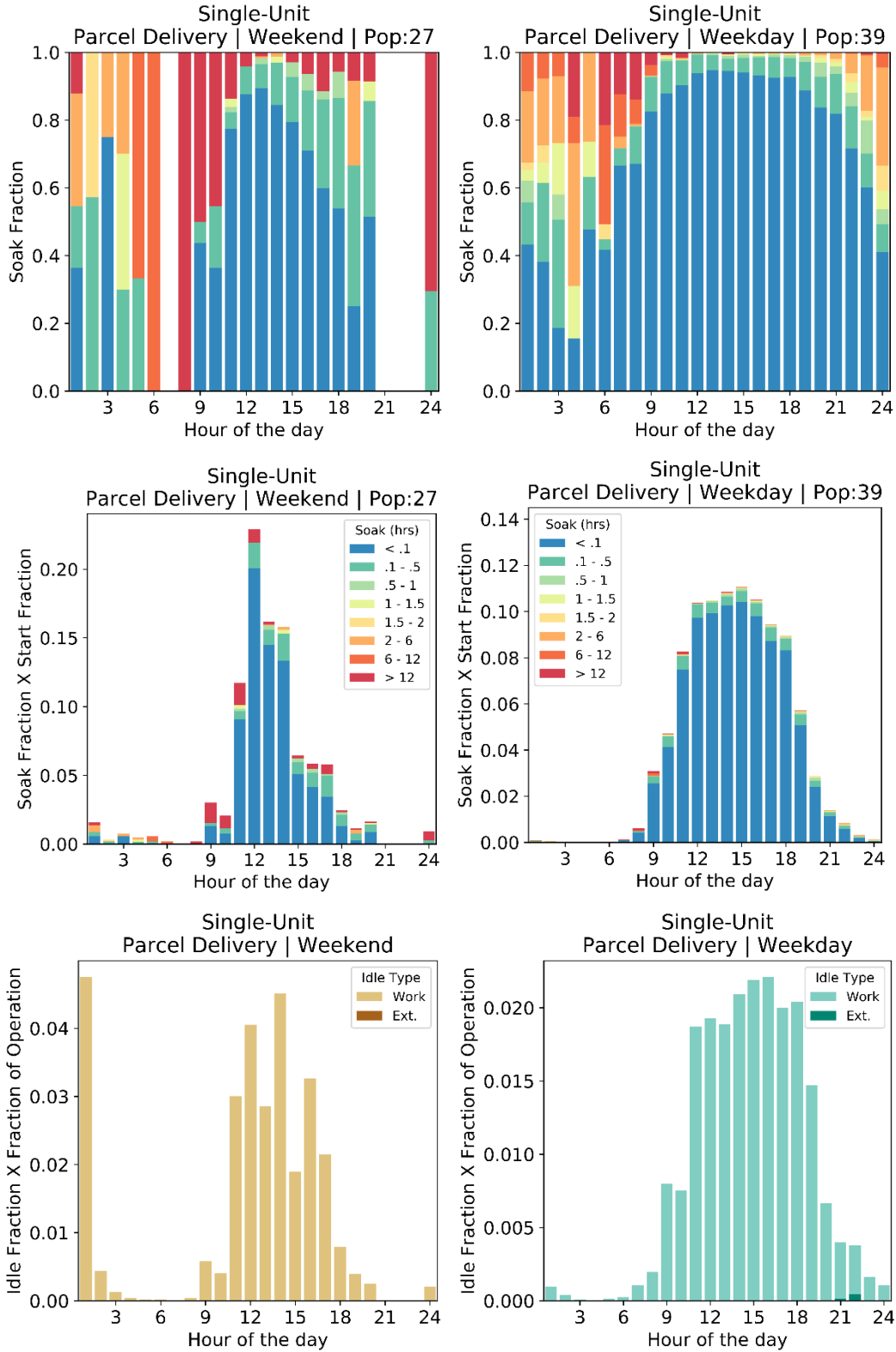


Figure I10. Start, soak, and idle performance of single-unit short haul – parcel delivery

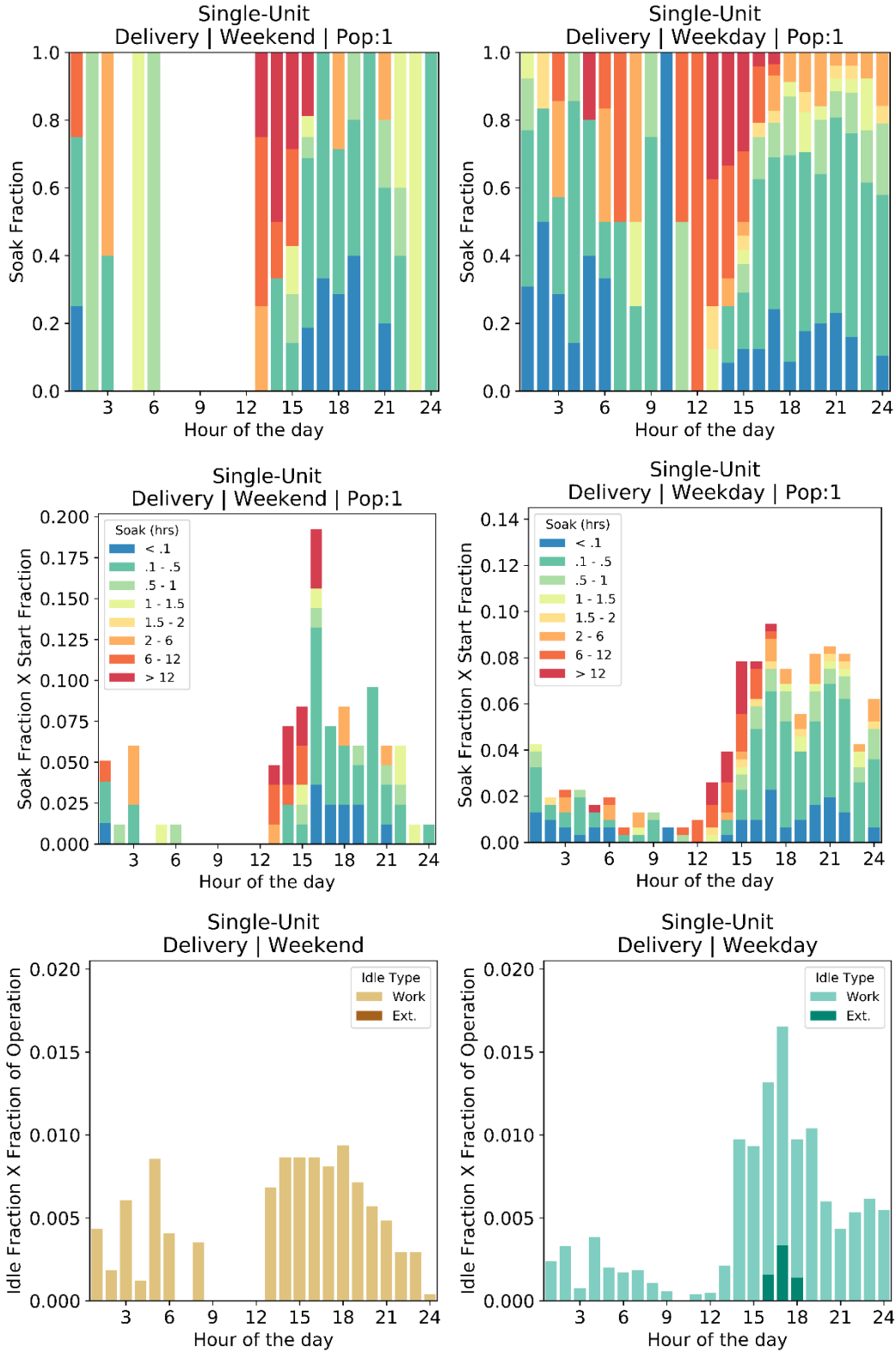


Figure I11. Start, soak, and idle performance of single-unit short haul – delivery

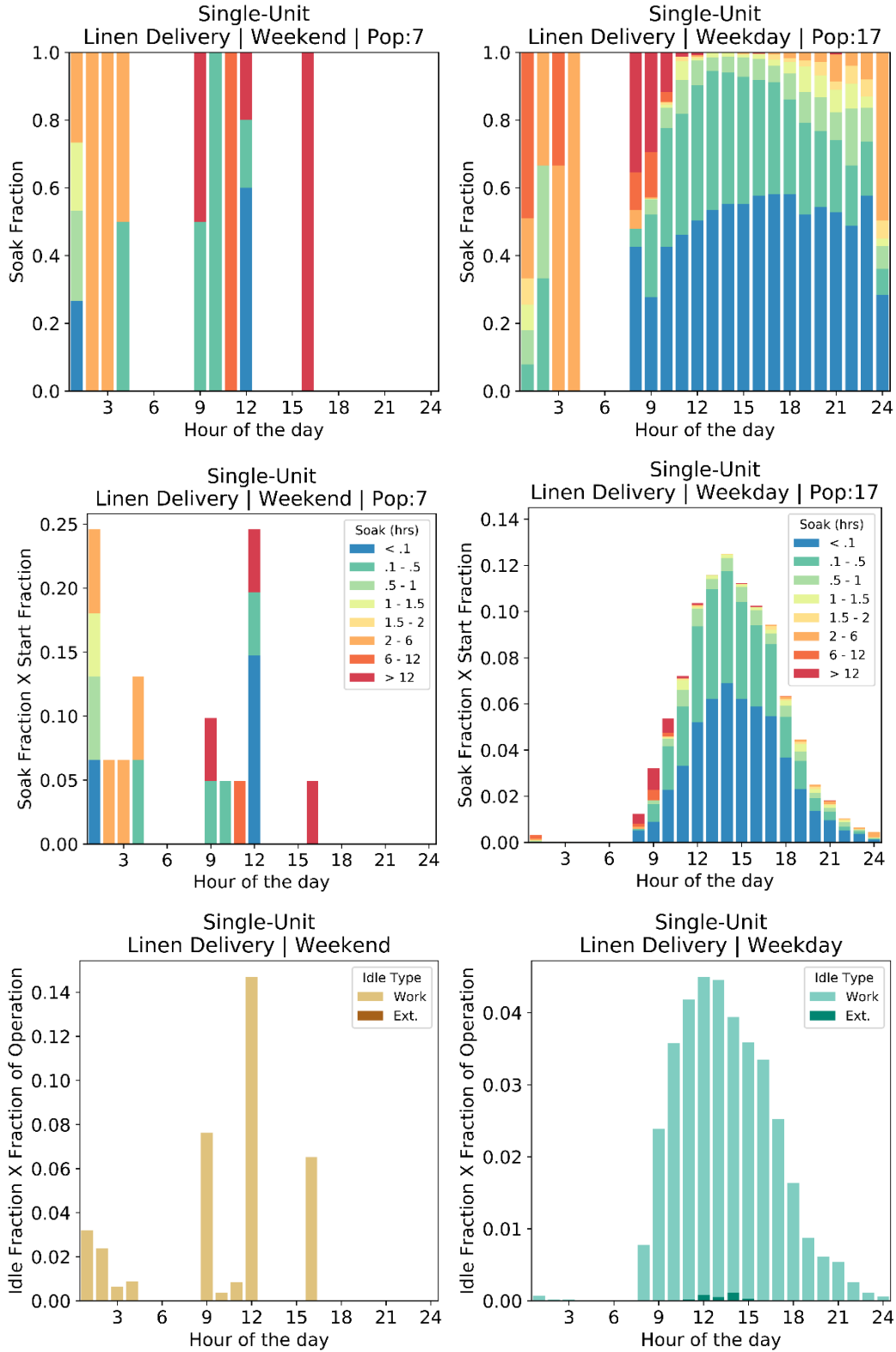


Figure I12. Start, soak, and idle performance of single-unit short haul – linen delivery

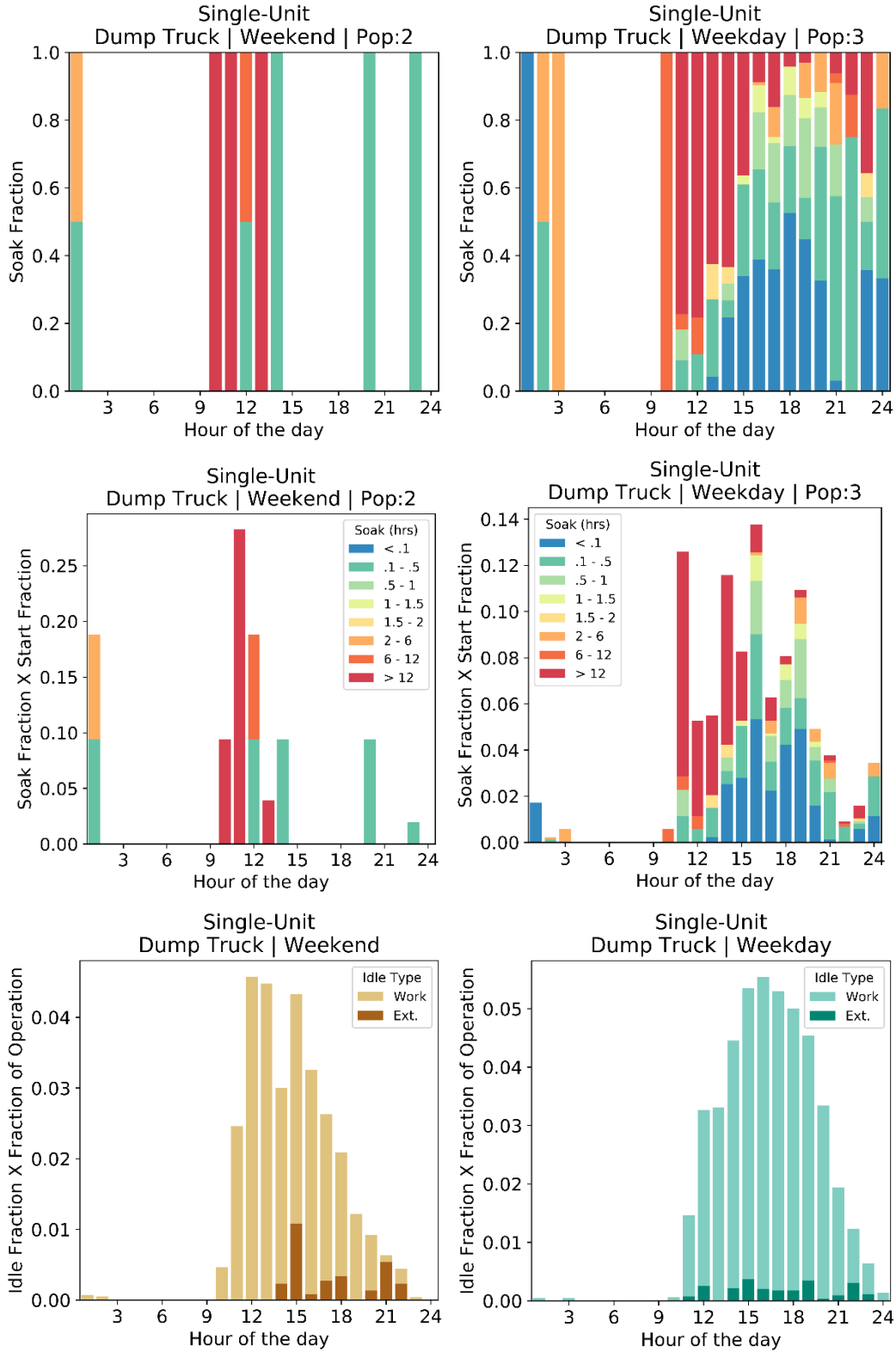


Figure I13. Start, soak, and idle performance of single-unit short haul – dump truck

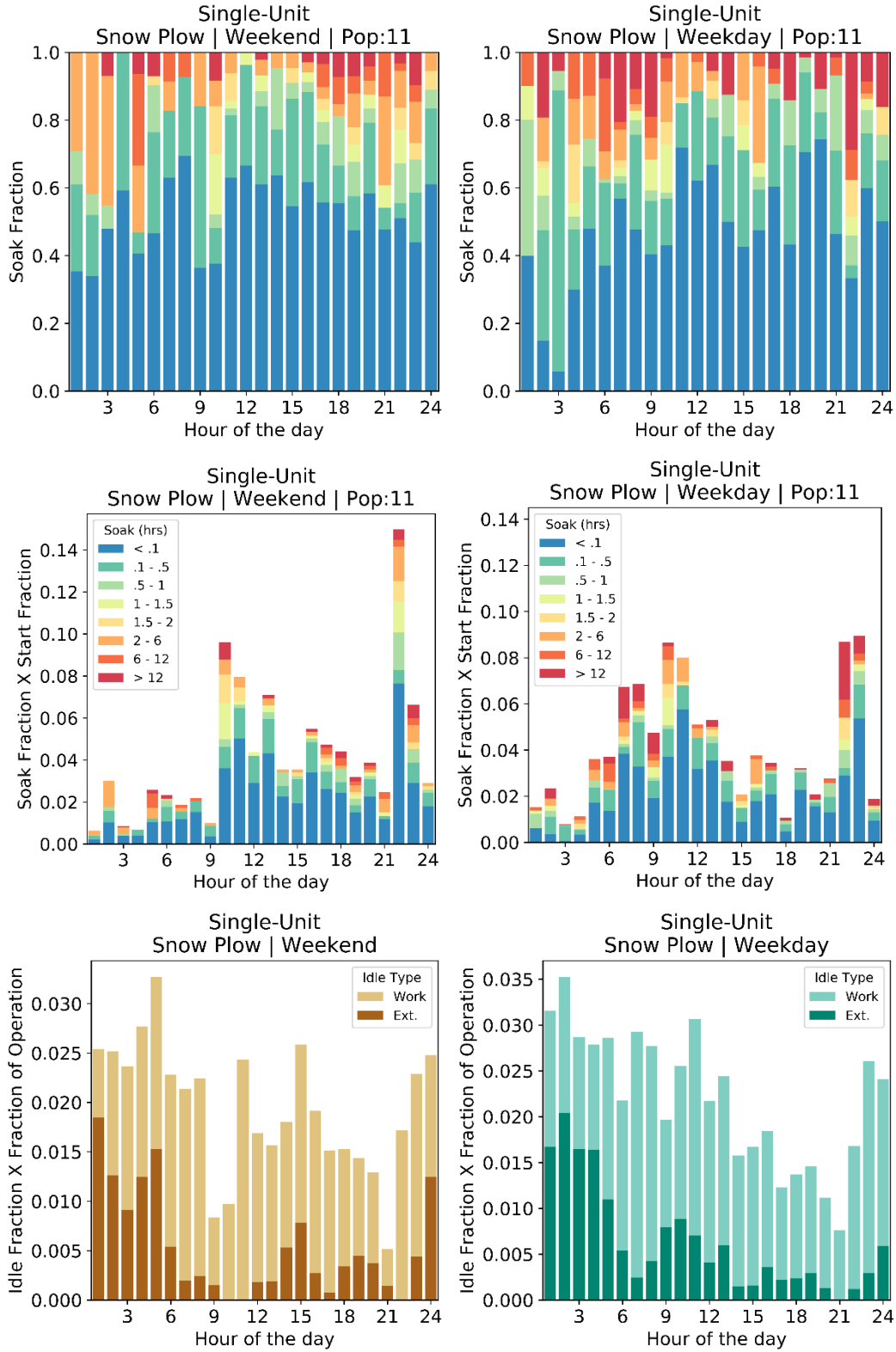


Figure I14. Start, soak, and idle performance of single-unit short haul – snow plow

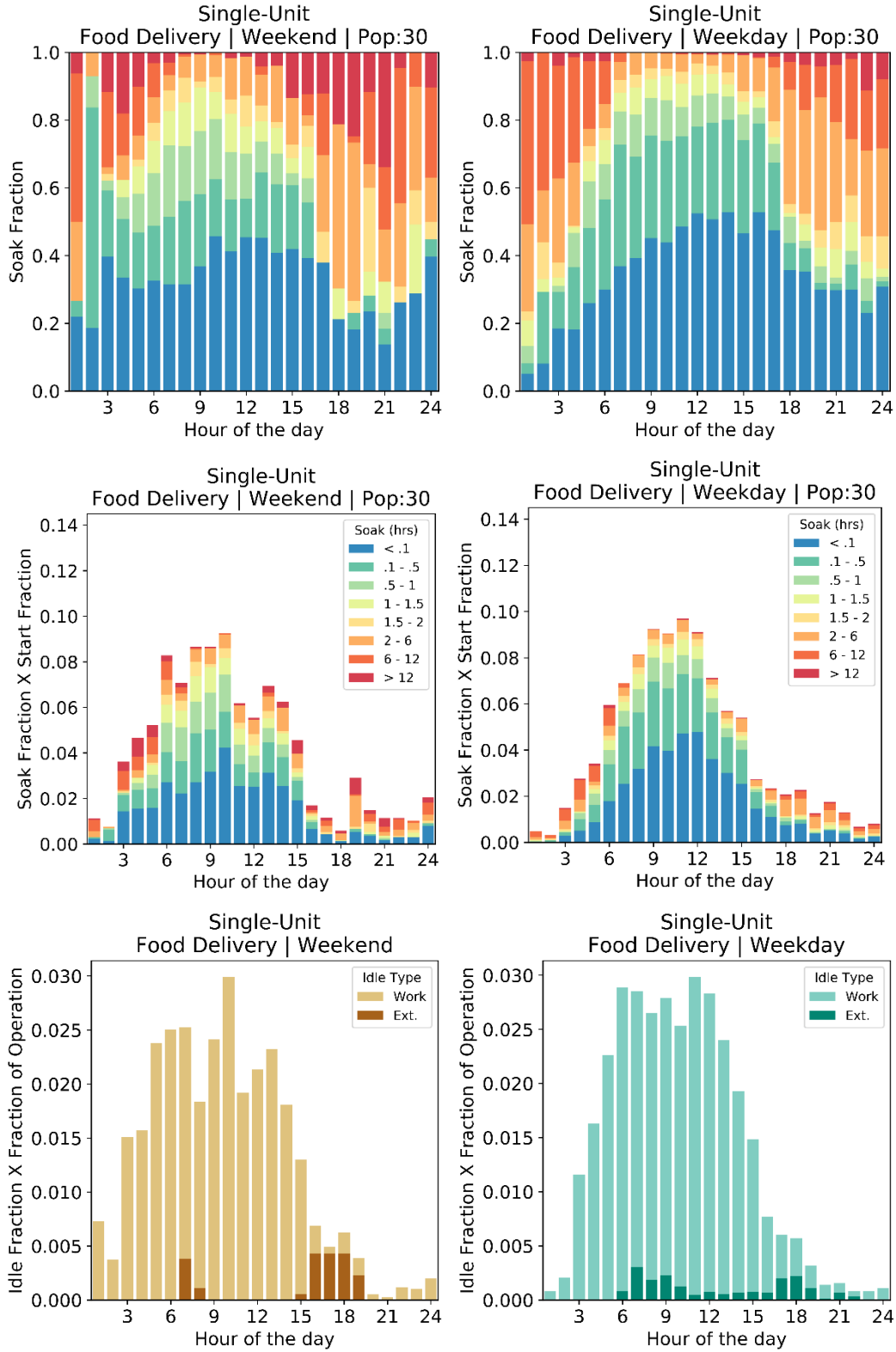


Figure I15. Start, soak, and idle performance of single-unit short haul – food delivery

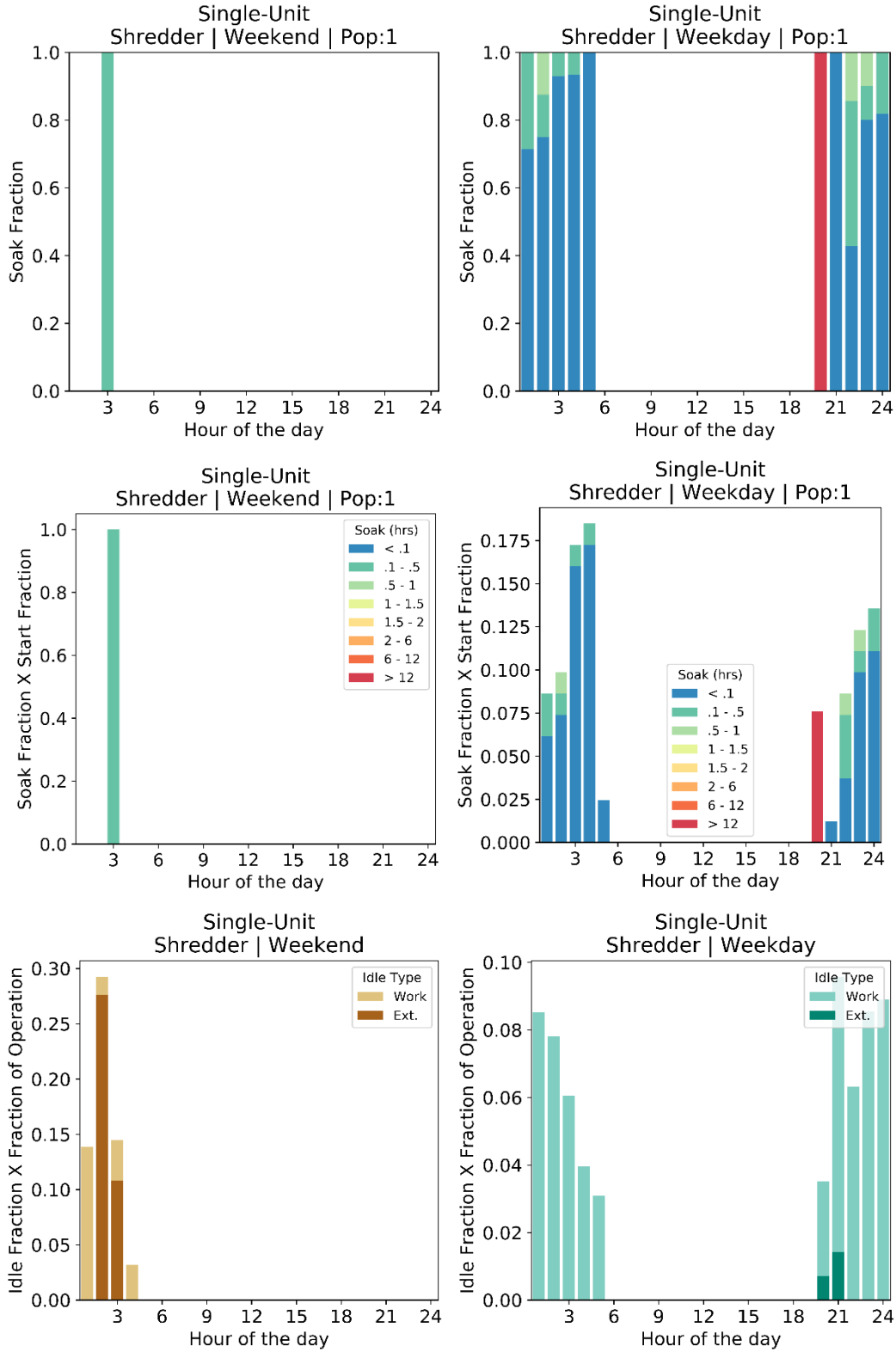


Figure I16. Start, soak, and idle performance of single-unit short haul – shredder

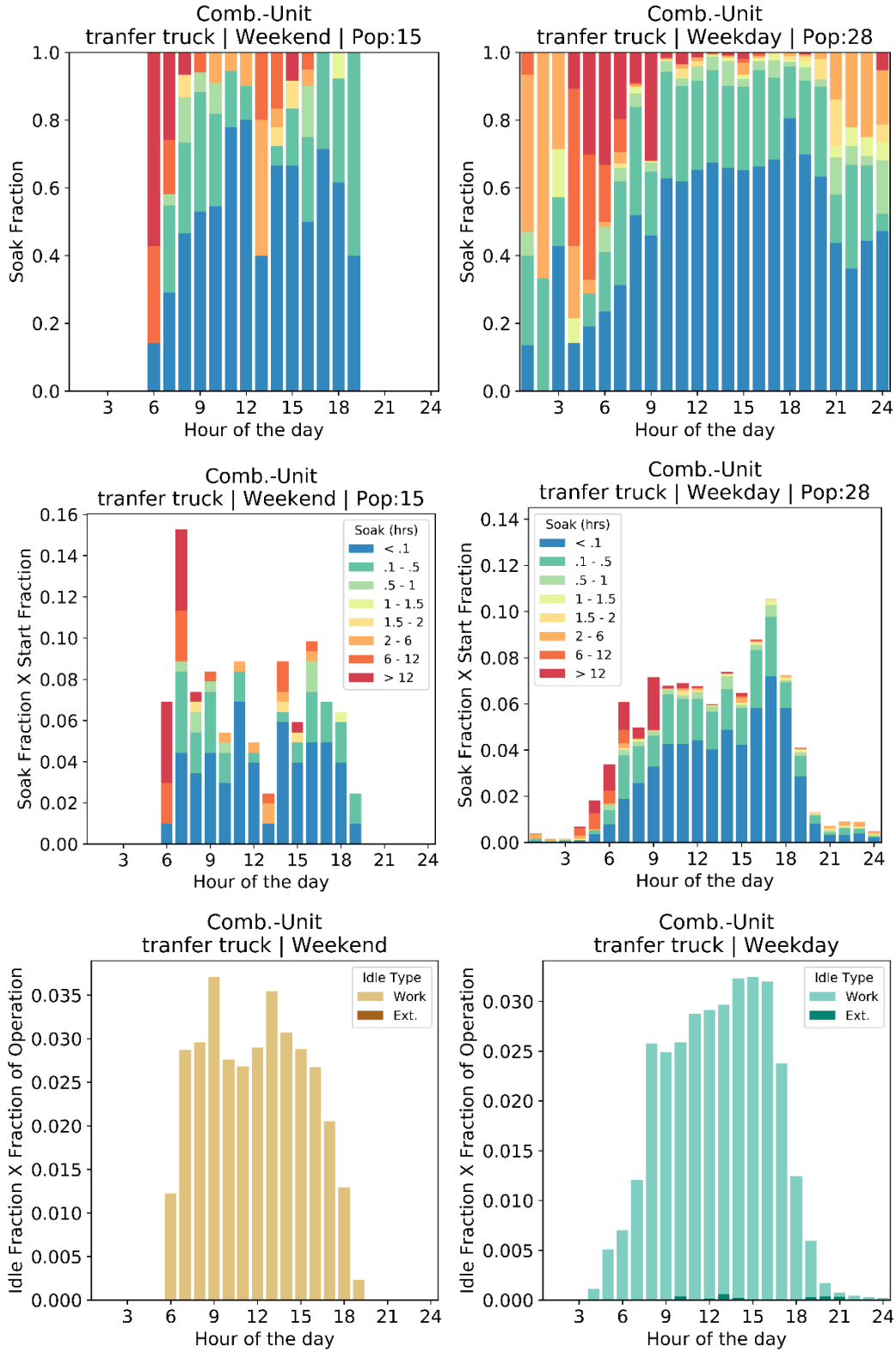


Figure I17. Start, soak, and idle performance of combination-unit short haul – transfer truck

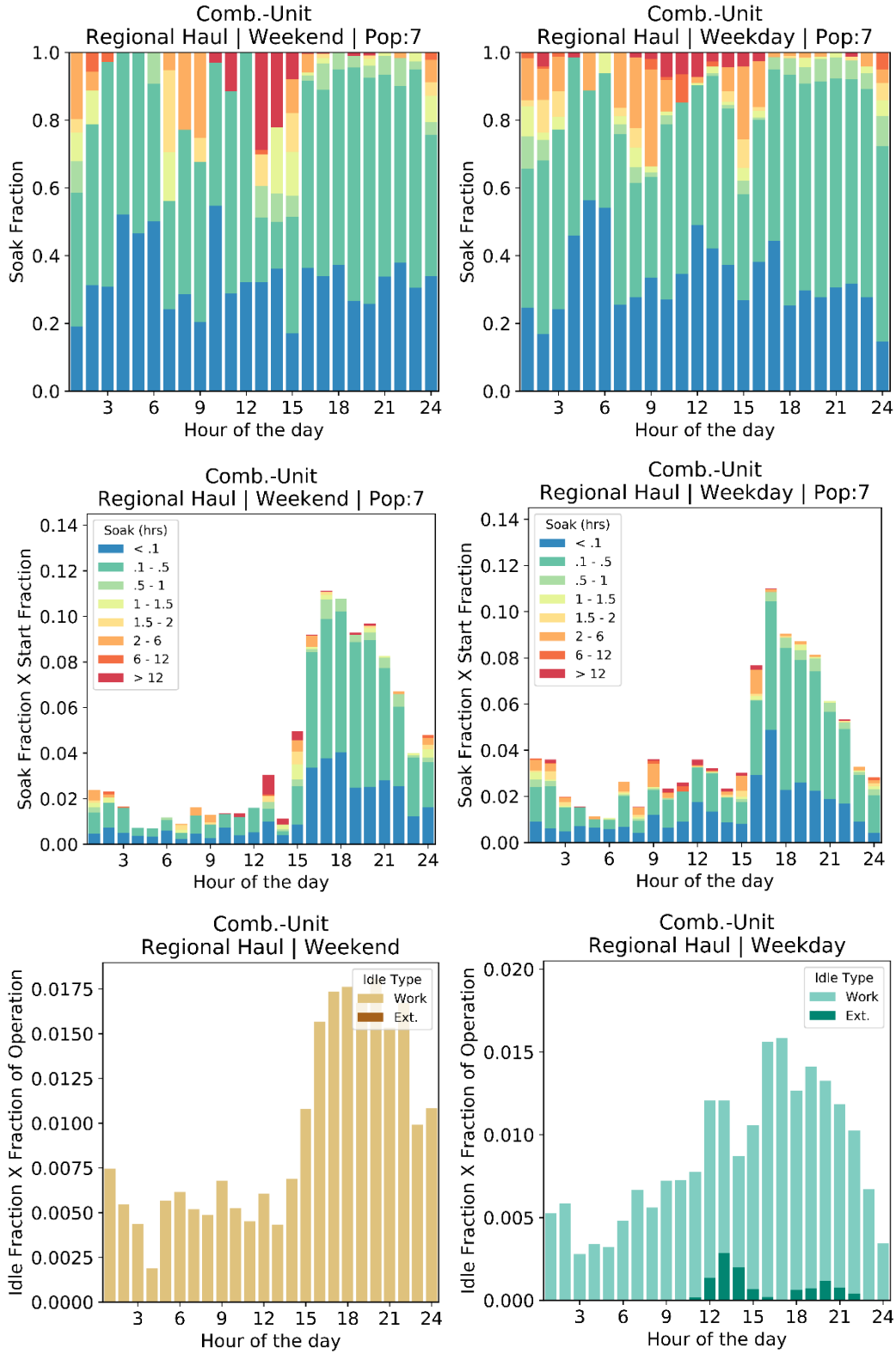


Figure I18. Start, soak, and idle performance of combination-unit short haul – regional haul

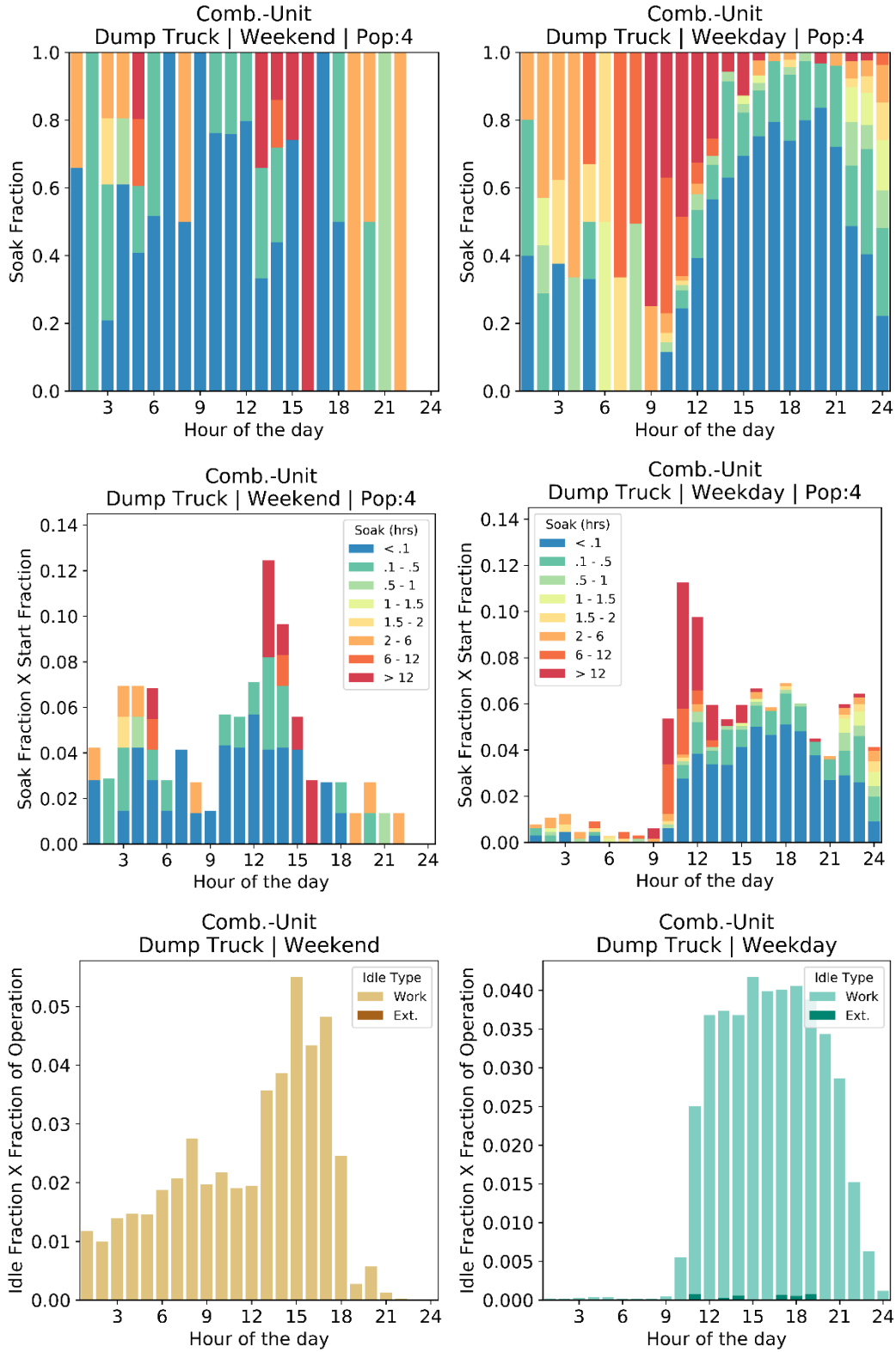


Figure I19. Start, soak, and idle performance of combination-unit short haul – dump truck

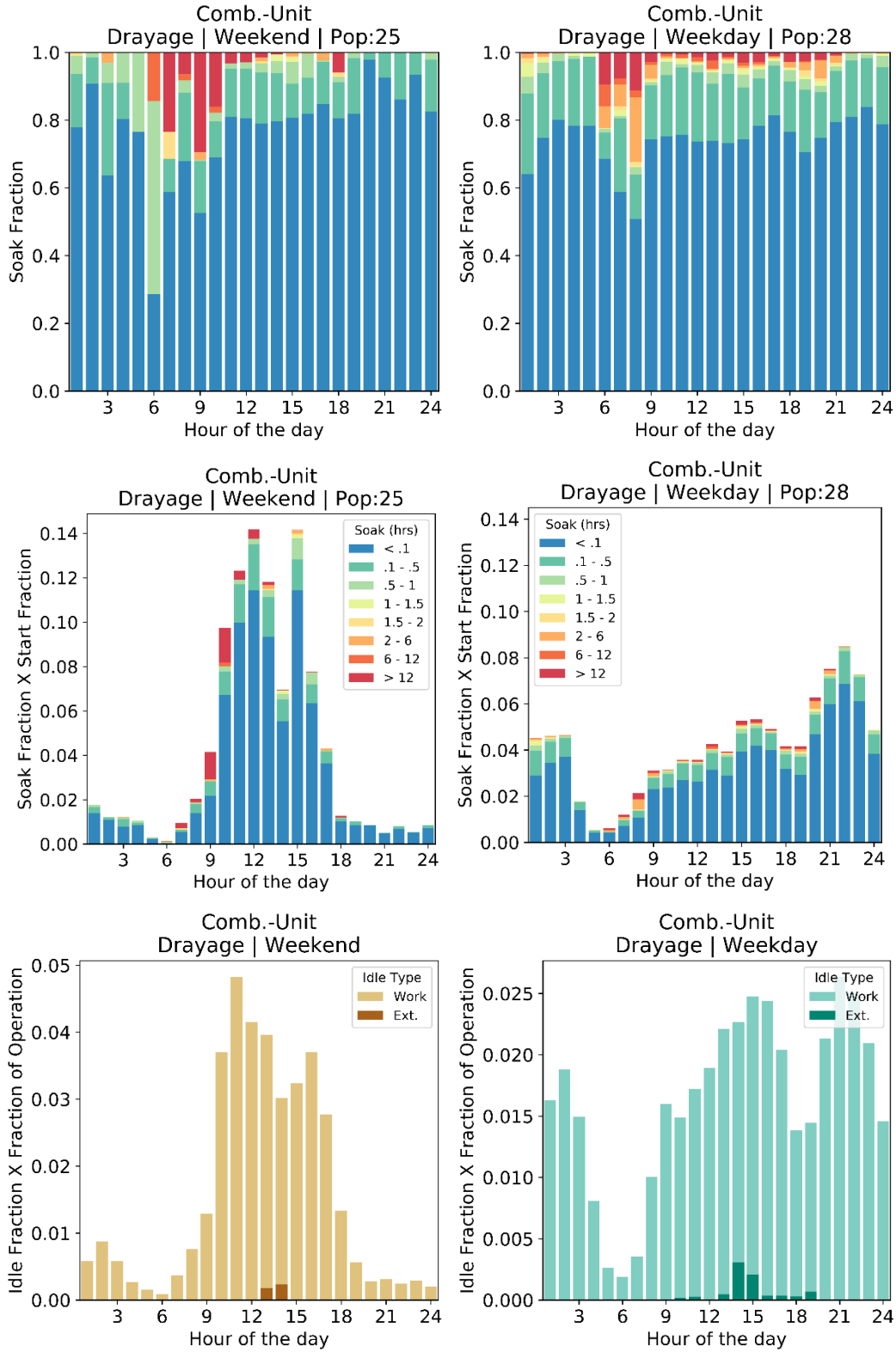


Figure I20. Start, soak, and idle performance of combination-unit short haul – drayage

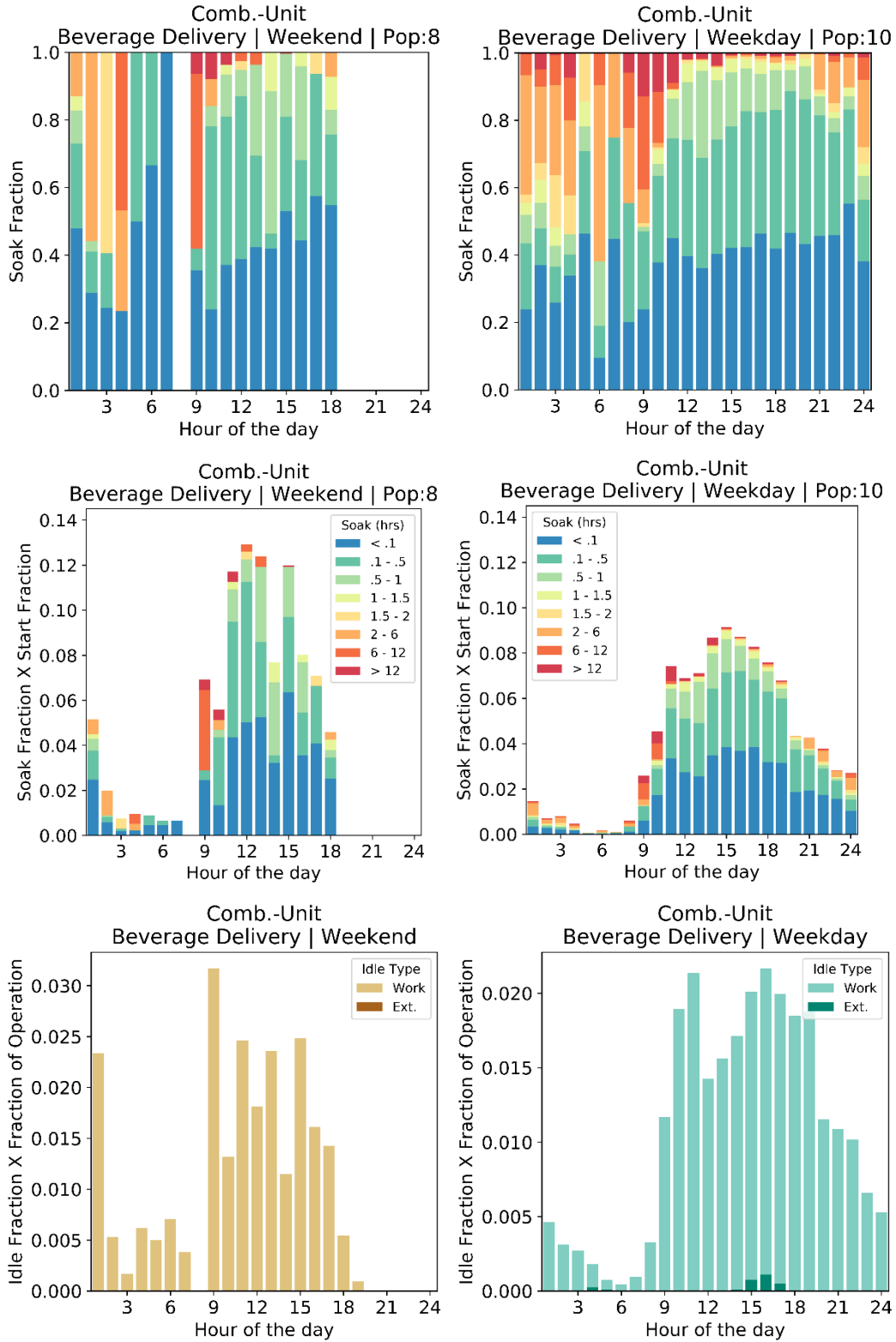


Figure I21. Start, soak, and idle performance of combination-unit short haul – beverage delivery

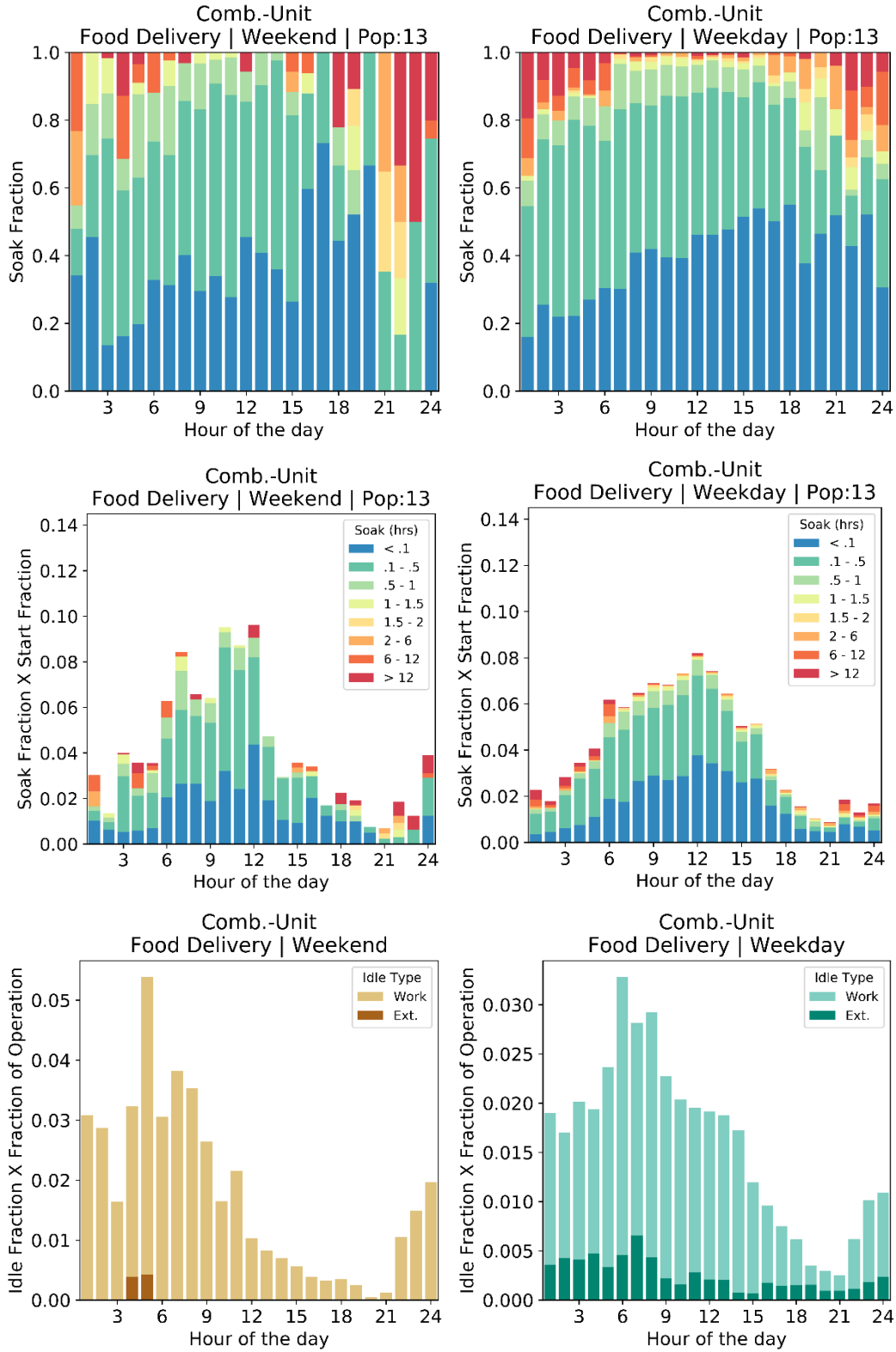


Figure I22. Start, soak, and idle performance of combination-unit short haul – food delivery

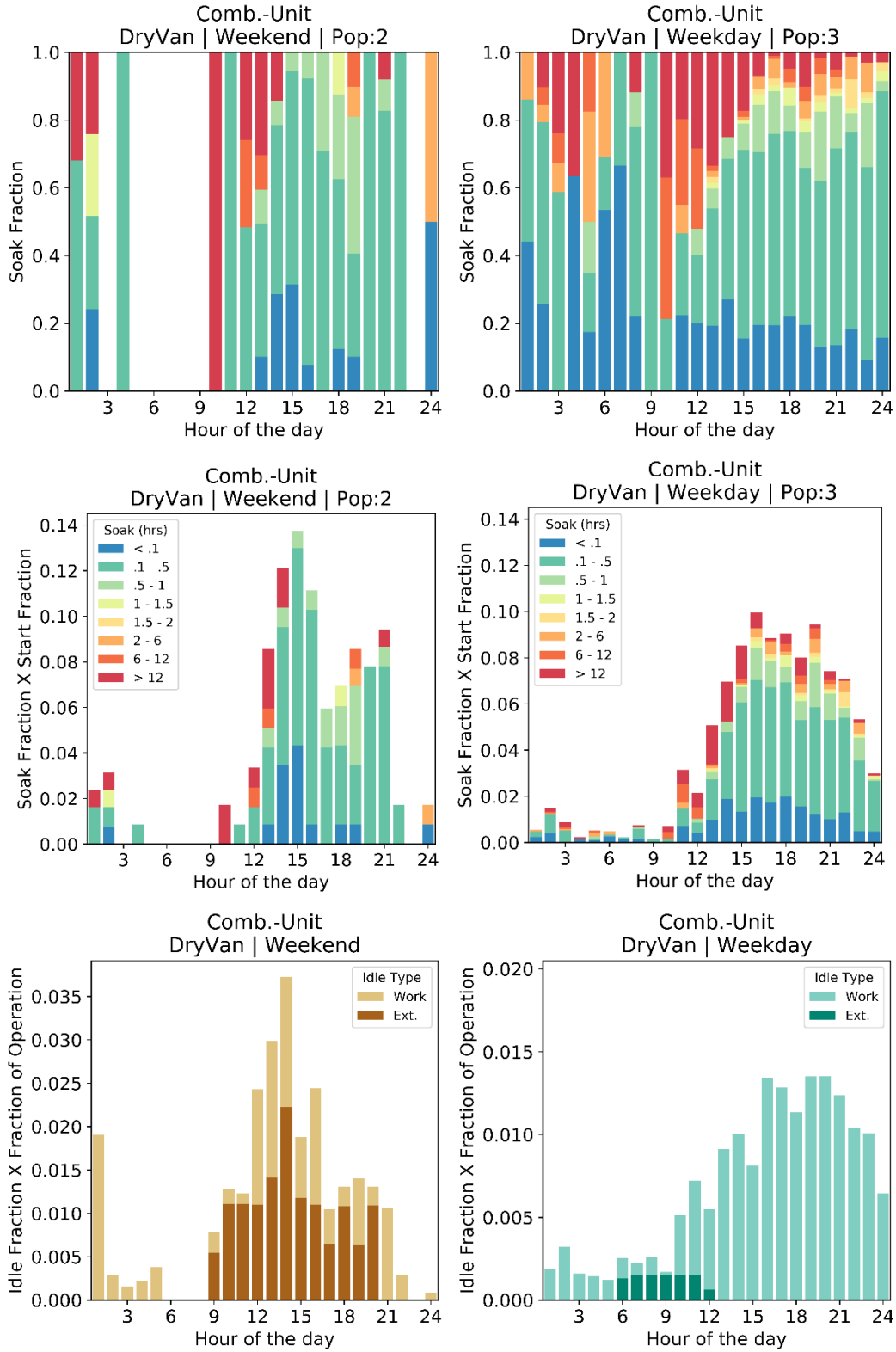


Figure I23. Start, soak, and idle performance of combination-unit short haul – dry van

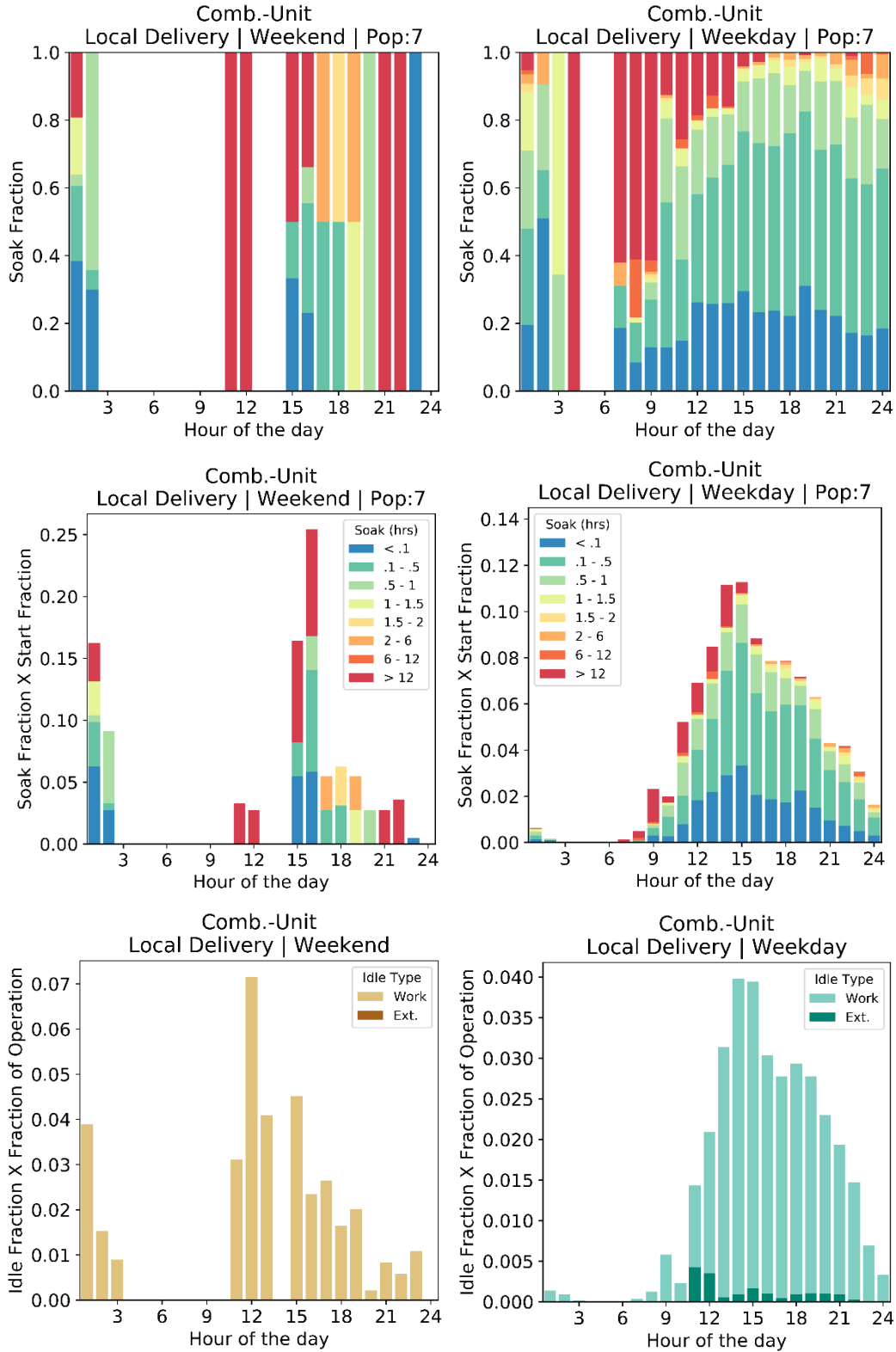


Figure I24. Start, soak, and idle performance of combination-unit short haul – local delivery

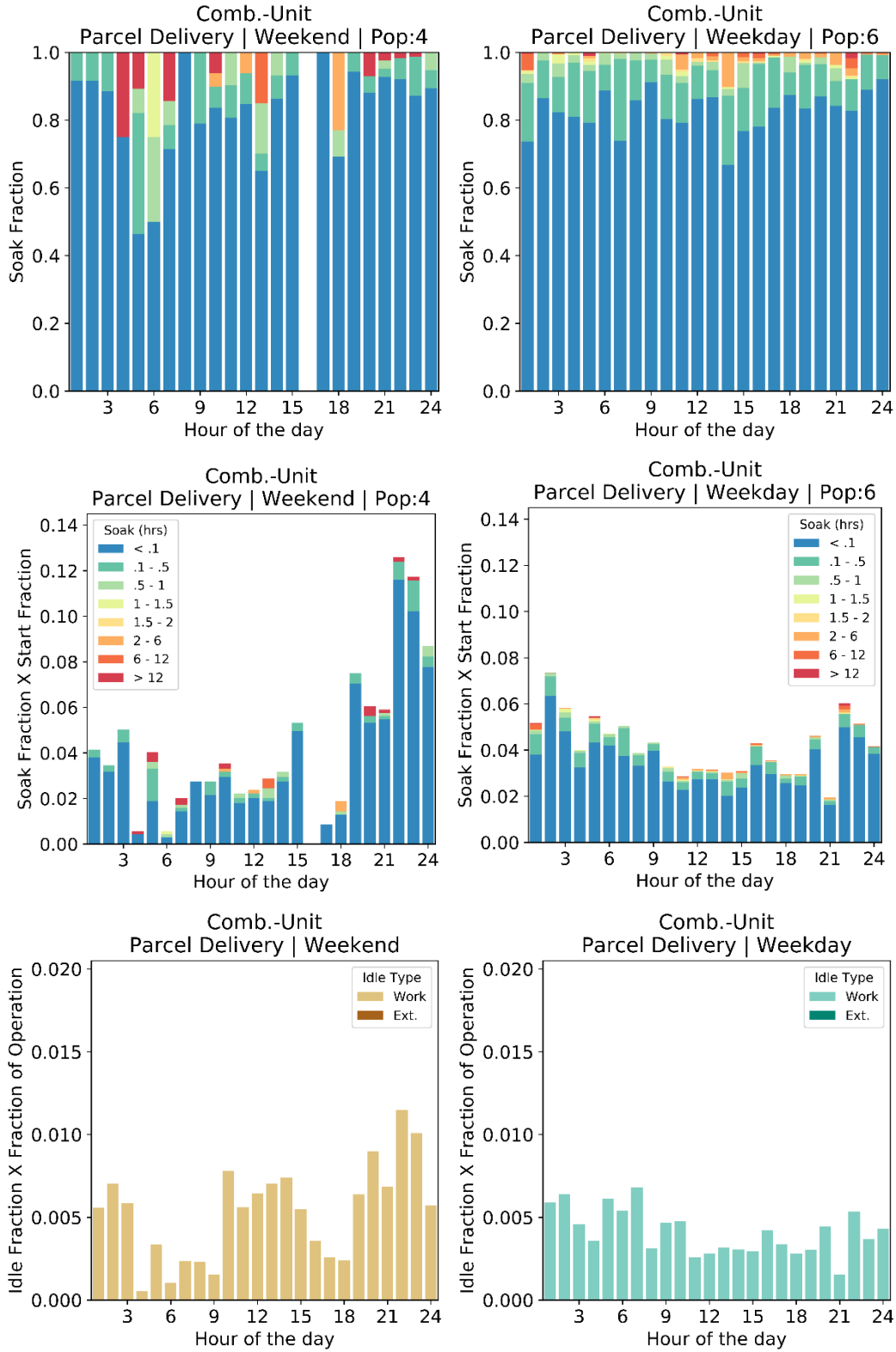


Figure I25. Start, soak, and idle performance of combination-unit short haul – parcel delivery

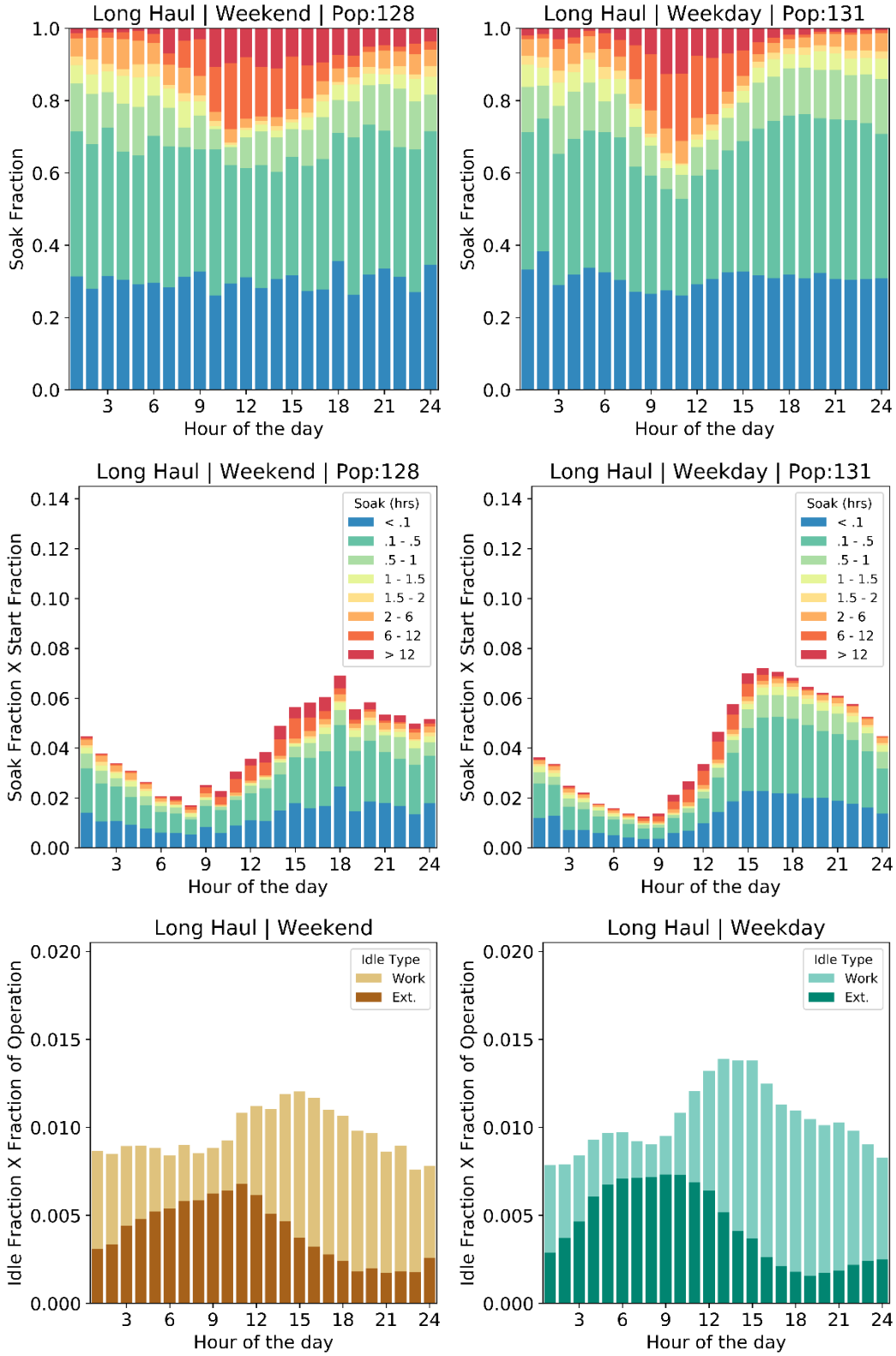


Figure I26. Start, soak, and idle performance of combination-unit long haul

Appendix J: Original and Additional Data in Fleet DNA

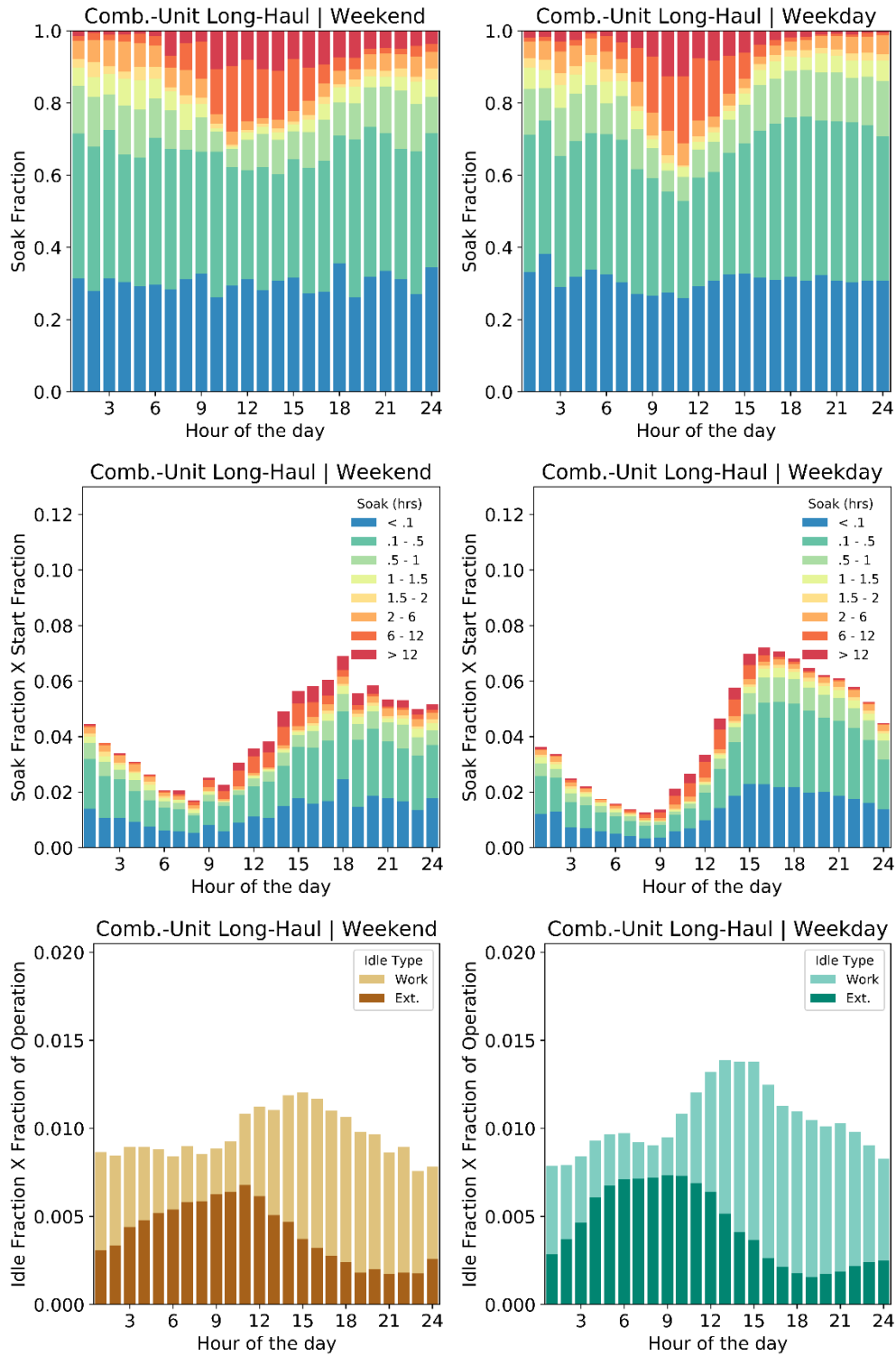


Figure J1. Start, soak, and idle performance of original combination-unit long haul

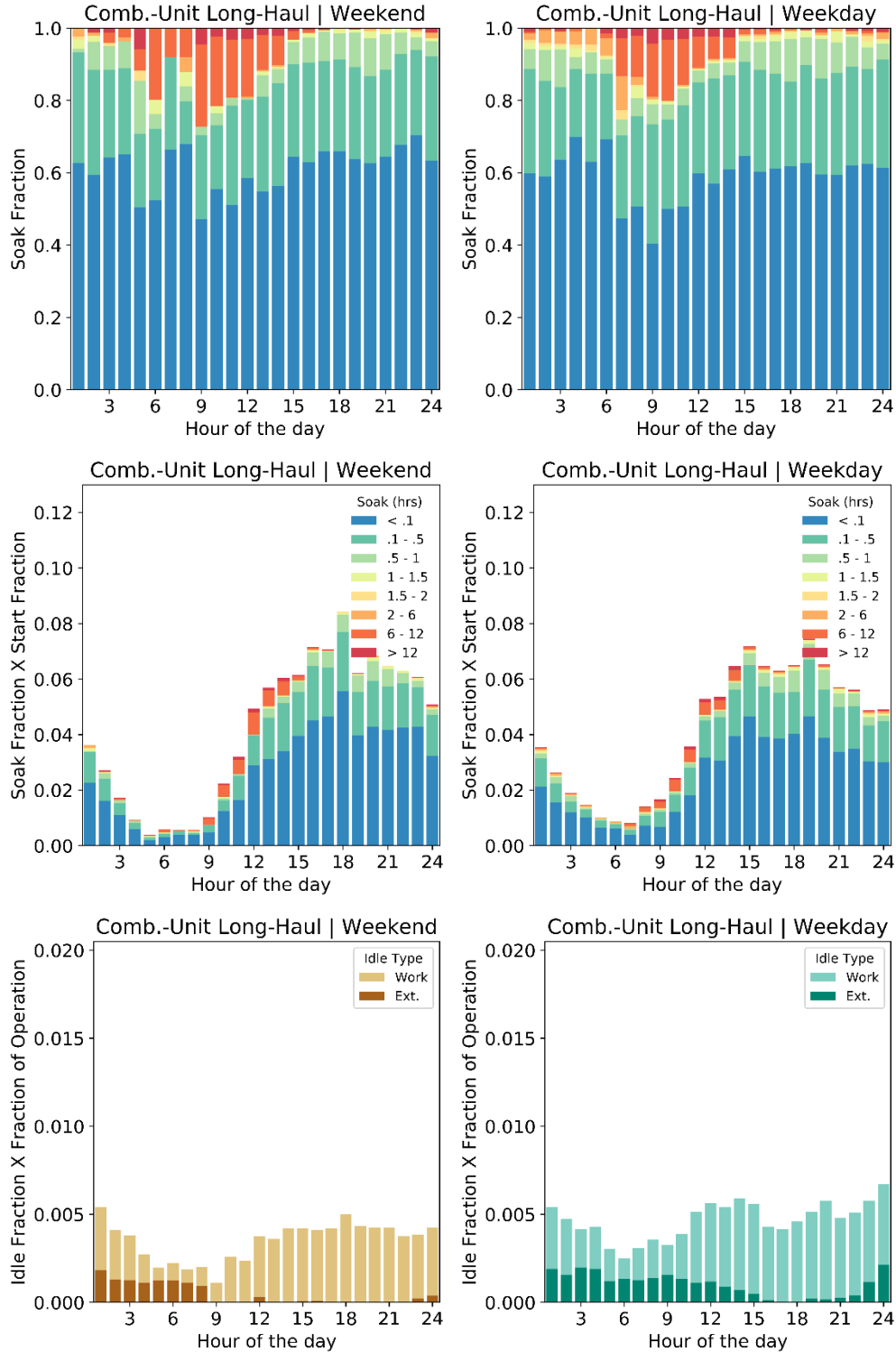


Figure J2. Start, soak, and idle performance of additional combination-unit long haul

Appendix K: Analytical Results from Combined Data

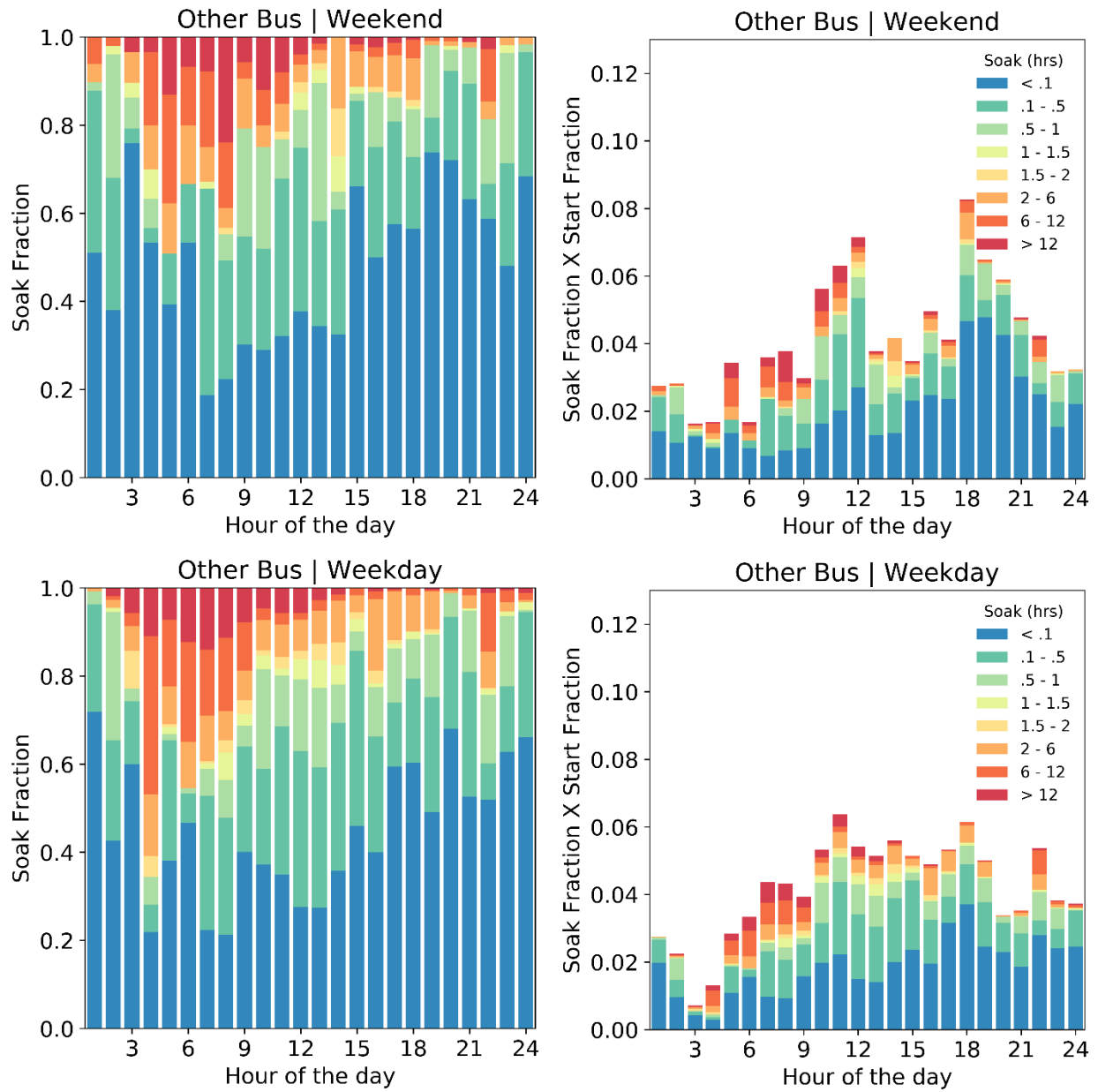


Figure K1. Soak fraction and start fraction vs. hour of the day for “other bus”

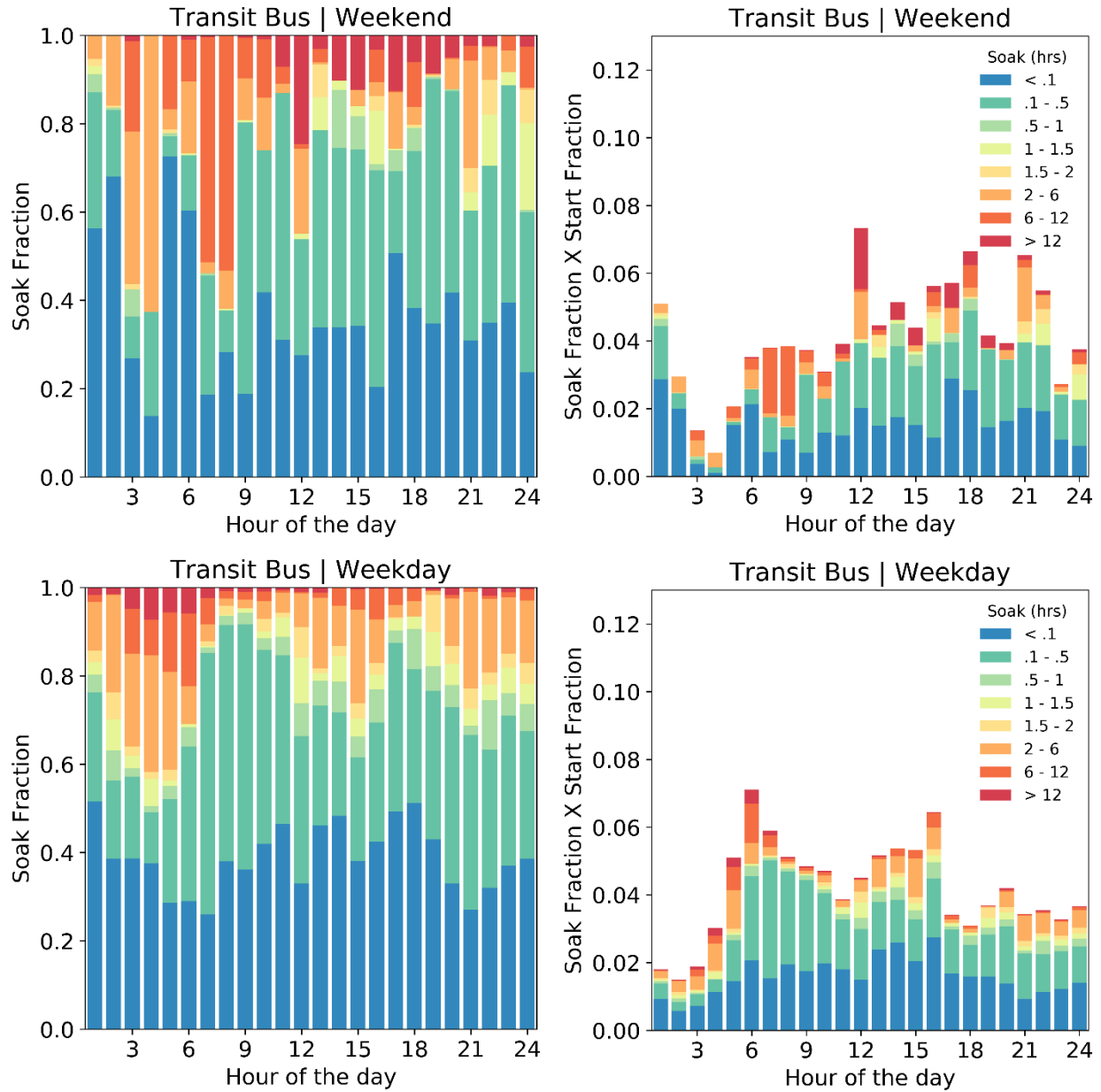


Figure K2. Soak fraction and start fraction vs. hour of the day for transit bus

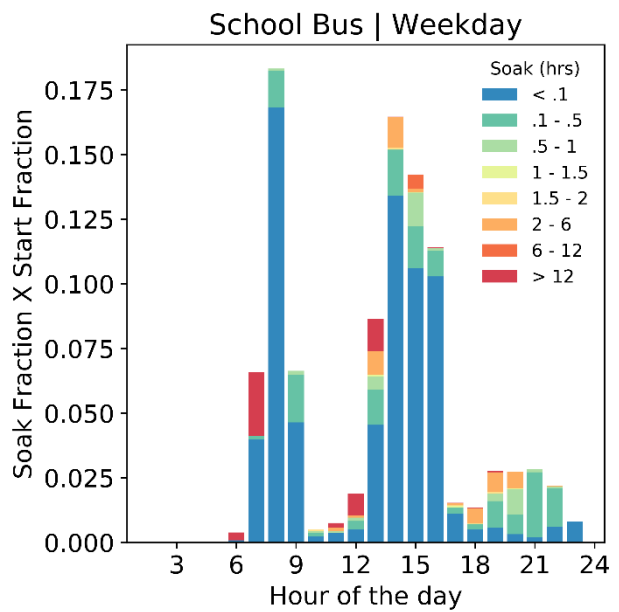
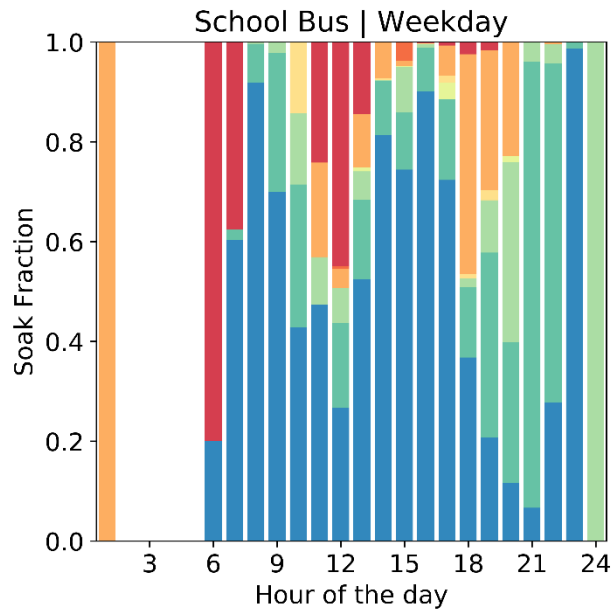
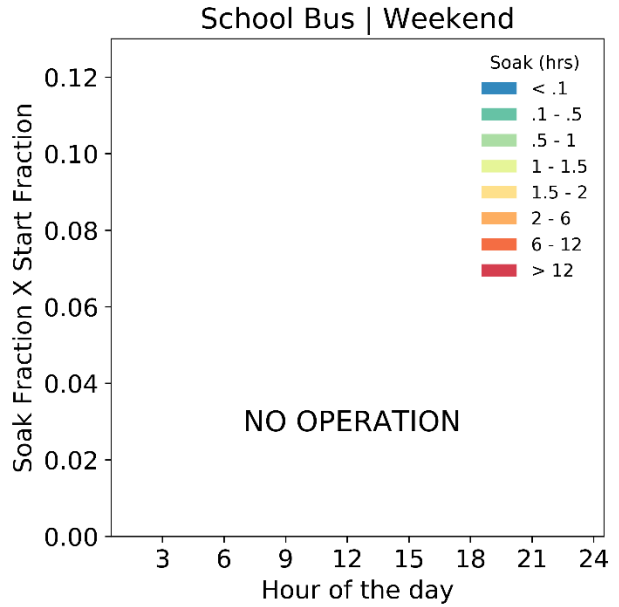
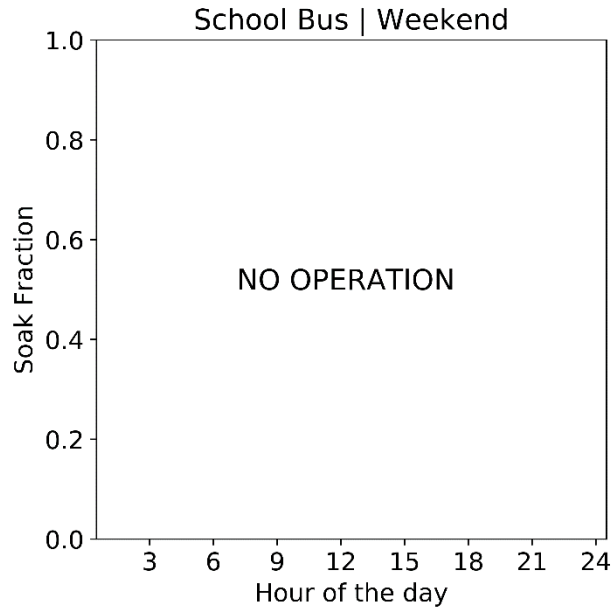


Figure K3. Soak fraction and start fraction vs. hour of the day for school bus

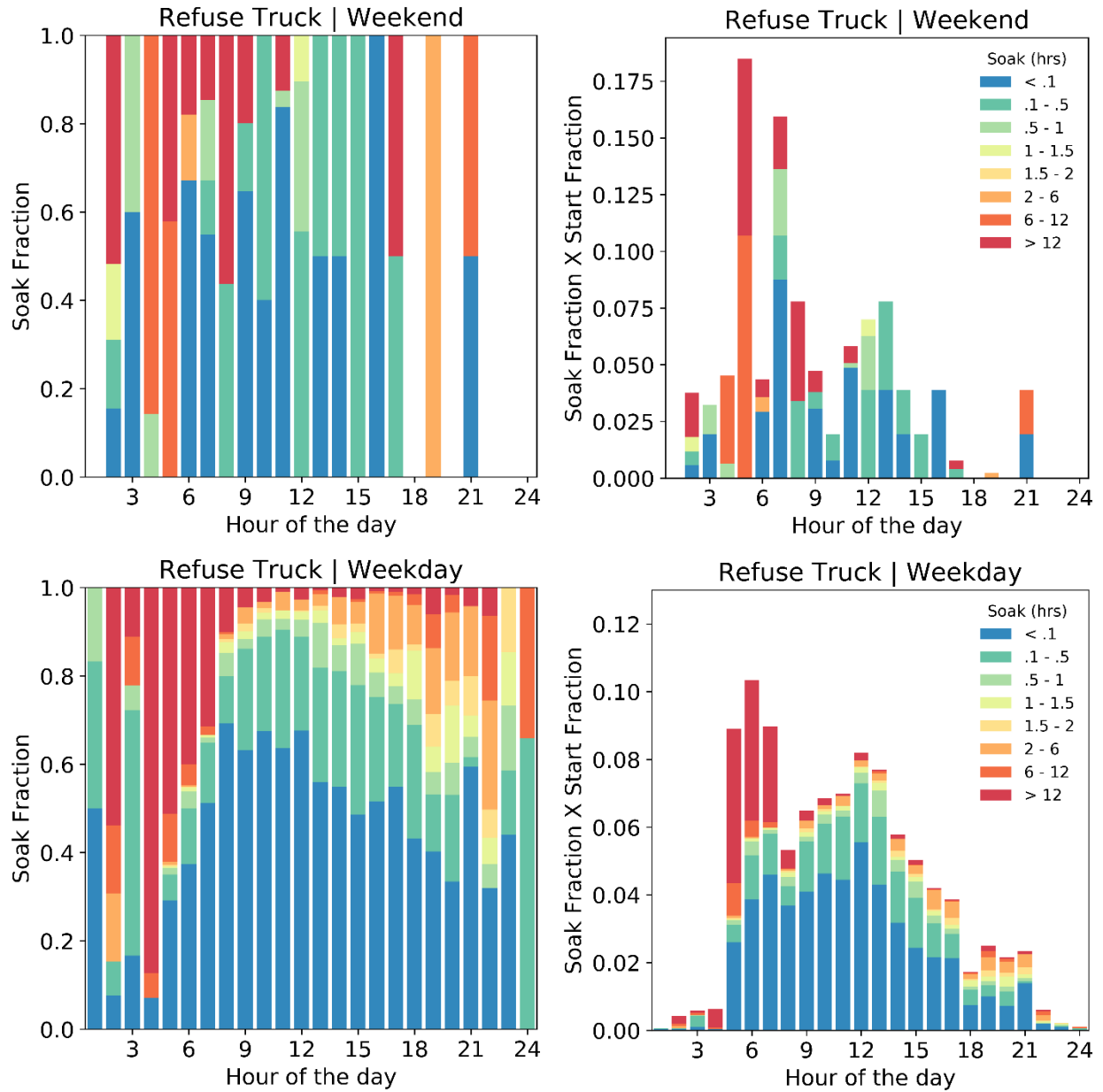


Figure K4. Soak fraction and start fraction vs. hour of the day for refuse truck

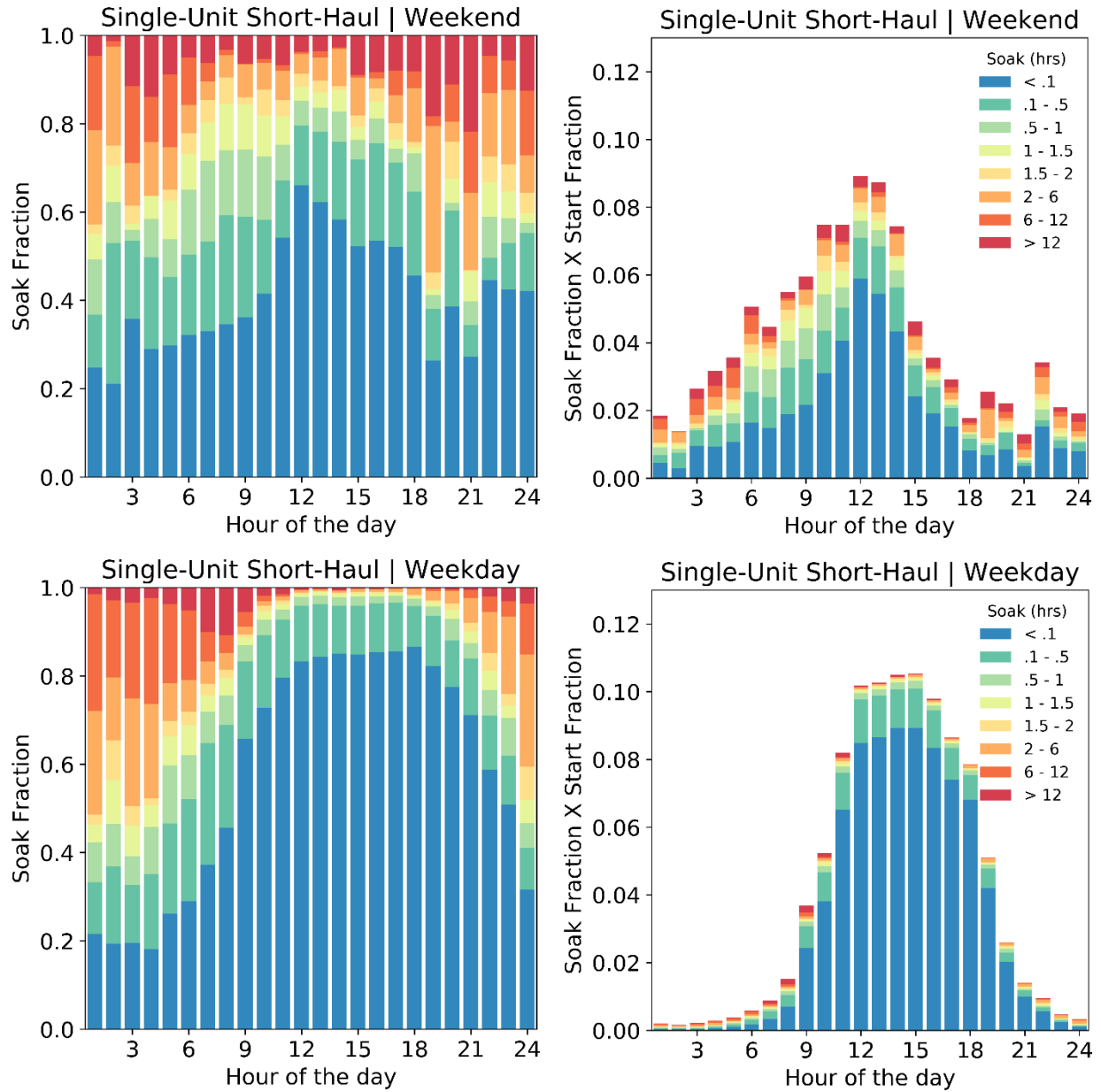


Figure K5. Soak fraction and start fraction vs. hour of the day for single-unit short haul

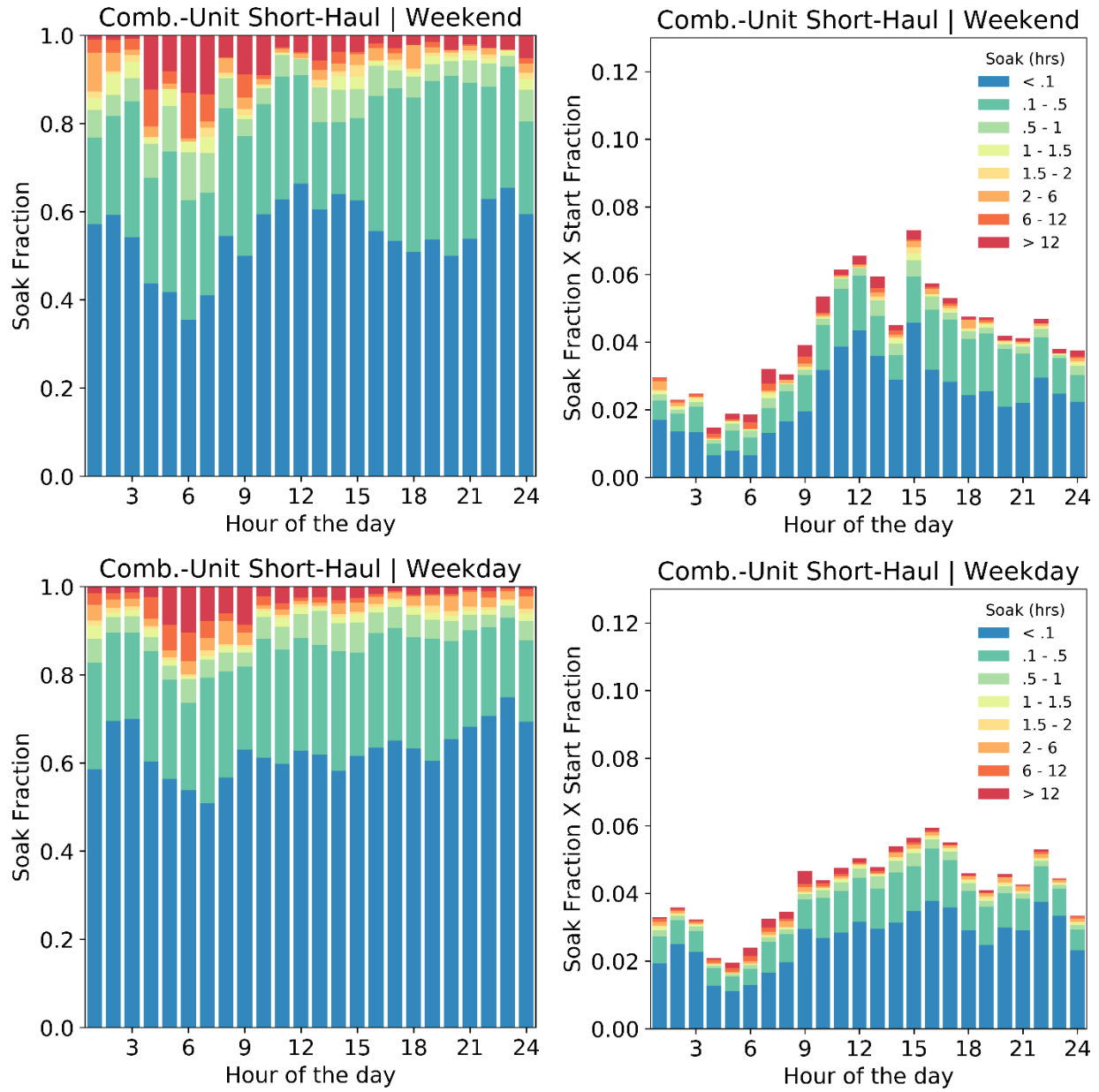


Figure K6. Soak fraction and start fraction vs. hour of the day for combination-unit short haul

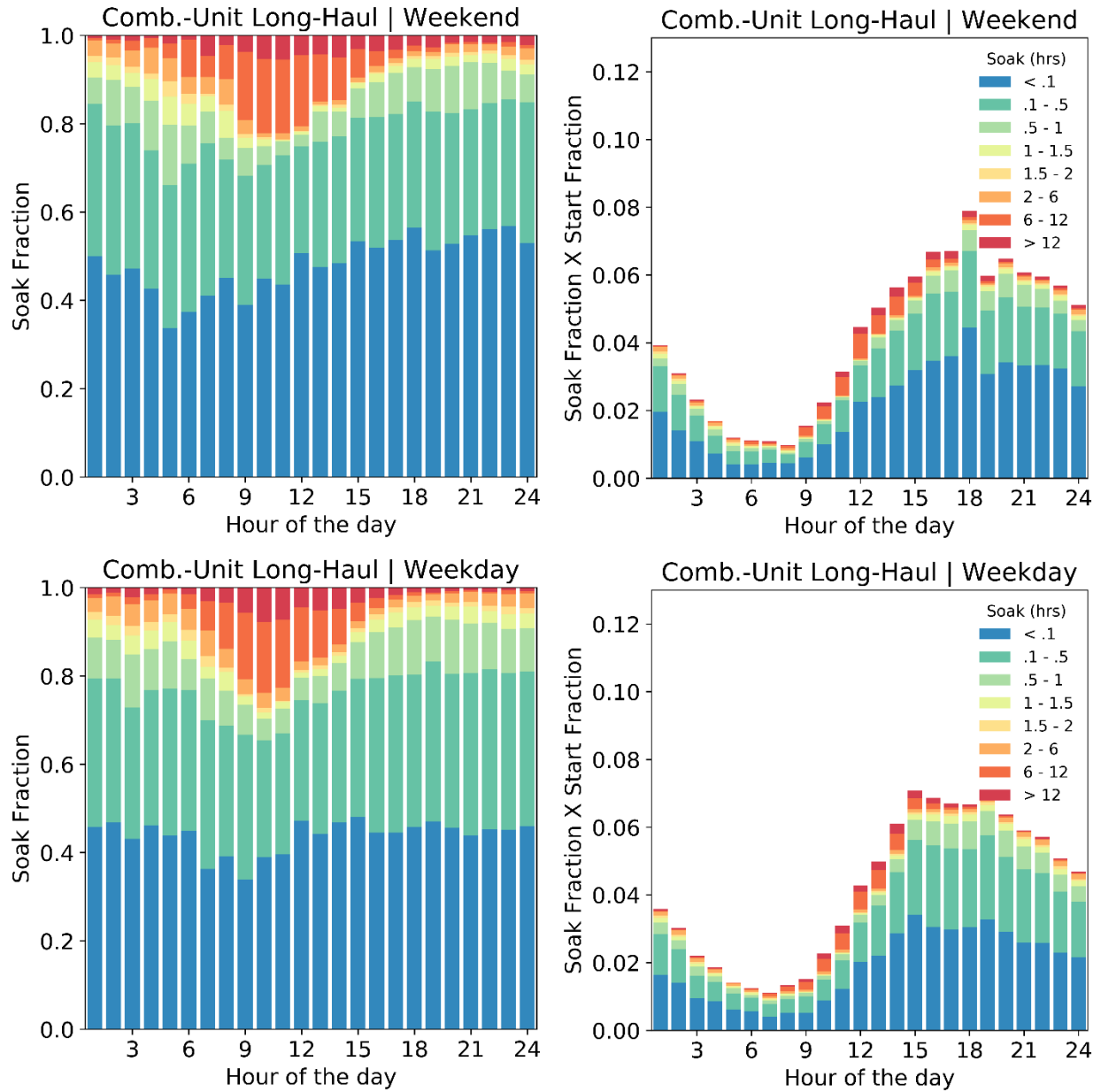


Figure K7. Soak fraction and start fraction vs. hour of the day for combination-unit long haul

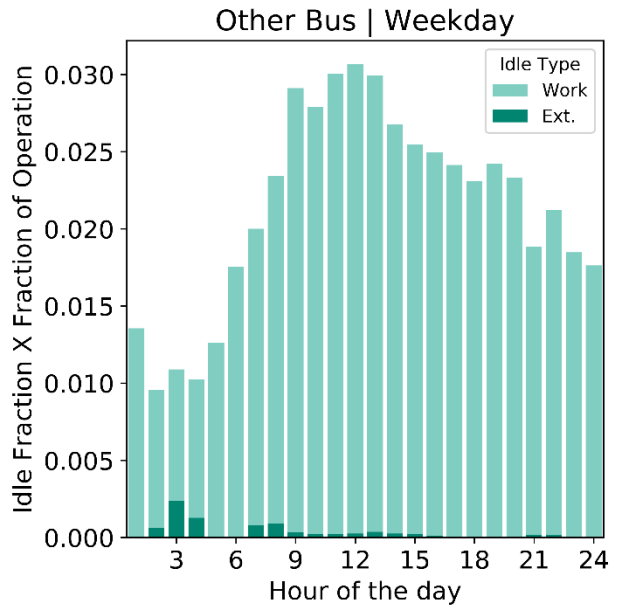
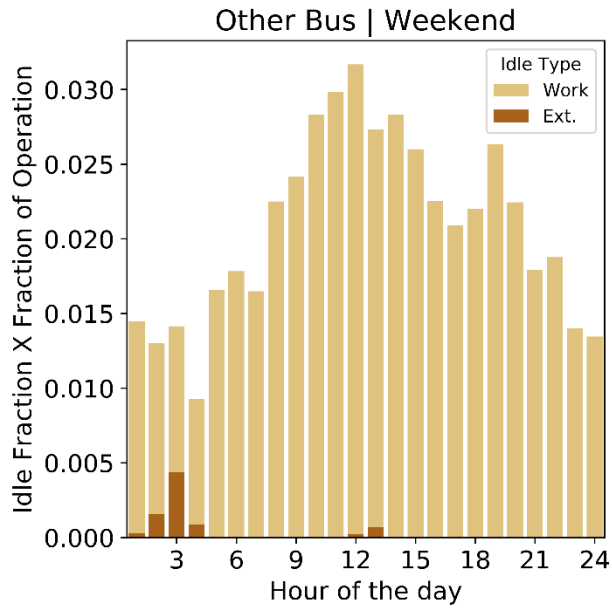


Figure K8. Hourly idle fraction vs. hour of the day for “other bus”

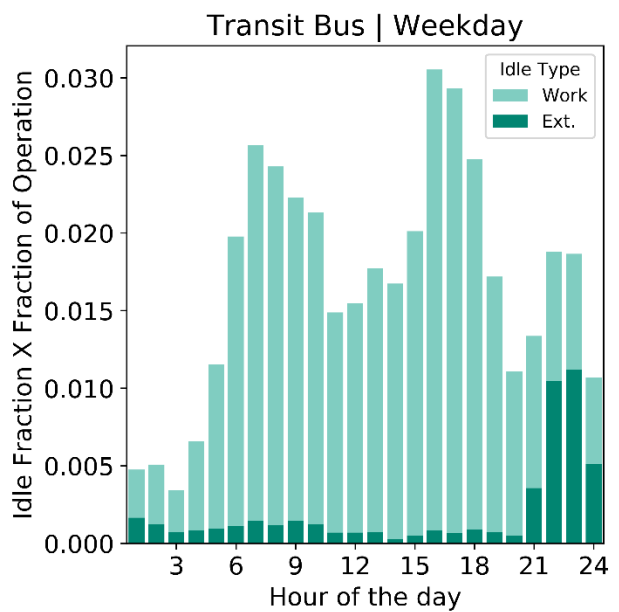
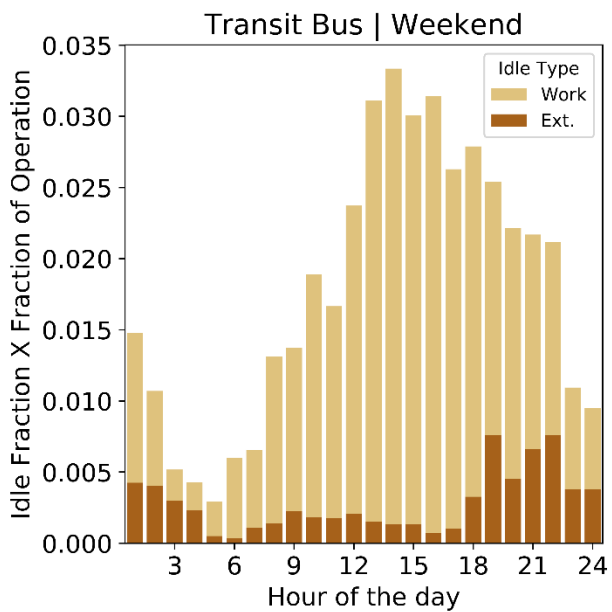


Figure K9. Hourly idle fraction vs. hour of the day for transit bus

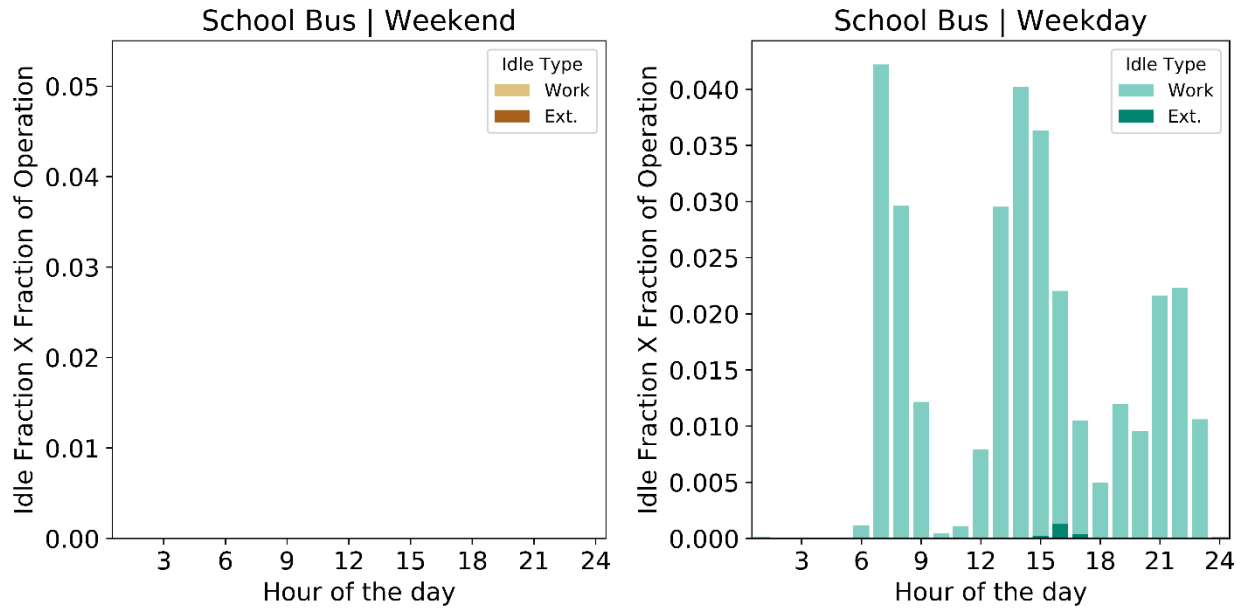


Figure K10. Hourly idle fraction vs. hour of the day for school bus

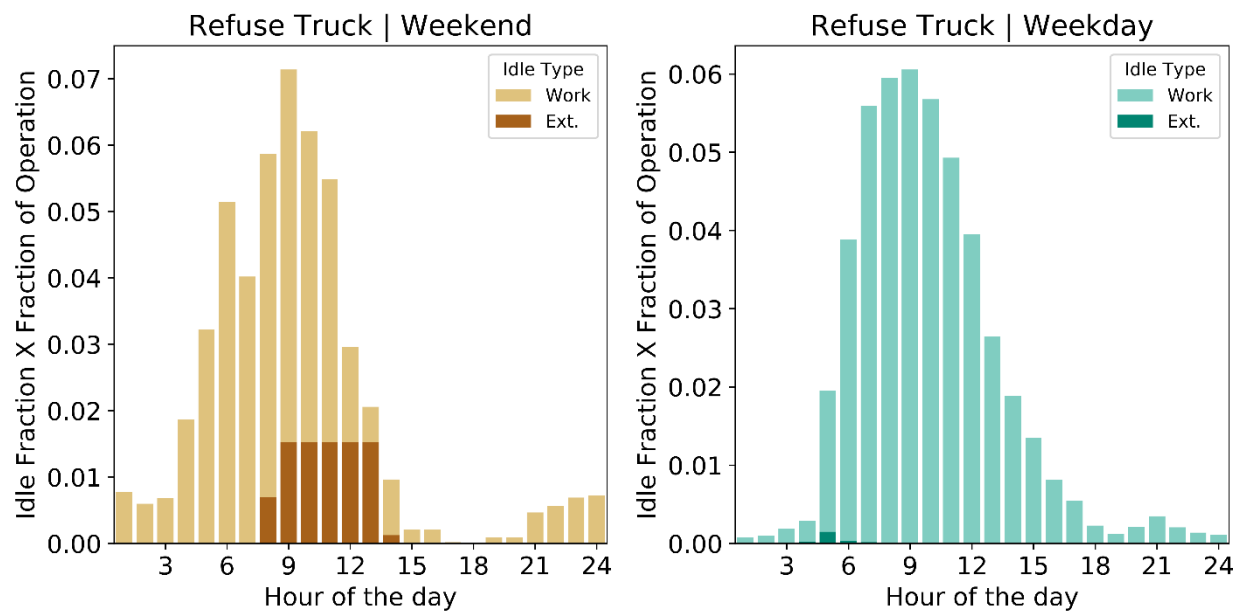


Figure K11. Hourly idle fraction vs. hour of the day for refuse truck

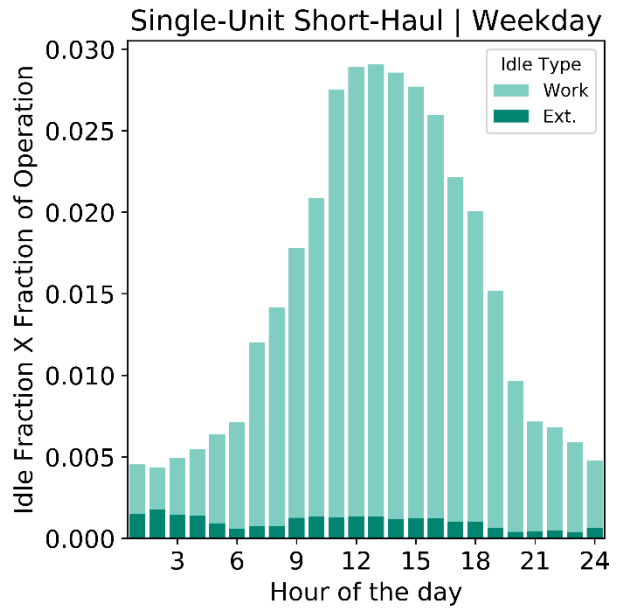
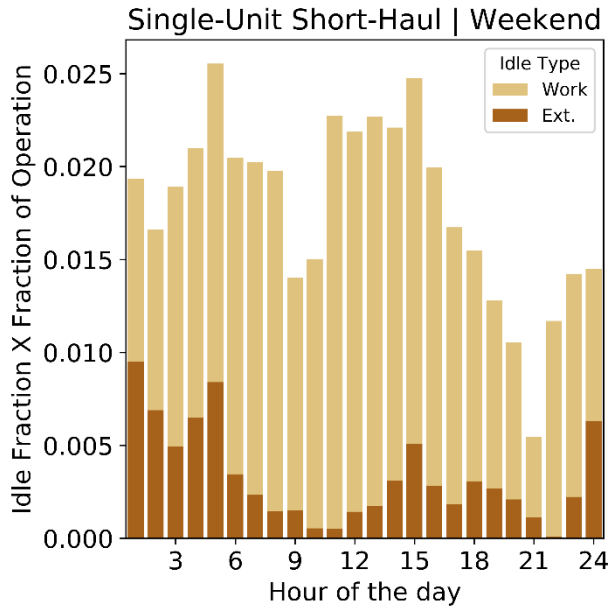


Figure K12. Hourly idle fraction vs. hour of the day for single-unit short haul

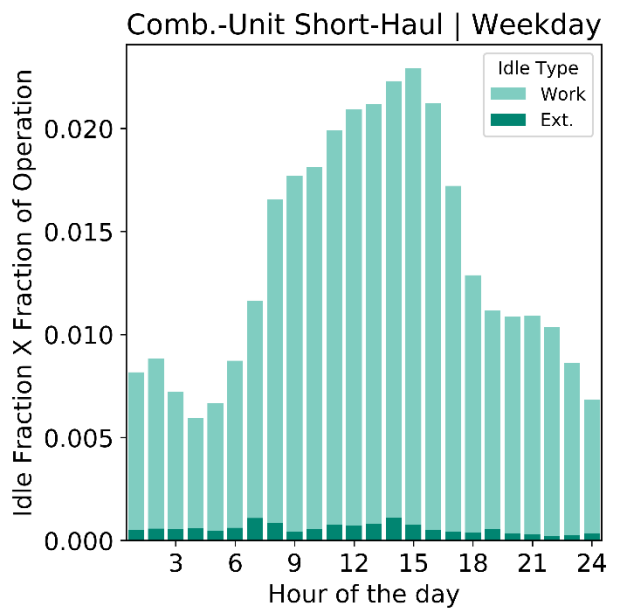
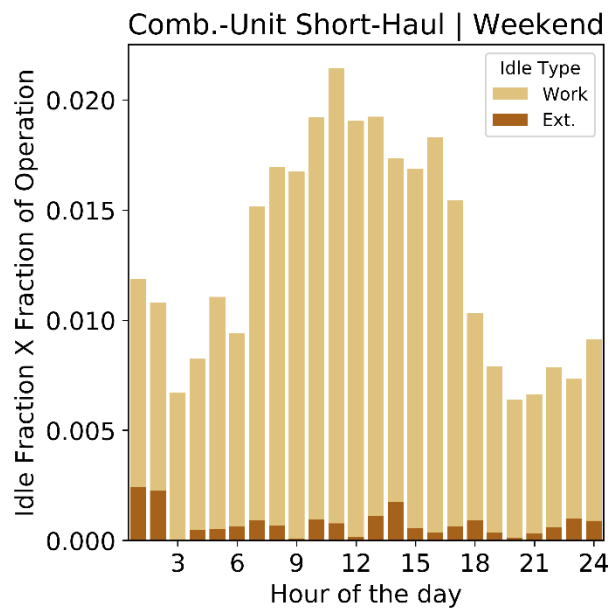


Figure K13. Hourly idle fraction vs. hour of the day for combination-unit short haul

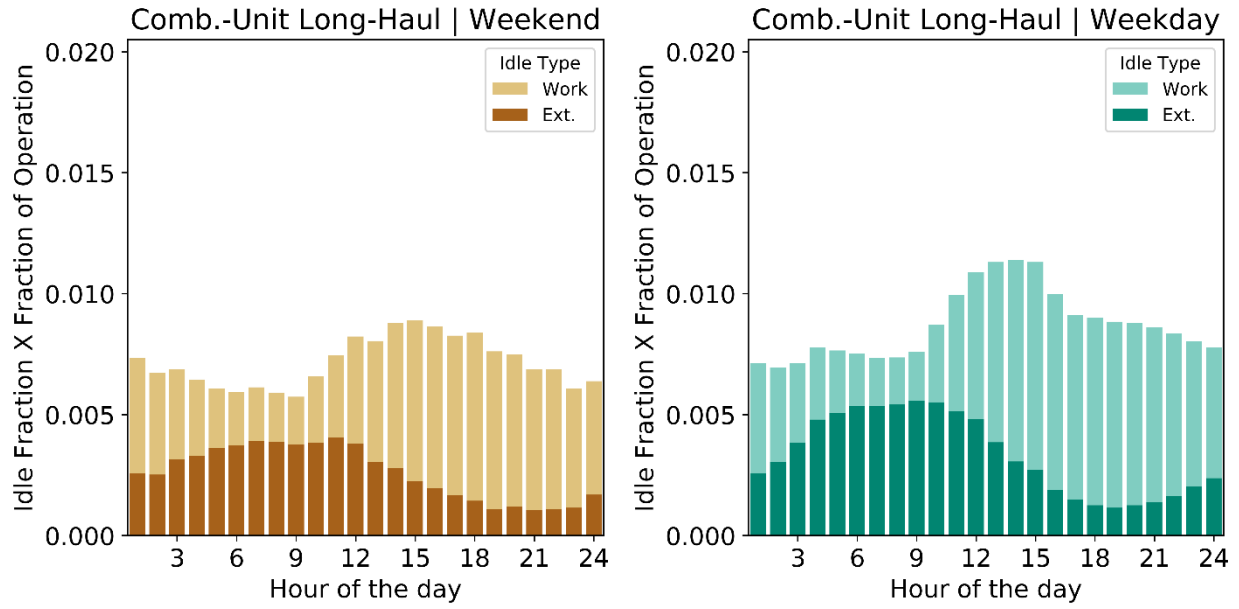


Figure K14. Hourly idle fraction vs. hour of the day for combination-unit long haul

Appendix L: Average Starts per Day from Fleet DNA and CE-CERT

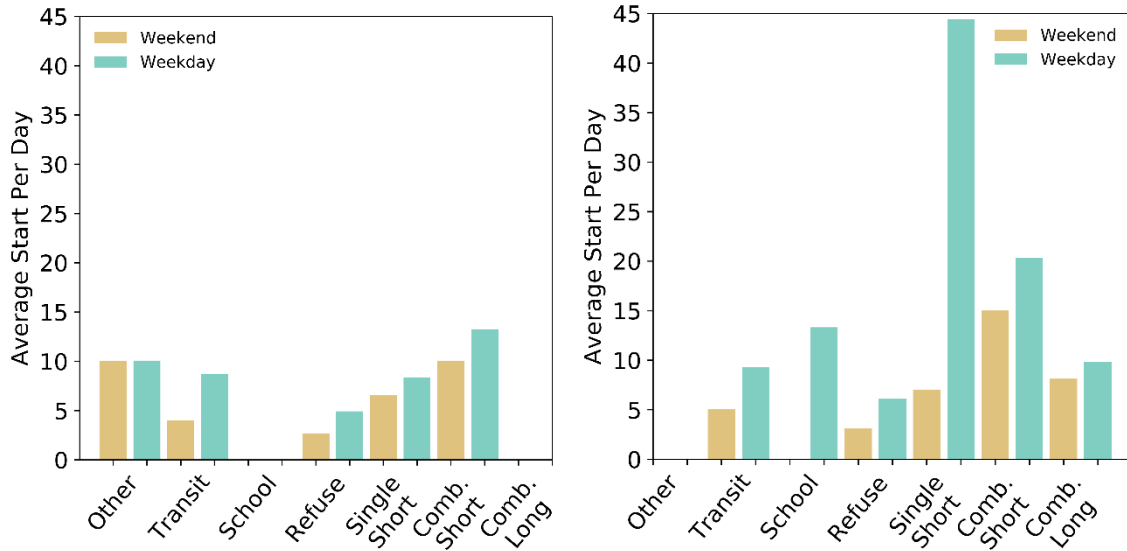


Figure L1. Average starts per day distribution based on vehicle types in CE-CERT (left) and Fleet DNA (right)

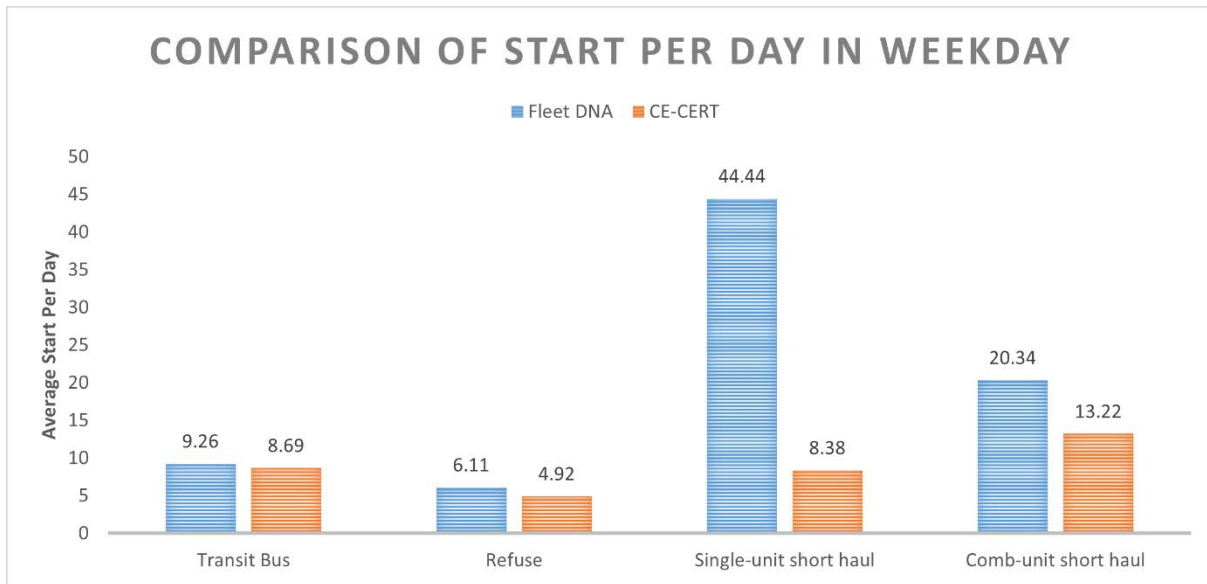


Figure L2. Detailed comparison of average starts per distribution in weekday from the common vocations between CE-CERT and Fleet DNA

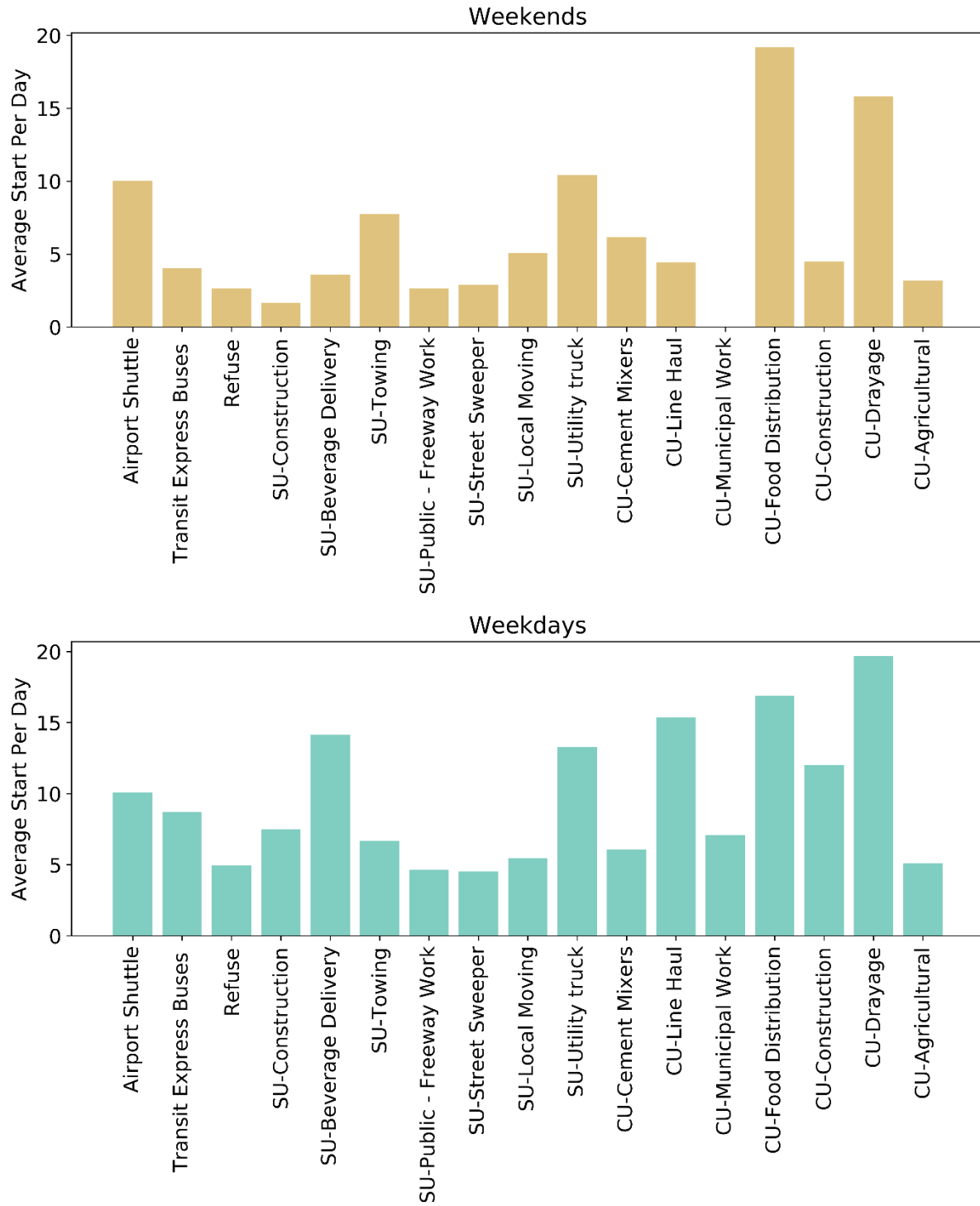


Figure L3. Average starts per day distribution based on vehicle vocations in CE-CERT

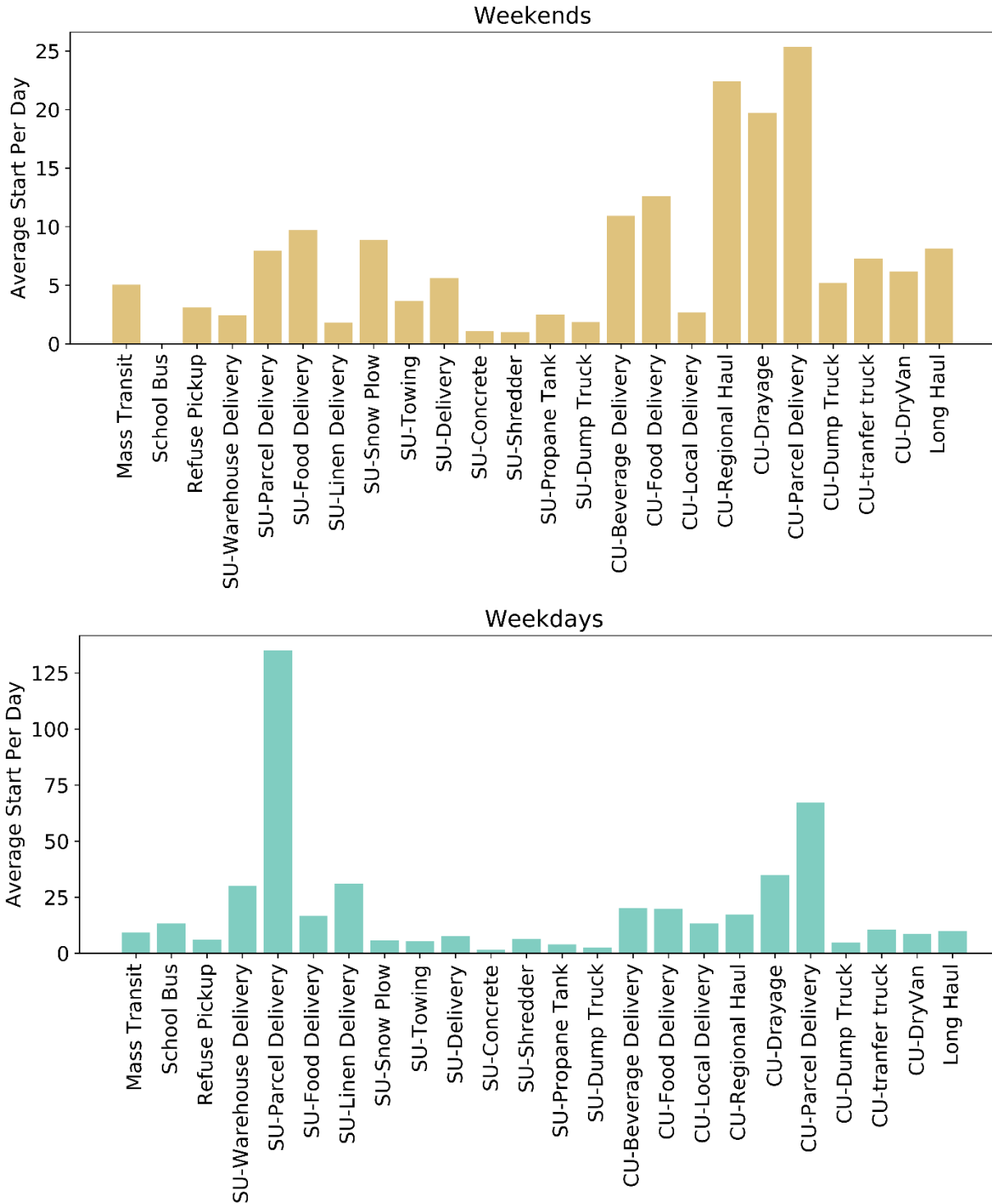


Figure L4. Average starts per day distribution based on vehicle vocations in Fleet DNA

Appendix M: Results File List

Original Fleet DNA

MetaData_original_fleetdna.csv

- This file provides the background information of each vehicle in the original Fleet DNA data set. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DepotState	State where depot is located
DepotCity	City where depot is located
DepotZipcode	ZIP code where depot is located
GPSState	State based on the mode of the recorded GPS data
GPSCity	City based on the mode of the recorded GPS data
SourceTypeID	ID of vehicle type
Vocation	Vocation of the vehicle
VINstem	First 9 digits of the VIN
Model	Vehicle model
Manufacturer	Vehicle model manufacturer
ModelYear	Vehicle model year
GVWR	Gross vehicle weight rating
Combination	If the vehicle is combination or single
SleeperCab	If the vehicle is a sleeper cab
Axles	Number of axles
Wheels	Number of wheels
EngineManufacturer	Manufacturer of the engine
EngineModelYear	Engine model year
Engine	Engine type
AuxillaryPower Unit	If the vehicle includes auxiliary power unit
HybridElectric	If the vehicle is hybrid electric
Fuel	Fuel used in the vehicle
Odometer	Miles at the beginning of the test
Age	Calendar year minus model year
MilesDrivenPerOperationDay	Miles driven per operation day

InstrumentedTimes_original_fleetdna.csv

- This file provides the information related to the instrumented day from each vehicle in the original Fleet DNA data set. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
InstrumentStartDate	Date that activity logger began collecting data
InstrumentStartTime	Start time when activity logger began collecting data
InstrumentEndDate	Date that activity logger stopped collecting data
InstrumentEndTime	End time when activity logger stopped collecting data
InstrumentedDays	Number of days with instrumentation
Instrumented Weekday	Number of Instrumented days in weekdays
Instrumented Weekend	Number of Instrumented days in weekend
OperationDays	Number of InstrumentedDays with vehicle operation
Operation Weekday	Number of operation days in weekdays
Operation Weekend	Number of operation days in weekend

IdleEvents_original_fleetdna.csv

- This file provides the related information of the idle events experienced by each vehicle in the original Fleet DNA. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
BeginIdleDate	Date that vehicle began idling
BeginDayID	Date ID that vehicle began idling (weekday = 5, weekend = 2)
BeginHourID	Hour ID that vehicle began idling
BeginIdleTime	Time instant when vehicle began idling
EndIdleDate	Date that vehicle stopped idling
EndIdleTime	Time instant when vehicle stopped idling
IdleDuration	EndIdleTime minus BeginIdleTime (seconds)

IdleOperationByDateDayHour_original_fleetdna.csv

- This file provides detailed information related to workday and extended idle fractions of each idle event experienced by the vehicles in the original Fleet DNA database. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
Date	Date
DayID	Date ID (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
OperationTime	Time with engine operation in the specific hour (seconds)
IdleTime	Total engine idle time in the specific hour (seconds)
WorkDayIdleTime	Total workday idle time in the specific hour (seconds)
ExtendedIdleTime	Total extended idle time in the specific hour (seconds)
MilesDriven	Miles driven along this operation time

IdleOperationByDayHour_original_fleetdna.csv

- This file provides hourly workday and extended idle fractions for each vehicle in the original Fleet DNA database. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DayID	Date ID (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
InstrumentedHours	Instrumented hours by DayID and HourID
OperationTime	Time with engine operation in the DayID and the HourID (seconds)
IdleTime	Total engine idle time in the DayID and the HourID (seconds)
WorkDayIdleTime	Total engine work idle time in the DayID and the HourID (seconds)
ExtendedIdleTime	Total engine extended idle time in the DayID and the HourID (seconds)
MilesDriven	Miles driven in the DayID and the HourID
IdleFraction	IdleTime divided by OperationTime
WorkDayIdleFraction	WorkDayIdleTime divided by OperationTime
ExtendedIdleFraction	ExtendedIdleTime divided by OperationTime

StartSoaksEvents_original_fleetdna.csv

- This file provides the related information of the soak events experienced by each vehicle in the original Fleet DNA. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
StartDate	Date that vehicle's engine started
StartDayID	Date ID that vehicle's engine started (weekday = 5, weekend = 2)
StartTime	Time instant when vehicle's engine started
StartHourID	Hour ID that vehicle's engine started (1–24)
PreviousEngineOffDate	Date that vehicle's engine stopped last time
PreviousEngineOffTime	Time instant when vehicle's engine stopped last time
SoakLength	StartTime minus PreviousEngineOffTime (seconds)
EngineOffDate	Date that vehicle's engine stopped
EngineOffTime	Time instant when vehicle's engine stopped
OperationDuration	Operation time between engine start time and engine off time (seconds)
MilesDriven	Miles driven along this operation duration

StartSoaksByDayHour_original_fleetdna.csv

- This file provides numbers of soak events in each soak operation mode for each vehicle in the original Fleet DNA database. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DayID	Day type (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
InstrumentedHours	Instrumented hours by DayID and HourID
OperationModeID	Soak time operating mode
Starts	Number of starts in specific operating mode

CE-CERT Data

MetaData_CE_CERT_final.csv

- This file provides the background information of each vehicle in the CE-CERT data set. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DepotState	State where depot is located
DepotCity	City where depot is located
DepotZipcode	ZIP code where depot is located
GPSState	State based on the mode of the recorded GPS data
GPSCity	City based on the mode of the recorded GPS data
SourceTypeID	ID of vehicle type
Vocation	Vocation of the vehicle
VINstem	First 9 digits of the VIN
Model	Vehicle model
Manufacturer	Vehicle model manufacturer
ModelYear	Vehicle model year
GVWR	Gross vehicle weight rating
Combination	If the vehicle is combination or single
SleeperCab	If the vehicle is a sleeper cab
Axles	Number of axles
Wheels	Number of wheels
EngineManufacturer	Manufacturer of the engine
EngineModelYear	Engine model year
Engine	Engine type
AuxillaryPower Unit	If the vehicle includes auxiliary power unit
HybridElectric	If the vehicle is hybrid electric
Fuel	Fuel used in the vehicle
Odometer	Miles at the beginning of the test
Age	Calendar year minus model year
MilesDrivenPerOperationDay	Miles driven per operation day

InstrumentedTimes_CE_CERT.csv

- This file provides the information related to the instrumented day from each vehicle in the CE-CERT data set. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
InstrumentStartDate	Date that activity logger began collecting data
InstrumentStartTime	Start time when activity logger began collecting data
InstrumentEndDate	Date that activity logger stopped collecting data
InstrumentEndTime	End time when activity logger stopped collecting data
InstrumentedDays	Number of days with instrumentation
Instrumented Weekday	Number of Instrumented days in weekdays
Instrumented Weekend	Number of Instrumented days in weekend
OperationDays	Number of InstrumentedDays with vehicle operation
Operation Weekday	Number of operation days in weekdays
Operation Weekend	Number of operation days in weekend

IdleEvents_CE_CERT.csv

- This file provides the related information of the idle events experienced by each vehicle in the CE-CERT database. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
BeginIdleDate	Date that vehicle began idling
BeginDayID	Date ID that vehicle began idling (weekday = 5, weekend = 2)
BeginHourID	Hour ID that vehicle began idling
BeginIdleTime	Time instant when vehicle began idling
EndIdleDate	Date that vehicle stopped idling
EndIdleTime	Time instant when vehicle stopped idling
IdleDuration	EndIdleTime minus BeginIdleTime (seconds)

IdleOperationByDateDayHour_CE_CERT.csv

- This file provides detailed information related to workday and extended idle fractions of each idle event experienced by the vehicles in the CE-CERT database. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
Date	Date
DayID	Date ID (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
OperationTime	Time with engine operation in the specific hour (seconds)
IdleTime	Total engine idle time in the specific hour (seconds)
WorkDayIdleTime	Total workday idle time in the specific hour (seconds)
ExtendedIdleTime	Total extended idle time in the specific hour (seconds)
MilesDriven	Miles driven along this operation time

IdleOperationByDayHour_CE_CERT.csv

- This file provides hourly workday and extended idle fractions for each vehicle in the CE-CERT database. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DayID	Date ID (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
InstrumentedHours	Instrumented hours by DayID and HourID
OperationTime	Time with engine operation in the DayID and HourID (seconds)
IdleTime	Total engine idle time in the DayID and HourID (seconds)
WorkDayIdleTime	Total engine work idle time in the DayID and HourID (seconds)
ExtendedIdleTime	Total engine extended idle time in the DayID and HourID (seconds)
MilesDriven	Miles driven in the DayID and HourID
IdleFraction	IdleTime divided by OperationTime
WorkDayIdleFraction	WorkDayIdleTime divided by OperationTime
ExtendedIdleFraction	ExtendedIdleTime divided by OperationTime

StartSoaksEvents_CE_CERT.csv

- This file provides the related information of the soak events experienced by each vehicle in the CE-CERT database. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
StartDate	Date that vehicle's engine started
StartDayID	Date ID that vehicle's engine started (weekday = 5, weekend = 2)
StartTime	Time instant when vehicle's engine started
StartHourID	Hour ID that vehicle's engine started (1–24)
PreviousEngineOffDate	Date that vehicle's engine stopped last time
PreviousEngineOffTime	Time instant when vehicle's engine stopped last time
SoakLength	StartTime minus PreviousEngineOffTime (seconds)
EngineOffDate	Date that vehicle's engine stopped
EngineOffTime	Time instant when vehicle's engine stopped
OperationDuration	Operation time between engine start time and engine off time (seconds)
MilesDriven	Miles driven along this operation duration

StartSoaksByDayHour_CE_CERT.csv

- This file provides numbers of soak events in each soak operation mode for each vehicle in the CE-CERT database. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DayID	Day type (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
InstrumentedHours	Instrumented hours by DayID and HourID
OperationModeID	Soak time operating mode
Starts	Number of starts in specific operating mode

starts_final_CE_CERT_plot_divided_day.csv

- This file provides the start fraction for each source type (vehicle type) and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
start_fraction_final	Sum of the daily average starts for an individual hour, day, and type divided by the sum of the daily average starts for an individual day and type

soak_final_CE_CERT_plot_divided_day.csv

- This file provides the soak fraction for each source type (vehicle type), day type, hour of the day, and operation mode. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
op_mode	Operation mode of the soaks (101–108)
soak_fraction_final	Sum of the daily average soaks for an individual op_mode, hour, day, and type divided by the sum of daily average starts for an individual hour, day, and type

idle_final_CE_CERT_plot_divided_day.csv

- This file provides the idle fraction for each source type (vehicle type) and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
idle_fraction_final	Sum of the daily average idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
workday_idle_fraction_final	Sum of the daily average workday idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
extended_idle_fraction_final	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
sum_operation_hours	Sum of the daily average operating hours for all vehicles in the day and vehicle type
sum_idle_hours	Sum of the daily average idle hours for all vehicles in the day and vehicle type
sum_workday_idle_hours	Sum of the daily average workday idle hours for all vehicles in the day and vehicle type
sum_extended_idle_hours	Sum of the daily average extended idle hours for all vehicles in the day and vehicle type
sum_miles_driven	Sum of the average daily miles driven for that day type and vehicle type
extended_idle_hours/miles_driven	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average miles traveled for all vehicles in the day and vehicle type
population	Population of vehicles for that source type and day type

hourly_idle_final_CE_CERT_plot_divided_day.csv

- This file provides the total, workday, and extended idle fraction for each source type (vehicle type), day type and hour of the day along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
idle_fraction_final	Sum of the daily average idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in hour, day, and vehicle type
workday_idle_fraction_final	Sum of the daily average workday idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
extended_idle_fraction_final	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
sum_operating_hours	Sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
sum_idle_hours	Sum of the daily average idle hours for all vehicles in the hour, day, and vehicle type
sum_workday_idle_hours	Sum of the daily average workday idle hours for all vehicles in the hour, day, and vehicle type
sum_extended_idle_hours	Sum of the daily average extended idle hours for all vehicles in the hour, day, and vehicle type

starts_final_CE_CERT_plot_vocation.csv

- This file provides the start fraction for each vocation and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
Vocation	Vehicle vocation
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
start_fraction_final	Sum of the daily average starts for an individual hour, day, and type divided by the sum of the daily average starts for an individual day and vehicle type

soak_final_CE_CERT_plot_vocation.csv

- This file provides the soak fraction for each vocation, day type, hour of the day, and operation mode. The full list of parameters included in the file is as follows:

Column Name	Description
Vocation	Vehicle vocation
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
op_mode	Operation mode of the soaks (101–108)
soak_fraction_final	Sum of the daily average soaks for an individual op_mode, hour, day, and type divided by the sum of daily average starts for an individual hour, day, and type

idle_final_CE_CERT_plot_vocation.csv

- This file provides the idle fraction for each vocation and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
Vocation	Vehicle vocation
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
idle_fraction_final	Sum of the daily average idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and type
workday_idle_fraction_final	Sum of the daily average workday idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
extended_idle_fraction_final	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
sum_operation_hours	Sum of the daily average operating hours for all vehicles in the day and vehicle type
sum_idle_hours	Sum of the daily average idle hours for all vehicles in the day and vehicle type
sum_workday_idle_hours	Sum of the daily average workday idle hours for all vehicles in the day and vehicle type
sum_extended_idle_hours	Sum of the daily average extended idle hours for all vehicles in the day and vehicle type
sum_miles_driven	Sum of the average daily miles driven for that day type and vehicle type
extended_idle_hours/miles_driven	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average miles traveled for all vehicles in the day and vehicle type
population	Population of vehicles for that source type and day type

hourly_idle_final_CE_CERT_plot_vocation.csv

- This file provides the total, workday, and extended idle fraction for each vocation, day type, and hour of the day. The full list of parameters included in the file is as follows:

Column Name	Description
Vocation	Vehicle vocation
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
idle_fraction_final	Sum of the daily average idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in hour, day, and type
workday_idle_fraction_final	Sum of the daily average workday idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
extended_idle_fraction_final	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
sum_operating_hours	Sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
sum_idle_hours	Sum of the daily average idle hours for all vehicles in the hour, day, and vehicle type
sum_workday_idle_hours	Sum of the daily average workday idle hours for all vehicles in the hour, day, and vehicle type
sum_extended_idle_hours	Sum of the daily average extended idle hours for all vehicles in the hour, day, and vehicle type

starts_per_day_figure_CE_CERT_divided_day.csv

- This file provides the average start per day for each source and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
avg_starts_per_day	Average starts per day in this source type and day type

starts_per_day_figure_CE_CERT_plot_vocation.csv

- This file provides the average start per day for each vocation and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
Vocation	Vehicle vocation
day	Day type (weekday = 5, weekend = 2)
avg_starts_per_day	Average starts per day in this vocation and day type

Additional 64 Long-Haul Vehicles Data

MetaData_long_haul.csv

- This file provides the background information of each vehicle in the additional 64 long-haul vehicles. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DepotState	State where depot is located
DepotCity	City where depot is located
DepotZipcode	ZIP code where depot is located
GPSState	State based on the mode of the recorded GPS data
GPSCity	City based on the mode of the recorded GPS data
SourceTypeID	ID of vehicle type
Vocation	Vocation of the vehicle
VINstem	First 9 digits of the VIN
Model	Vehicle model
Manufacturer	Vehicle model manufacturer
ModelYear	Vehicle model year
GVWR	Gross vehicle weight rating
Combination	If the vehicle is combination or single
SleeperCab	If the vehicle is a sleeper cab
Axles	Number of axles
Wheels	Number of wheels
EngineManufacturer	Manufacturer of the engine
EngineModelYear	Engine model year
Engine	Engine type
AuxillaryPower Unit	If the vehicle includes auxiliary power unit
HybridElectric	If the vehicle is hybrid electric
Fuel	Fuel used in the vehicle
Odometer	Miles at the beginning of the test
Age	Calendar year minus model year
MilesDrivenPerOperationDay	Miles driven per operation day

InstrumentedTimes_long_haul.csv

- This file provides the information related to the instrumented day from each vehicle in the additional 64 long-haul vehicles. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
InstrumentStartDate	Date that activity logger began collecting data
InstrumentStartTime	Start time when activity logger began collecting data
InstrumentEndDate	Date that activity logger stopped collecting data
InstrumentEndTime	End time when activity logger stopped collecting data
InstrumentedDays	Number of days with instrumentation
Instrumented Weekday	Number of Instrumented days in weekdays
Instrumented Weekend	Number of Instrumented days in weekend
OperationDays	Number of InstrumentedDays with vehicle operation
Operation Weekday	Number of operation days in weekdays
Operation Weekend	Number of operation days in weekend

IdleEvents_long_haul.csv

- This file provides the related information of the idle events experienced by each vehicle in the additional 64 long-haul vehicles. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
BeginIdleDate	Date that vehicle began idling
BeginDayID	Date ID that vehicle began idling (weekday = 5, weekend = 2)
BeginHourID	Hour ID that vehicle began idling
BeginIdleTime	Time instant when vehicle began idling
EndIdleDate	Date that vehicle stopped idling
EndIdleTime	Time instant when vehicle stopped idling
IdleDuration	EndIdleTime minus BeginIdleTime (seconds)

IdleOperationByDateDayHour_long_haul.csv

- This file provides detailed information related to workday and extended idle fractions of each idle event experienced by the vehicles in the additional 64 long-haul vehicles. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
Date	Date
DayID	Date ID (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
OperationTime	Time with engine operation in the specific hour (seconds)
IdleTime	Total engine idle time in the specific hour (seconds)
WorkDayIdleTime	Total workday idle time in the specific hour (seconds)
ExtendedIdleTime	Total extended idle time in the specific hour (seconds)
MilesDriven	Miles driven along this operation time

IdleOperationByDayHour_long_haul.csv

- This file provides hourly workday and extended idle fractions for each vehicle in the additional 64 long-haul vehicles. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DayID	Date ID (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
InstrumentedHours	Instrumented hours by DayID and HourID
OperationTime	Time with engine operation in the DayID and HourID (seconds)
IdleTime	Total engine idle time in the DayID and HourID (seconds)
WorkDayIdleTime	Total engine work idle time in the DayID and HourID (seconds)
ExtendedIdleTime	Total engine extended idle time in the DayID and HourID (seconds)
MilesDriven	Miles driven in the DayID and HourID
IdleFraction	IdleTime divided by OperationTime
WorkDayIdleFraction	WorkDayIdleTime divided by OperationTime
ExtendedIdleFraction	ExtendedIdleTime divided by OperationTime

StartSoaksEvents_long_haul.csv

- This file provides the related information of the soak events experienced by each vehicle in the additional 64 long-haul vehicles. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
StartDate	Date that vehicle's engine started
StartDayID	Date ID that vehicle's engine started (weekday = 5, weekend = 2)
StartTime	Time instant when vehicle's engine started
StartHourID	Hour ID that vehicle's engine started (1–24)
PreviousEngineOffDate	Date that vehicle's engine stopped last time
PreviousEngineOffTime	Time instant when vehicle's engine stopped last time
SoakLength	StartTime minus PreviousEngineOffTime (seconds)
EngineOffDate	Date that vehicle's engine stopped
EngineOffTime	Time instant when vehicle's engine stopped
OperationDuration	Operation time between engine start time and engine off time (seconds)
MilesDriven	Miles driven along this operation duration

StartSoaksByDayHour_long_haul.csv

- This file provides numbers of soak events in each soak operation mode for each vehicle in the additional 64 long-haul vehicles. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DayID	Day type (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
InstrumentedHours	Instrumented hours by DayID and HourID
OperationModeID	Soak time operating mode
Starts	Number of starts in specific operating mode

starts_final_Long_haul_plot_divided_day.csv

- This file provides the start fraction for each source type (vehicle type) and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
start_fraction_final	Sum of the daily average starts for an individual hour, day, and vehicle type divided by the sum of the daily average starts for an individual day and vehicle type

soak_final_Long_haul_plot_divided_day.csv

- This file provides the soak fraction for each source type (vehicle type), day type, hour of the day, and operation mode. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
op_mode	Operation mode of the soaks (101–108)
soak_fraction_final	Sum of the daily average soaks for an individual op_mode, hour, day, and vehicle type divided by the sum of daily average starts for an individual hour, day, and vehicle type

idle_final_Long_haul_plot_divided_day.csv

- This file provides the idle fraction for each source type (vehicle type) and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
idle_fraction_final	Sum of the daily average idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
workday_idle_fraction_final	Sum of the daily average workday idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
extended_idle_fraction_final	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
sum_operation_hours	Sum of the daily average operating hours for all vehicles in the day and vehicle type
sum_idle_hours	Sum of the daily average idle hours for all vehicles in the day and vehicle type
sum_workday_idle_hours	Sum of the daily average workday idle hours for all vehicles in the day and vehicle type
sum_extended_idle_hours	Sum of the daily average extended idle hours for all vehicles in the day and vehicle type
sum_miles_driven	Sum of the average daily miles driven for that day type and vehicle type
extended_idle_hours/miles_driven	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average miles traveled for all vehicles in the day and vehicle type
population	Population of vehicles for that source type and day type

hourly_idle_final_Long_haul_plot_divided_day.csv

- This file provides the total, workday, and extended idle fraction for each source type (vehicle type), day type, and hour of the day along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
idle_fraction_final	Sum of the daily average idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in hour, day, and vehicle type
workday_idle_fraction_final	Sum of the daily average workday idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
extended_idle_fraction_final	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
sum_operating_hours	Sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
sum_idle_hours	Sum of the daily average idle hours for all vehicles in the hour, day, and vehicle type
sum_workday_idle_hours	Sum of the daily average workday idle hours for all vehicles in the hour, day, and vehicle type
sum_extended_idle_hours	Sum of the daily average extended idle hours for all vehicles in the hour, day, and vehicle type

starts_per_day_figure_Long_haul_divided_day.csv

- This file provides the average start per day for each source and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
avg_starts_per_day	Average starts per day in this source type and day type

Combined all Fleet DNA and CE-CERT data

MetaData_final_all.csv

- This file provides the background information of each vehicle in the two data sets. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DepotState	State where depot is located
DepotCity	City where depot is located
DepotZipcode	ZIP code where depot is located
GPSState	State based on the mode of the recorded GPS data
GPSCity	City based on the mode of the recorded GPS data
SourceTypeID	ID of vehicle type
Vocation	Vocation of the vehicle
VINstem	First 9 digits of the VIN
Model	Vehicle model
Manufacturer	Vehicle model manufacturer
ModelYear	Vehicle model year
GVWR	Gross vehicle weight rating
Combination	If the vehicle is combination or single
SleeperCab	If the vehicle is a sleeper cab
Axles	Number of axles
Wheels	Number of wheels
EngineManufacturer	Manufacturer of the engine
EngineModelYear	Engine model year
Engine	Engine type
AuxillaryPower Unit	If the vehicle includes auxiliary power unit
HybridElectric	If the vehicle is hybrid electric
Fuel	Fuel used in the vehicle
Odometer	Miles at the beginning of the test
Age	Calendar year minus model year
MilesDrivenPerOperationDay	Miles driven per operation day

InstrumentedTimes_final_all.csv

- This file provides the information related to the instrumented day from each vehicle in the two data sets. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
InstrumentStartDate	Date that activity logger began collecting data
InstrumentStartTime	Start time when activity logger began collecting data
InstrumentEndDate	Date that activity logger stopped collecting data
InstrumentEndTime	End time when activity logger stopped collecting data
InstrumentedDays	Number of days with instrumentation
Instrumented Weekday	Number of Instrumented days in weekdays
Instrumented Weekend	Number of Instrumented days in weekend
OperationDays	Number of InstrumentedDays with vehicle operation
Operation Weekday	Number of operation days in weekdays
Operation Weekend	Number of operation days in weekend

IdleEvents_final_all.csv

- This file provides the related information of the idle events experienced by each vehicle in the two databases. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
BeginIdleDate	Date that vehicle began idling
BeginDayID	Date ID that vehicle began idling (weekday = 5, weekend = 2)
BeginHourID	Hour ID that vehicle began idling
BeginIdleTime	Time instant when vehicle began idling
EndIdleDate	Date that vehicle stopped idling
EndIdleTime	Time instant when vehicle stopped idling
IdleDuration	EndIdleTime minus BeginIdleTime (seconds)

IdleOperationByDateDayHour_final_all.csv

- This file provides detailed information related to workday and extended idle fractions of each idle event experienced by the vehicles in the two databases. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
Date	Date
DayID	Date ID (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
OperationTime	Time with engine operation in the specific hour (seconds)
IdleTime	Total engine idle time in the specific hour (seconds)
WorkDayIdleTime	Total workday idle time in the specific hour (seconds)
ExtendedIdleTime	Total extended idle time in the specific hour (seconds)
MilesDriven	Miles driven along this operation time

IdleOperationByDayHour_final_all.csv

- This file provides hourly workday and extended idle fractions for each vehicle in the two databases. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DayID	Date ID (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
InstrumentedHours	Instrumented hours by DayID and HourID
OperationTime	Time with engine operation in the DayID and HourID (seconds)
IdleTime	Total engine idle time in the DayID and HourID (seconds)
WorkDayIdleTime	Total engine work idle time in the DayID and HourID (seconds)
ExtendedIdleTime	Total engine extended idle time in the DayID and HourID (seconds)
MilesDriven	Miles driven in the DayID and HourID
IdleFraction	IdleTime divided by OperationTime
WorkDayIdleFraction	WorkDayIdleTime divided by OperationTime
ExtendedIdleFraction	ExtendedIdleTime divided by OperationTime

StartSoaksEvents_final_all.csv

- This file provides the related information of the soak events experienced by each vehicle in the two databases. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
StartDate	Date that vehicle's engine started
StartDayID	Date ID that vehicle's engine started (weekday = 5, weekend = 2)
StartTime	Time instant when vehicle's engine started
StartHourID	Hour ID that vehicle's engine started (1–24)
PreviousEngineOffDate	Date that vehicle's engine stopped last time
PreviousEngineOffTime	Time instant when vehicle's engine stopped last time
SoakLength	StartTime minus PreviousEngineOffTime (seconds)
EngineOffDate	Date that vehicle's engine stopped
EngineOffTime	Time instant when vehicle's engine stopped
OperationDuration	Operation time between engine start time and engine off time (seconds)
MilesDriven	Miles driven along this operation duration

StartSoaksByDayHour_final_all.csv

- This file provides numbers of soak events in each soak operation mode for each vehicle in the two databases. The full list of parameters included in the file is as follows:

Column Name	Description
VehicleID	ID number of vehicles
DayID	Day type (weekday = 5, weekend = 2)
HourID	Hour of the day (1–24)
InstrumentedHours	Instrumented hours by DayID and HourID
OperationModeID	Soak time operating mode
Starts	Number of starts in specific operating mode

starts_final_all_plot_divided_day.csv

- This file provides the start fraction for each source type (vehicle type) and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
start_fraction_final	Sum of the daily average starts for an individual hour, day, and type divided by the sum of the daily average starts for an individual day and type

soak_final_all_plot_divided_day.csv

- This file provides the soak fraction for each source type (vehicle type), day type, hour of the day, and operation mode. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
op_mode	Operation mode of the soaks (101–108)
soak_fraction_final	Sum of the daily average soaks for an individual op_mode, hour, day, and type divided by the sum of daily average starts for an individual hour, day, and type

idle_final_all_plot_divided_day.csv

- This file provides the idle fraction for each source type (vehicle type) and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
idle_fraction_final	Sum of the daily average idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
workday_idle_fraction_final	Sum of the daily average workday idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
extended_idle_fraction_final	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
sum_operation_hours	Sum of the daily average operating hours for all vehicles in the day and vehicle type
sum_idle_hours	Sum of the daily average idle hours for all vehicles in the day and vehicle type
sum_workday_idle_hours	Sum of the daily average workday idle hours for all vehicles in the day and vehicle type
sum_extended_idle_hours	Sum of the daily average extended idle hours for all vehicles in the day and vehicle type
sum_miles_driven	Sum of the average daily miles driven for that day type and vehicle type
extended_idle_hours/miles_driven	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average miles traveled for all vehicles in the day and vehicle type
population	Population of vehicles for that source type and day type

hourly_idle_final_all_plot_divided_day.csv

- This file provides the total, workday, and extended idle fraction for each source type (vehicle type), day type and hour of the day along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
idle_fraction_final	Sum of the daily average idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in hour, day, and vehicle type
workday_idle_fraction_final	Sum of the daily average workday idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
extended_idle_fraction_final	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
sum_operating_hours	Sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
sum_idle_hours	Sum of the daily average idle hours for all vehicles in the hour, day, and vehicle type
sum_workday_idle_hours	Sum of the daily average workday idle hours for all vehicles in the hour, day, and vehicle type
sum_extended_idle_hours	Sum of the daily average extended idle hours for all vehicles in the hour, day, and vehicle type

starts_final_all_plot_vocation.csv

- This file provides the start fraction for each vocation and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
Vocation	Vehicle vocation
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
start_fraction_final	Sum of the daily average starts for an individual hour, day, and type divided by the sum of the daily average starts for an individual day and vehicle type

soak_final_all_plot_vocation.csv

- This file provides the soak fraction for each vocation, day type, hour of the day, and operation mode. The full list of parameters included in the file is as follows:

Column Name	Description
Vocation	Vehicle vocation
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
op_mode	Operation mode of the soaks (101–108)
soak_fraction_final	Sum of the daily average soaks for an individual op_mode, hour, day, and type divided by the sum of daily average starts for an individual hour, day, and type

idle_final_all_plot_vocation.csv

- This file provides the idle fraction for each vocation and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
Vocation	Vehicle vocation
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
idle_fraction_final	Sum of the daily average idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and type
workday_idle_fraction_final	Sum of the daily average workday idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
extended_idle_fraction_final	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the day and vehicle type
sum_operation_hours	Sum of the daily average operating hours for all vehicles in the day and vehicle type
sum_idle_hours	Sum of the daily average idle hours for all vehicles in the day and vehicle type
sum_workday_idle_hours	Sum of the daily average workday idle hours for all vehicles in the day and vehicle type
sum_extended_idle_hours	Sum of the daily average extended idle hours for all vehicles in the day and vehicle type
sum_miles_driven	Sum of the average daily miles driven for that day type and vehicle type
extended_idle_hours/miles_driven	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average miles traveled for all vehicles in the day and vehicle type
population	Population of vehicles for that source type and day type

hourly_idle_final_all_plot_vocation.csv

- This file provides the total, workday, and extended idle fraction for each vocation, day type, and hour of the day. The full list of parameters included in the file is as follows:

Column Name	Description
Vocation	Vehicle vocation
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
hour	Hour of the day (1–24)
idle_fraction_final	Sum of the daily average idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in hour, day, and type
workday_idle_fraction_final	Sum of the daily average workday idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
extended_idle_fraction_final	Sum of the daily average extended idle hours for all vehicles divided by sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
sum_operating_hours	Sum of the daily average operating hours for all vehicles in the hour, day, and vehicle type
sum_idle_hours	Sum of the daily average idle hours for all vehicles in the hour, day, and vehicle type
sum_workday_idle_hours	Sum of the daily average workday idle hours for all vehicles in the hour, day, and vehicle type
sum_extended_idle_hours	Sum of the daily average extended idle hours for all vehicles in the hour, day, and vehicle type

starts_per_day_figure_all_divided_day.csv

- This file provides the average start per day for each source and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
day	Day type (weekday = 5, weekend = 2)
avg_starts_per_day	Average starts per day in this source type and day type

starts_per_day_figure_all_plot_vocation.csv

- This file provides the average start per day for each vocation and day type along with statistics of the data. The full list of parameters included in the file is as follows:

Column Name	Description
source_type	Source type
Vocation	Vehicle vocation
day	Day type (weekday = 5, weekend = 2)
avg_starts_per_day	Average starts per day in this vocation and day type

Appendix N: Quality Assurance Evaluation

In accordance with the Quality Assurance Project Plan created for this project, NREL documented that the NREL and CE-CERT datasets analyzed in this report are appropriate for developing MOVES inputs according to the quality guidelines set forth in EPA's General Assessment Factors (EPA, 2003).

Quality Assurance Evaluation for the Fleet DNA database

1. Soundness

a. What methods and equipment were used to collect the data?

Two methods were used to collect the Fleet DNA: 1) NREL has collected these data over the years through the fleet evaluation process using the ISAAC dataloggers which record data from the vehicle diagnostic port. 2) NREL has received these data from third parties as part of cooperative research projects which are collected using various data logging systems from the vehicle diagnostic port.

b. Does the data quality vary among different methods and equipment used to collect the data?

Yes, the data quality varies as a result of both the data logger and the vehicle that the logger is installed on. However, the data varies in terms of its errors meaning some vehicles have more errors and some vehicles have less errors. Errors are accounted for using the QA process described in the next paragraph and in the report.

c. What quality assurance procedures are used when incorporating new data into the dataset?

Data broadcast across the diagnostic port conforms to the SAE J1939 data standard, however different vehicles and vehicle systems handle data broadcast differently. Further, various data loggers have different methods of handling the data. NREL has put in place checks, of these different known intricacies to remove these erroneous data by ensuring time stamp accurately reflects the sampling rate and all data are in the same units. However, many "non-valid" but correctly broadcast data are left in Fleet DNA to keep the data in its raw format allowing users to understand the operating state of the vehicle. For instance, when the engine controller shuts down it can broadcast over 8000RPM which is not possible. Because of this, quality assurance procedures are put in place specific to a given project. The quality assurance check depends on the data point. Here are the quality assurance checks: Vehicle Reported Speed – data that is over 150 mph is set to zero, and if all of this data is zero, GPS speed is used; GPS Speed – data over 150 mph is filtered out, and data below 1mph is set to zero since GPS does not have a true zero; Engine Speed – all speed above 7000 rpm are filtered out, and all speed below 500 are set to zero; GPS Locations – All locations outside of the US are removed; Gaps in data – when a vehicle has a time gap in its data greater than 6 hours a zero is inserted into the data to ensure that gap is counted as a stop. Further details of the QA process are defined in the reports.

- d. Are there any known data quality issues, where the data was retained for the analysis?

It is unknown if the data are in local time or system time set to the locale of the data logger programming computer for many of the heavy-duty long-haul combination trucks in the original NREL data set. Also, some vehicles displayed time gaps where the time stamp jumped without shutting the engine off. In Section 2.2.2 we accommodate this by assumed a gap length of 6 hours or greater is an engine shut off.

- e. What data storage procedures are used to assure that the data are not compromised?

The data is stored on NREL's redundant backup system that ensures data remains intact, and previous versions are saved should anything change.

2. Applicability and Utility

- a. Are the collected data relevant for the intended use in MOVES?

The data are relevant to MOVES as they are from in-use service of fleet vehicles recorded at 1 second intervals (1Hz).

- b. Are there any limitations of the data for its intended use?

The limitations are that the vehicles within Fleet DNA only show the data that are collected, and do not contain every vehicle's or type of vehicle's operation. Some MOVES inputs require fine-grained, dense data with many vehicles operating for a given hour, day type and road type. For example, the data is sparser than ideal some vehicle groups including refuse trucks and school buses during certain hours of the day. This results in gaps in coverage for some MOVES inputs. The Fleet DNA represents a large in-use sample of instrumented heavy-duty trucks and buses, but only represents a small fraction of the national vehicle fleet. Important vocations, truck types, and geographic regions that influence vehicle activity are not represented in the Fleet DNA database. As such it is difficult to assess how representative the Fleet DNA database is of the national in-use heavy-duty vehicle fleet.

3. Clarity and Completeness

- a. Are the data sources of the dataset clearly documented?

Yes, each data source has a project and project folder associated with it.

- b. Can the data be traced to the original data? If not, what processes assure that the data integrity is preserved?

Not as provided, but NREL has a dictionary which associates each data point with a data source. This was done to protect Non-Disclosure Agreements (NDAs) that NREL and the DOE have with the associated data providers.

4. Uncertainty and Variability

- a. What factors contribute to variability in the dataset?

Variability is a result of the vehicle drive cycles since no vehicle can completely recreate another vehicle's driving pattern.

- b. Can data that contributes the variability in the data be provided (e.g. state of operation, time of day, size of fleet), so they can be accounted for?

Yes, each dataset has a date, time, location, vocation, fleet size and size of data.

- c. What is the uncertainty regarding the data or any of the fields collected, and are the fields with uncertainty appropriately identified? (e.g. location of operation and time of day for long-haul trucks)

All precision conforms to the J1939 standard, and the uncertainty is defined by the sensor/broadcast message. GARMIN GPS 18x-5Hz differential GPS sensors were used for data collected by NREL. Like any GPS the signal accuracy is dependent on many factors. When the vehicle is stopped, typical accuracy is 3 meters, and as the vehicle starts moving the accuracy improves. However, the signal can be distorted by tall buildings, geographic features or atmospheric conditions. Road classification is based on GPS location, so errors in the location could affect the results. Further, the data near cities and mountains may be disproportionately affected.

5. Evaluation and Review

- a. What evaluation and review has the dataset undergone?

Each dataset was filtered for vocation and applicability to the MOVES classification of data. Further, only conventional vehicles are used to ensure augmented driving patterns from alternative fueled vehicles do not distort the output results.

- b. What review will be used to assure that the data is used appropriately?

Each dataset was tested to see if outputs conform to physics and that outliers are not erroneous. This includes removing data where the vehicle speed and engine speed is higher than the vehicle is physically capable of going and setting vehicle speeds less than 1mph to zero.

In addition to removing erroneous data, the results are graphed and summarized. Outlies are examined to ensure the data is correct, and intermediate results are reviewed with the EPA. Final results are peer reviewed by NREL and EPA employees not associated with the project.

6. Limitations

- a. Are there any other limitations of the datasets for its intended use to provide activity data in MOVES (not discussed above)?

Datasets provided by third parties are only as accurate as the reporting of the source providing them.

Quality Assurance Evaluation for the CE-CERT database

1. Soundness

a. What methods and equipment were used to collect the data?

Data was provided from the University of California Riverside's College of Engineering Center for Environmental Research and Technology and was collected using HEM data loggers. The dataset is referenced in this study and is part of revision version 7.1.

b. Does the data quality vary among different methods and equipment used to collect the data?

Yes, the data quality varies as a result of the vehicle that the logger is installed on. However, the data varies in terms of its errors meaning some vehicles have more errors and some vehicles have less errors. Errors are accounted for using the QA process described in the next paragraph.

c. What quality assurance procedures are used when incorporating new data into the dataset?

Data broadcast across the diagnostic port conforms to the SAE J1939 data standard, however different vehicles and vehicle systems handle data broadcast differently. NREL has put in place checks, of these different known intricacies to remove these erroneous data. The quality assurance check depends on the data point. Here are the quality assurance checks: Vehicle Reported Speed – data that is over 150 mph is set to zero, and if all of this data is zero, GPS speed is used; GPS Speed – data over 150 mph is filtered out, and data below 1mph is set to zero since GPS does not have a true zero; Engine Speed – all speed above 7000 rpm are filtered out, and all speed below 500 are set to zero; GPS Locations – All locations outside of the US are removed; Gaps in data – when a vehicle has a time gap in its data greater than 6 hours a zero is inserted into the data to ensure that gap is counted as a stop. Further details of the QA process are defined in the reports.

d. Are there any known data quality issues, where the data was retained for the analysis?

Data was provided from CE-CERT which did data filtering in accordance with the CE-CERT report1. All conventional vehicle data was kept.

e. What data storage procedures are used to assure that the data are not compromised?

The data is stored on NREL's redundant backup system that ensures data remains intact, and previous versions are saved should anything change.

2. Applicability and Utility

a. Are the collected data relevant for the intended use in MOVES?

The data are relevant to MOVES as they are from in-use service of fleet vehicles recorded at 1 second intervals (1Hz).

- b. Are there any limitations of the data for its intended use?

The limitations are that the vehicles within CE-CERT only show the data that are collected, and do not contain every vehicle's or type of vehicle's operation. Further, this dataset is only from California. Some MOVES inputs require fine-grained, dense data with many vehicles operating for a given hour, day type and road type. However, some vehicle categories have very few vehicles in them resulting in gaps in coverage for some MOVES inputs

3. Clarity and Completeness

- a. Are the data sources of the dataset clearly documented?

Yes, all data are documented in the CE-CERT report (Boriboonsomsin et al. 2017).

- b. Can the data be traced to the original data? If not, what processes assure that the data integrity is preserved?

Yes, all data sources are documented in the CE-CERT report (Boriboonsomsin et al. 2017).

4. Uncertainty and Variability

- a. What factors contribute to variability in the dataset?

Variability is a result of the vehicle drive cycles since no vehicle can completely recreate another vehicle's driving pattern.

- b. Can data that contributes the variability in the data be provided (e.g. state of operation, time of day, size of fleet), so they can be accounted for?

Yes, each dataset has a date, time, location, vocation, fleet size and size of data.

- c. What is the uncertainty regarding the data or any of the fields collected, and are the fields with uncertainty appropriately identified? (e.g. location of operation and time of day for long-haul trucks)

All precision conforms to the J1939 standard, and the uncertainty is defined by the sensor/broadcast message. GPS sensors were used for data collected by CE-CERT. Like any GPS the signal accuracy is dependent on many factors. When the vehicle is stopped, typical accuracy is 3 meters, and as the vehicle starts moving the accuracy improves. However, the signal can be distorted by tall buildings, geographic features or atmospheric conditions. Road classification is based on GPS location, so errors in the location could affect the results. Further, the data near cities and mountains may be disproportionately affected.

5. Evaluation and Review

- a. What evaluation and review has the dataset undergone?

Each dataset was filtered for vocation and applicability to the MOVES classification of data. Further, only conventional vehicles are used to ensure augmented driving patterns from alternative fueled vehicles do not distort the output results.

b. What review will be used to assure that the data is used appropriately?

Each dataset was tested to see if outputs conform to physics and that outliers are not erroneous. This includes removing data where the vehicle speed and engine speed is higher than the vehicle is physically capable of going and setting vehicle speeds less than 1mph to zero.

In addition to removing erroneous data, the results are graphed and summarized. Outlies are examined to ensure the data is correct, and intermediate results are reviewed with the EPA. Final results are peer reviewed by NREL and EPA employees not associated with the project.

6. Limitations

a. Are there any other limitations of the datasets for its intended use to provide activity data in MOVES (not discussed above)?

Datasets provided by third parties are only as accurate as the reporting of the source providing them.