Depot vs On-Route Charging

Utility Bus and Truck Working Council

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NYCT Electric Bus Fleet Demonstration

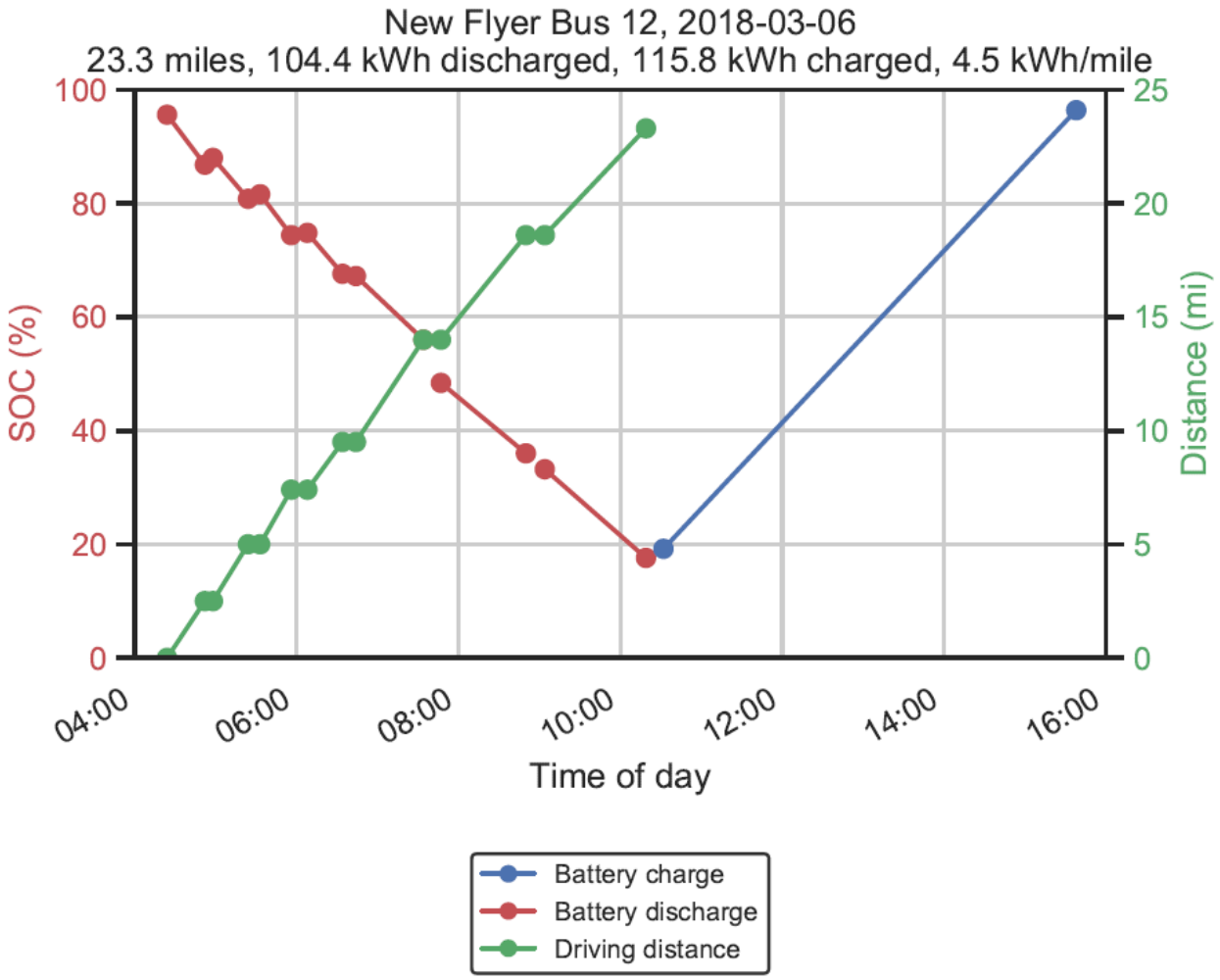
Program

- 10 buses were deployed in January 2018
  - 5 Blade buses (Proterra) deployed in Brooklyn, Queens, and Manhattan
  - 5 Cross Rail buses (New Flyer) deployed in Manhattan
- Chargers
  - One Blade On-Route charger (500 kW) is at the Williamsburg Terminal in Brooklyn
  - Two Cross Rail chargers (350 kW) are located on both sides of Manhattan near 42nd Street
  - Eight Manual DC Chargers (50 and 60 kW) are deployed at the two depots
- Data has been collected and has been analyzed over 16 months of operation
  - More than 65,000 miles traveled
  - More than 5,200 charges including depot and on-route

Future Plan

- NYCT has added 15 more buses in 2019 and 45 more in 2020 (Total 70 buses)
- Eventually, 5,800 existing buses will be replaced with electric buses

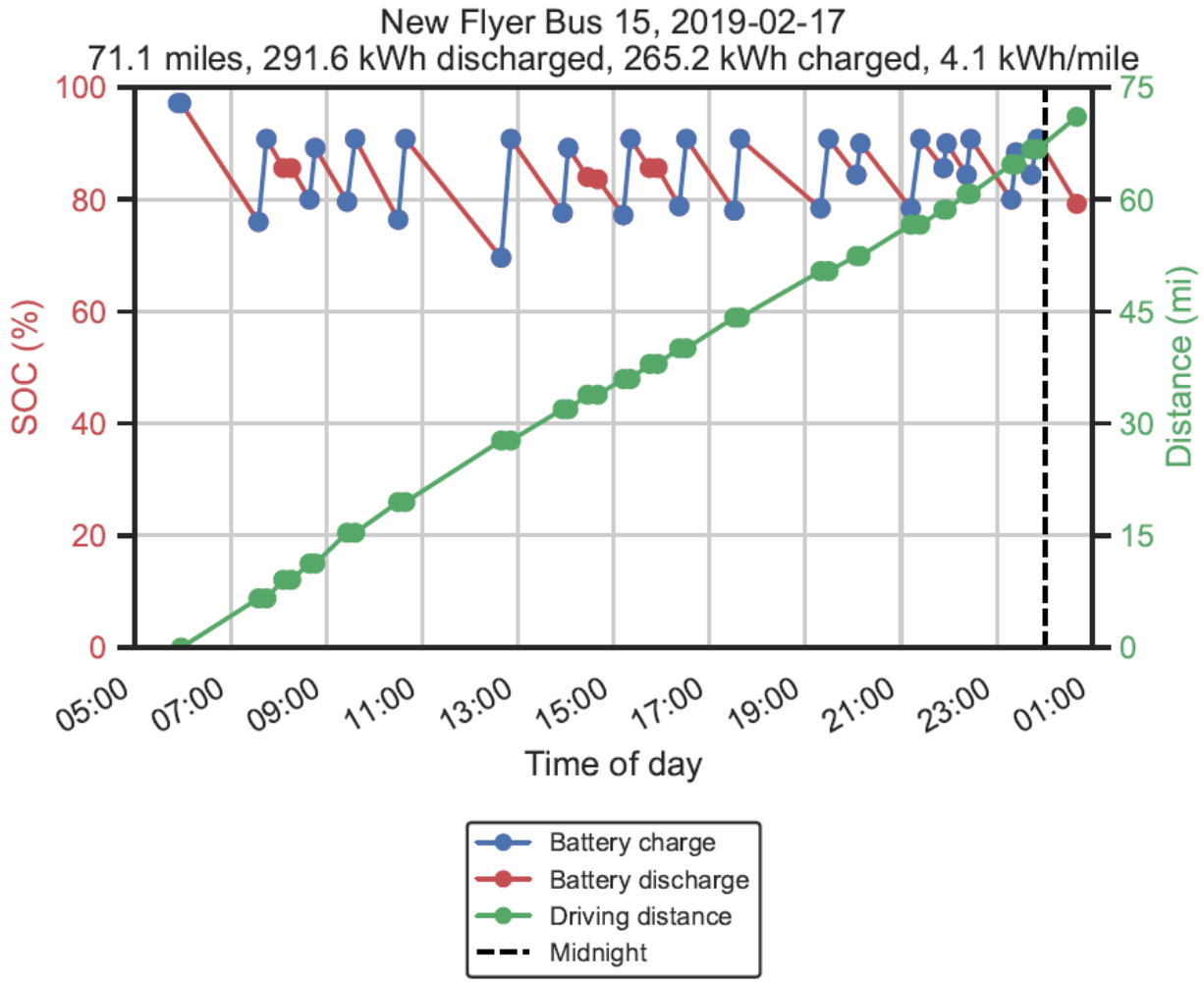
New Flyer Depot Charge Pattern- March 6, 2018



- One depot charge
- The bus leaves the depot at 4:30 am.
- A slight break occurs just prior to 8:00 am.
- By about 10:30 am, the 23.3 miles route is complete in 6 hours (11.5 hours total)
- Bus begins a 5.5-hour depot charge (48% charge time)
- Travel Effectiveness 23.3 miles/11.5 hours = 1.9 miles/hour
- Effectiveness factor = Charged Energy/ Discharged Energy
- Effectiveness Factor= 115.8 kWh /104.4 kWh = 1.115
- Corrected Travel Effectiveness = 1.9 *1.115 = 2.2 miles/hour

New Flyer On-Route Charge Pattern- February 17, 2019

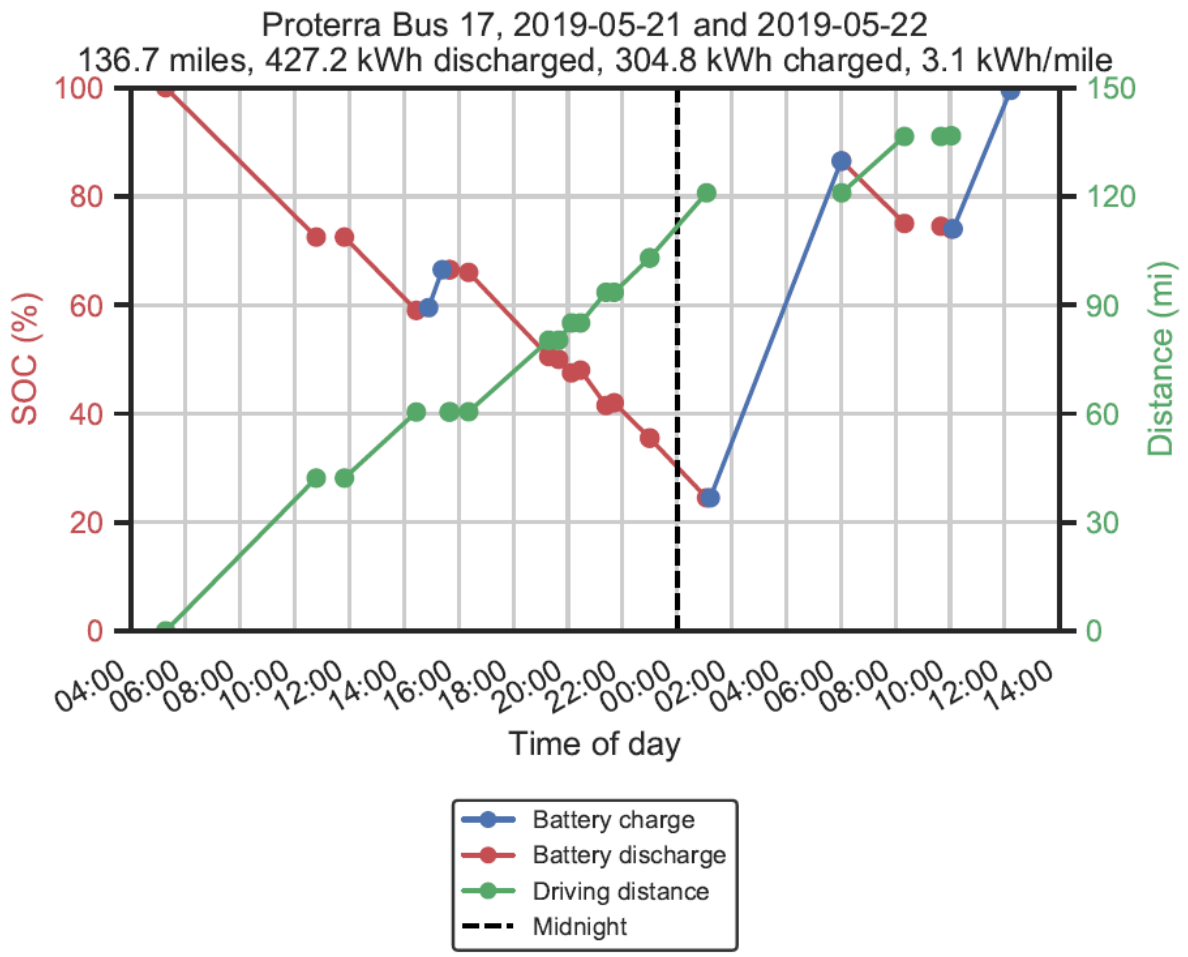
The on-route chargers are much more powerful than the depot chargers. The buses need much less time to charge at an on-route charger than a depot charger.



- 16 charges over a 19-hour day traveling 71 miles. Charge time = 2.23 hours (12% charge time) Average charge duration = 8.3 minutes
- The SOC mostly stays above the 78% SOC mark.
- Travel Effectiveness 71.1/19 = 3.7 miles/ hour
- Effectiveness Factor= 265 kWh/292 kWh = 0.907
- Corrected Travel Effectiveness = 3.7 *0.907 = 3.4 miles /hour
- An extended day is the outcome. And the bus is ready to go again (no need for a depot charge).

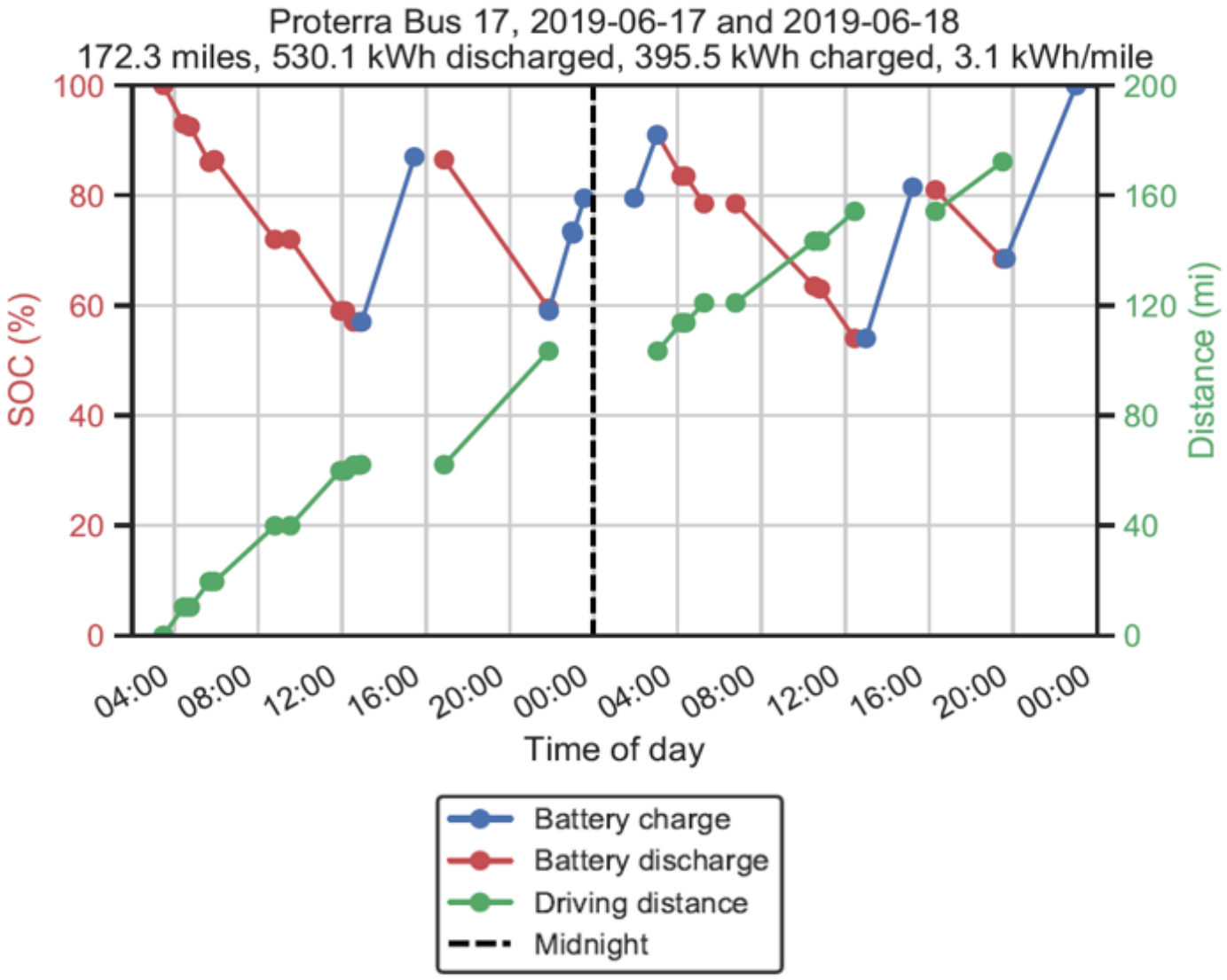
Proterra Depot Charge Pattern- May 21 to 22

Basically, use the bus continuously, depleting the battery near the end of the operation, then take it back to the depot and slow charge the battery for a longer time (6 to 8 hours) on the next shift. Multiple chargers are required in the depot for the multiples of buses.



- 3 depot charges over a 31-hour period traveling a total of 137 miles
- The depot charges lasted 8 hours of the 31-hours (26% charge time) were used to depot charge, with the last charge event lasting two hours to bring the bus back to full SOC.
- Travel Effectiveness 136.7/31 = 4.4 miles/ hour
- Effectiveness Factor= 305/427 = 0.714
- Corrected Travel Effectiveness = 4.4 *0.714 = 3.1 miles /hour
- An extended day is the outcome. And the bus is ready to go again.

Proterra Charge Pattern- June 17 and 18



- 5 depot charges over a 44-hour period (almost two days) traveling 172 miles.
- 16 hours across two days were used to depot charge back full SOC. (36% charge time)
- And the bus is ready to go again.
- Travel Effectiveness 172/44 = 3.9 miles/ hour
- Effectiveness Factor= 396 kWh /530 kWh = 0.747
- Corrected Travel Effectiveness = 3.9 *0.747 = 2.9 miles /hour

Big Battery, Depot Charge versus Small Battery, On-route Charge

- The Proterra and New Flyer buses had 352 and 120 kWh useable energy of battery storage, respectively.
- The New Flyer buses had two on-route chargers on west and east sides of 42nd street in Manhattan.
- The main thought about a larger battery is that on-route charging could be eliminated. The battery size should depend on the daily-use of the bus.
- The higher the travel effectiveness the more effective the system is. A given bus architecture (battery size and charge type) can be evaluated to provide the most traveled miles in the least amount of time including charging.

Big Battery, Depot Charge versus Small Battery, On-route Charge

Summarizing the last four charts

	Bus #	Date	# of Charges	Event Distance (mi)	Event Discharge (kWh)	Event Charge (kWh)	Net Charge (%)	Event Duration (h)	Travel Effectiveness* (miles/hour)	Corrected Travel Effectiveness ** (miles /hour)	Battery Size	Charge Type
New Flyer	15	2/17/2019	16	71.1	292	265	-9.2%	19	3.7	3.4	Small (120 kWh)	On-route
Proterra	17	5/21/2019	3	136.7	427	305	-28.6%	31	4.4	3.1	Large (352 kWh)	Depot
Proterra	17	6/17/2019	5	172.3	530	396	-25.3%	44	3.9	2.9	Large (352 kWh)	Depot
New Flyer	12	3/6/2018	1	23.3	104	116	11.5%	12	1.9	2.2	Small (120 kWh)	Depot

* Travel Effectiveness = event distance / event duration = miles/hour

** Corrected Travel Effectiveness = Travel Effectiveness * Net Charge (%) = miles/hour

The data suggests:

The small battery and on-route charger had the largest Corrected Travel Effectiveness (3.4 miles/hour)

The large battery and depot charged were similar to the on-route case (3.1 and 2.9 miles/hour)

The small battery depot charged bus had the smallest Corrected Travel Effectiveness (2.2 miles/hour)

Big Battery, Depot Charge versus Small Battery, On-route Charge

- In summary, regarding battery size and charging location (Depot vs On-route),
  - Every fleet needs to plan its routes, locations of the depots, and the location of the on-route chargers
  - Travel effectiveness should be calculated
  - On-route chargers should be placed where the throughput is very high
    - i.e. many charges during operation
  - To minimize the battery cost, batteries should not be excessively over-sized.
  - Depot and on-route charging can both be cost effective
    - On-route chargers can be effective if the size of the fleet is large
  - Depot and on-route charging can be operationally effective
    - i.e. either can have a high travel effectiveness
  - Depot charging a Small battery scenario is not as effective as the others

Questions ????

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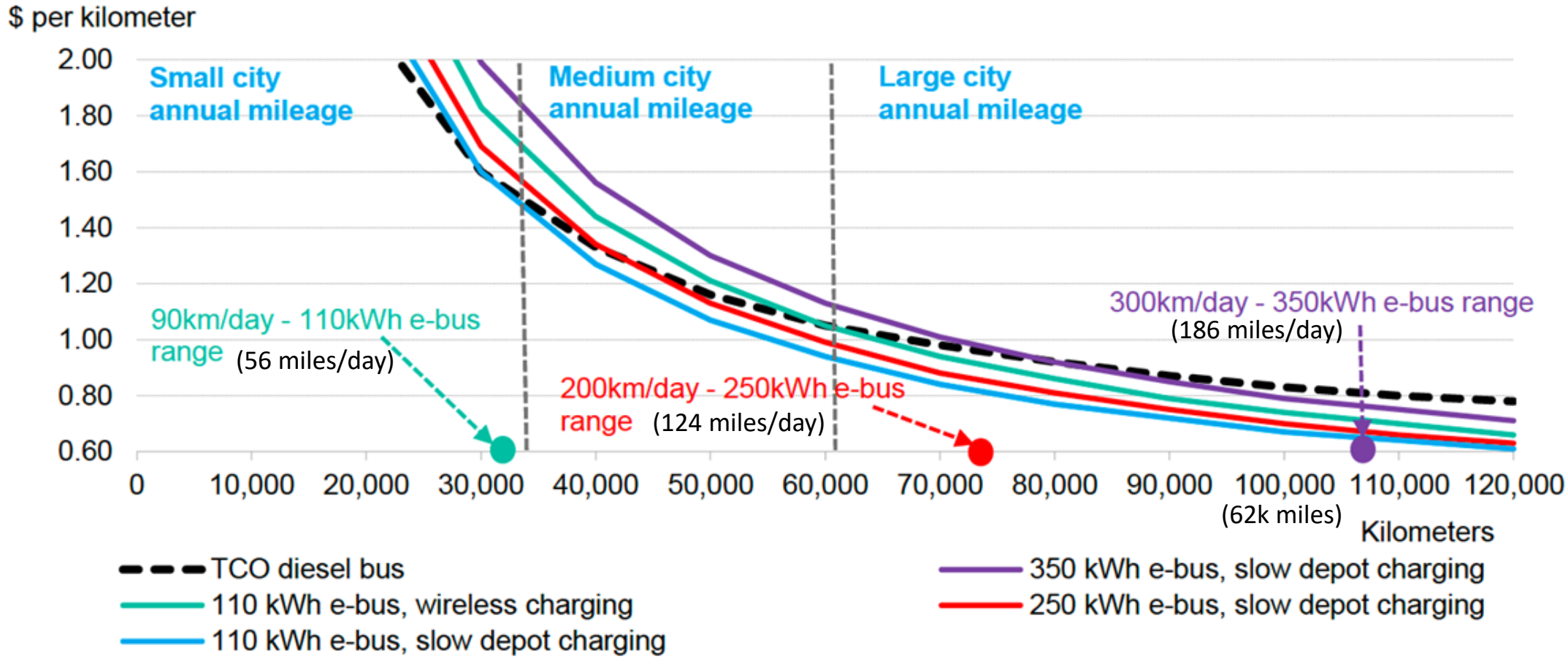
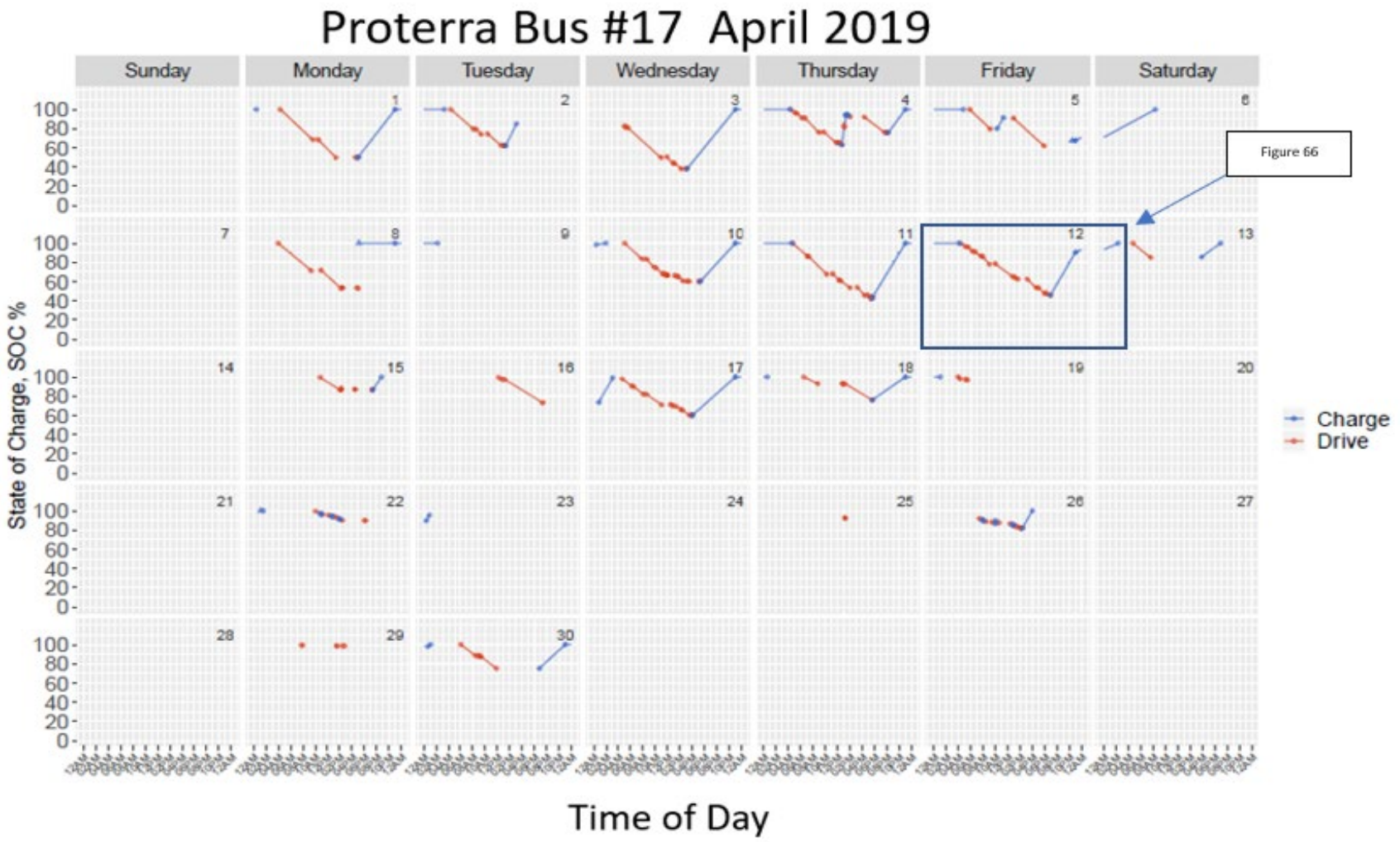
Together...Shaping the Future of Electricity

Total Cost of Bus Ownership Comparison



Source: Bloomberg New Energy Finance, AFLEET, Advanced Clean Transit Notes: Diesel price at $0.66/liter ($2.5/gallon), electricity price at $0.10/kWh, annual kilometers traveled – variable. Bus route length will not always correspond with city size.

Proterra Monthly Discharge and Charge Patterns

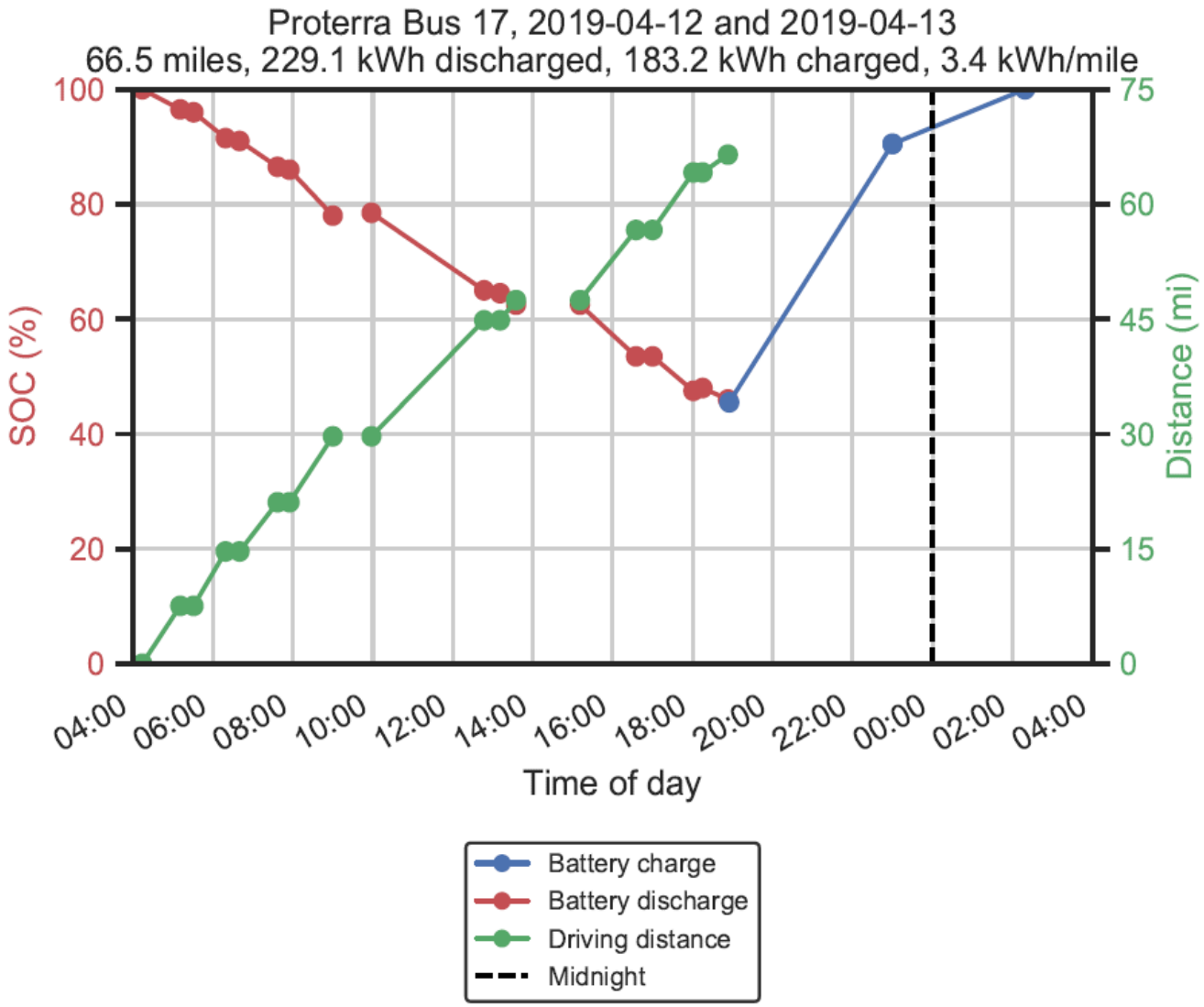


Each day of the April 2019 is shown with the discharge (red-drive) and charge patterns (blue-charge)

Buses were not used on Sundays. Typically, the buses began to drive in the early morning.

The Proterra bus was primarily depot charged after a discharge.

Proterra Charge Pattern- April 12 to 13



- Proterra daily pattern with one depot charge over a 22-hour day traveling 66.5 miles.
- The larger battery allowed the bus to travel further without on-route charging.
- An extended day is the outcome.
- The last 7 hours of the day and the following morning are used to depot charge back full SOC.
- And the bus is ready to go again.

Driving Data Summary

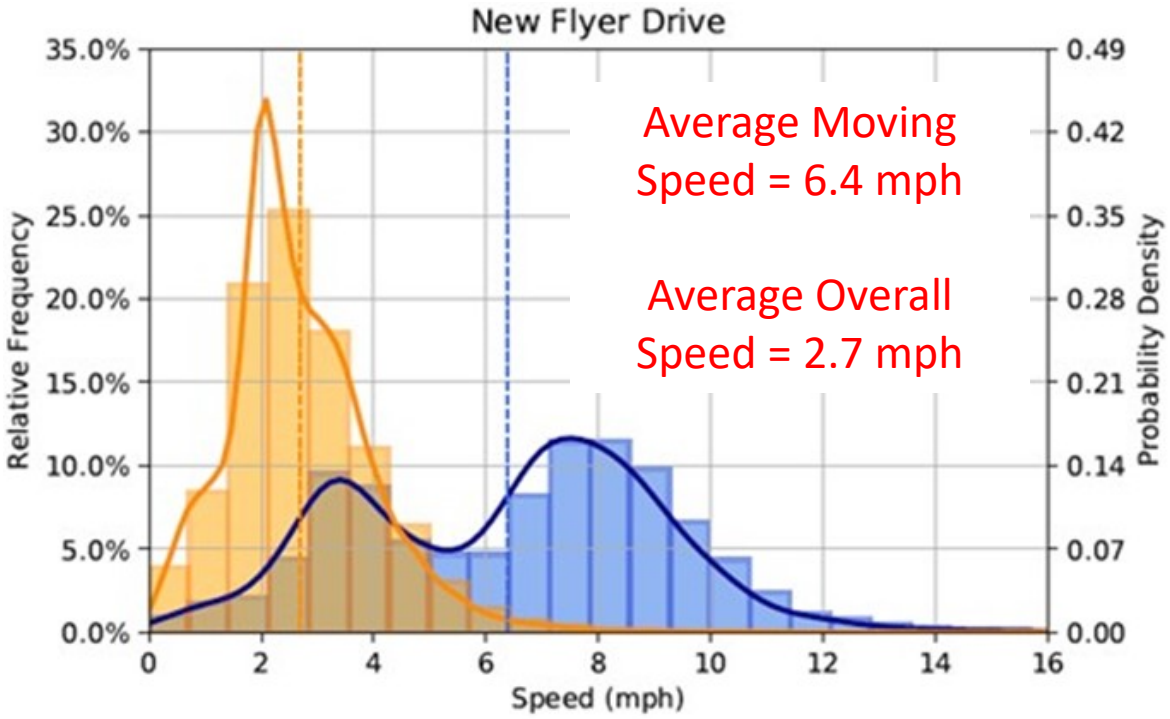
	# of Drives	Total Distance* (miles)	Operating Duration (h)	Total Energy (kWh)	Total Non-Moving Energy (kWh)	Average Moving Speed** (mph)	Average Overall Speed** (mph)	Average Consumption*** (kWh/mi)
New Flyer	9,941	30,903.7	9,745.4	123,005.7	58,607	6.4	2.7	3.7
Proterra	2,250	34,759.7	5,225.7	121,065.9	19,269	6.2	5.4	3.5
Total	12,191	65,663	14,971	244,072	77,876			

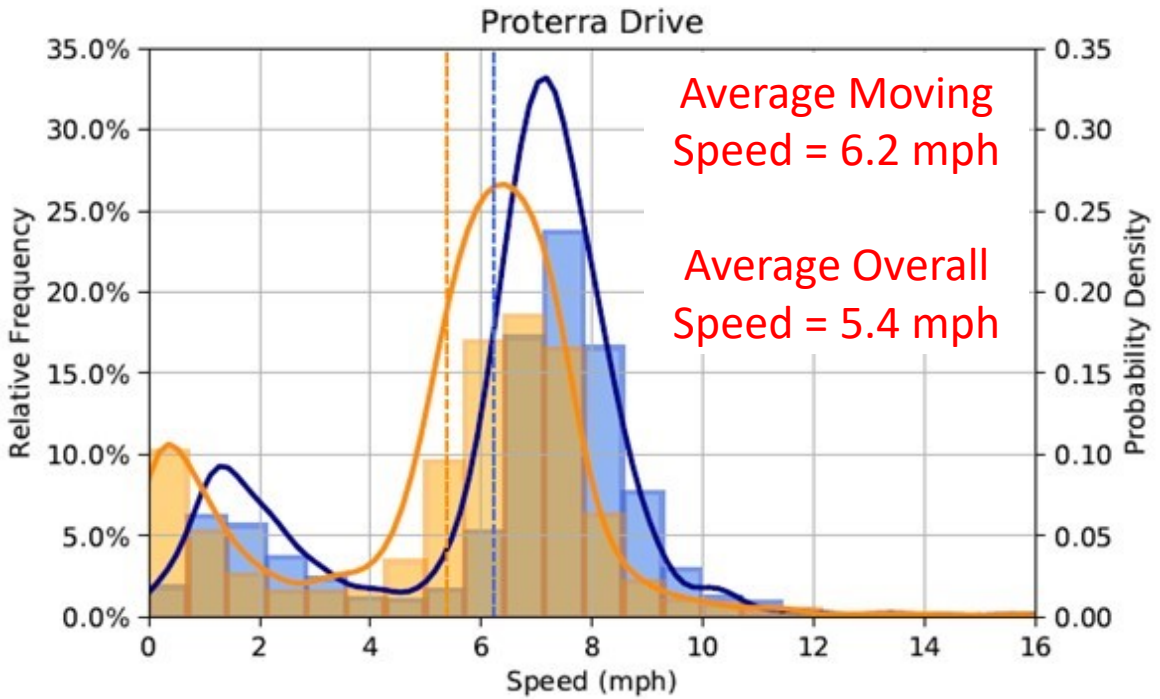
New Flyer includes 2/1/2018 to 4/4/2019

Proterra includes 12/26/2017 to 6/14/2019

- The data was collected on an event basis.
  - One second data was accumulated over an event.
  - An event is described as the duration between the start of the drive to the end of the drive (or the equivalent) or the beginning of a charge to the end of the charge.
- New Flyer had more drive events due to a smaller battery than the Proterra
  - New Flyer (120 kWh Useable) and Proterra (352 kWh Useable)

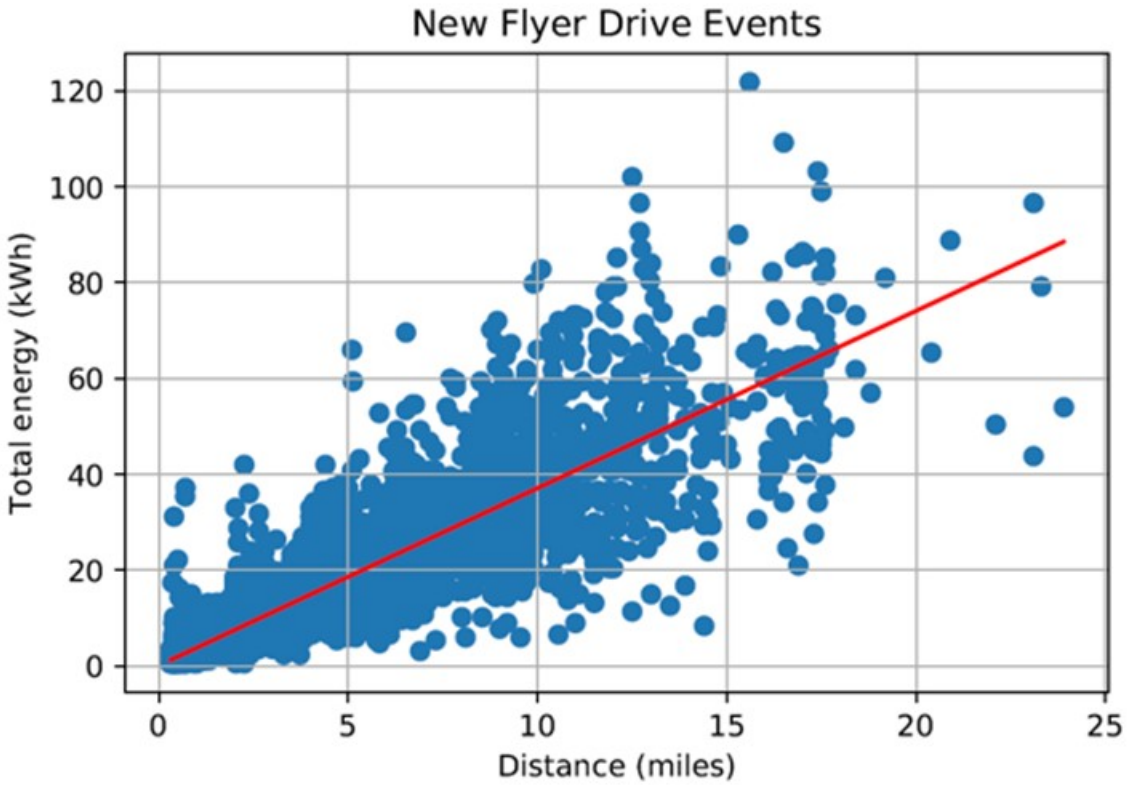
Vehicle Speed Data

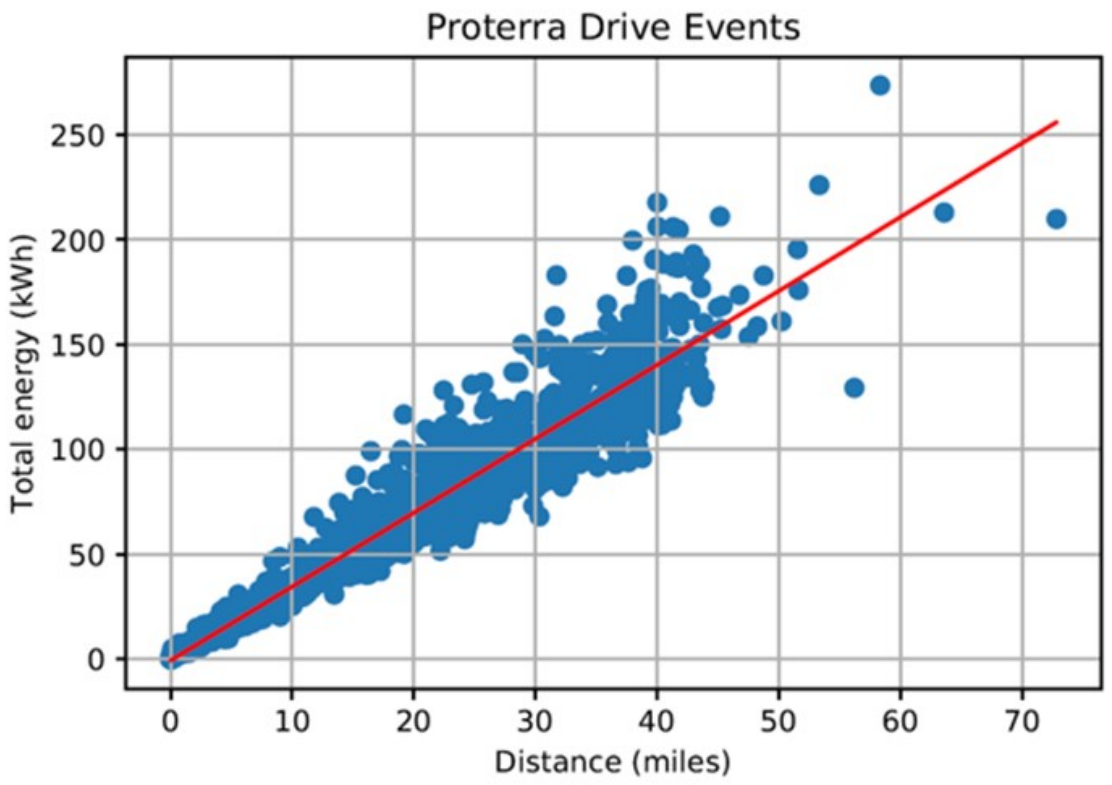




Moving Speed does not include time the vehicle is stopped

Driving Consumption Data





New Flyer Consumption = 3.7 kWh/mi
Proterra Consumption = 3.5 kWh/mi

Depot Charging Data Summary

Depot Charging	# of Charges	Charging Duration (h)	Excess Plug-in Duration (h)	Total Delivered Energy (kWh)	Average Charge Duration* (h/charge)	Average Charge Energy * (kWh/charge)	Average Charge Energy** (kWh/h)
New Flyer	2599	3,616.6	2,377.2	112,670.6	1.4	43.4	NA
Proterra	1650	3,749.7	1,774.1	116,479.4	2.3	73.6	37.6
Total	4249	7,366	4,151	229,150			

New Flyer includes 2/1/2018 to 4/4/2019

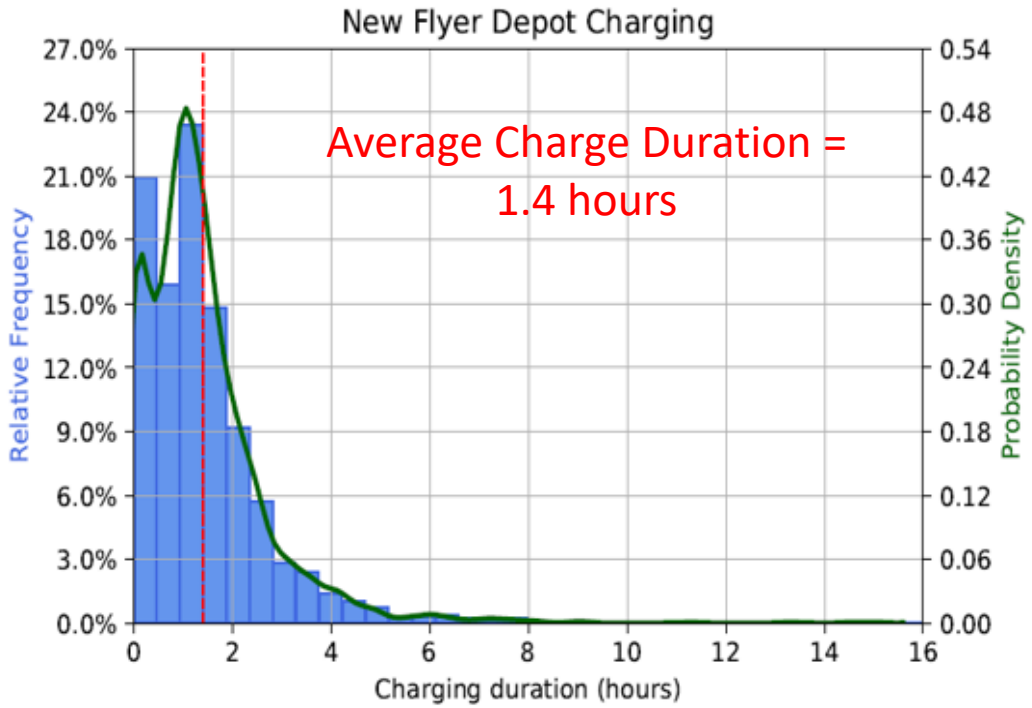
Proterra includes 12/26/2017 to 6/14/2019

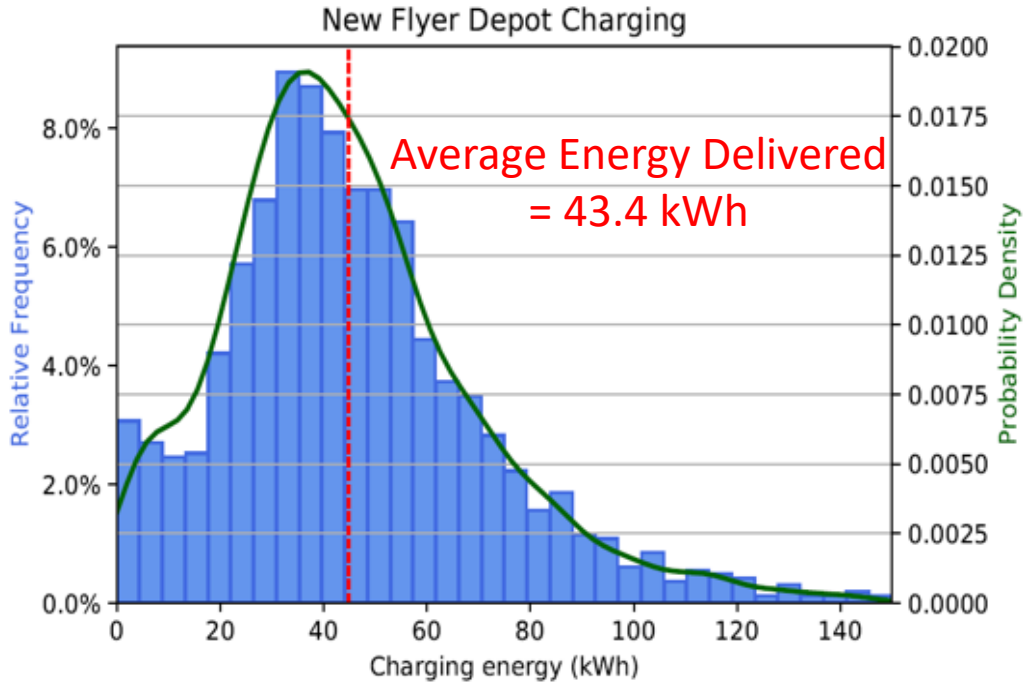
Overall, New Flyer buses were charging 60% of the time they were plugged in* at the depot

Overall, Proterra buses were charging 68% of the time they were plugged in at the depot

*Total plugged time = charge duration + excess plug-in duration

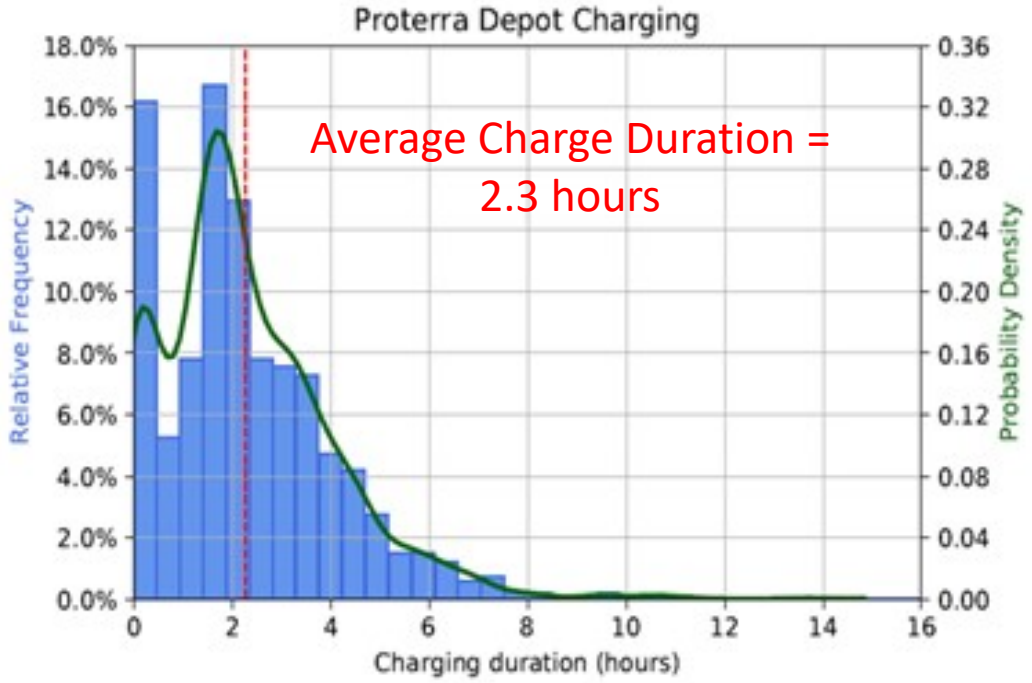
New Flyer Depot Charge Duration and Energy Data

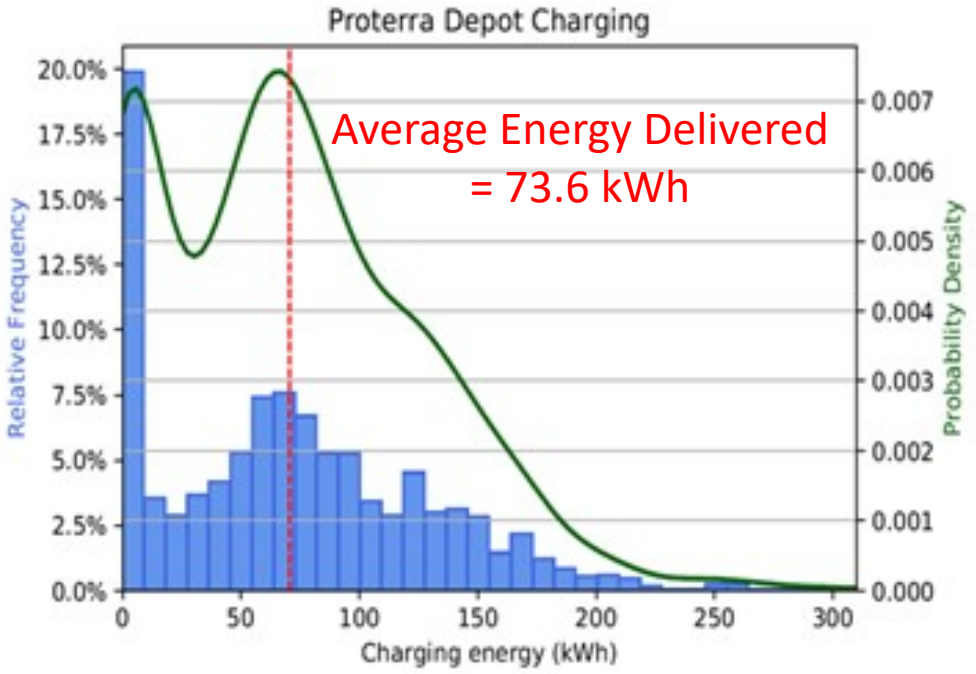




Number of Events: 2599
Maximum Active Peak Power: 60.0 kW
Average Peak Power: 50.1 kW
Maximum Battery Energy Delivered: 149.4 kWh
Average Battery Energy Delivered: 43.4 kWh
Average Charging Duration: 1.4 hours

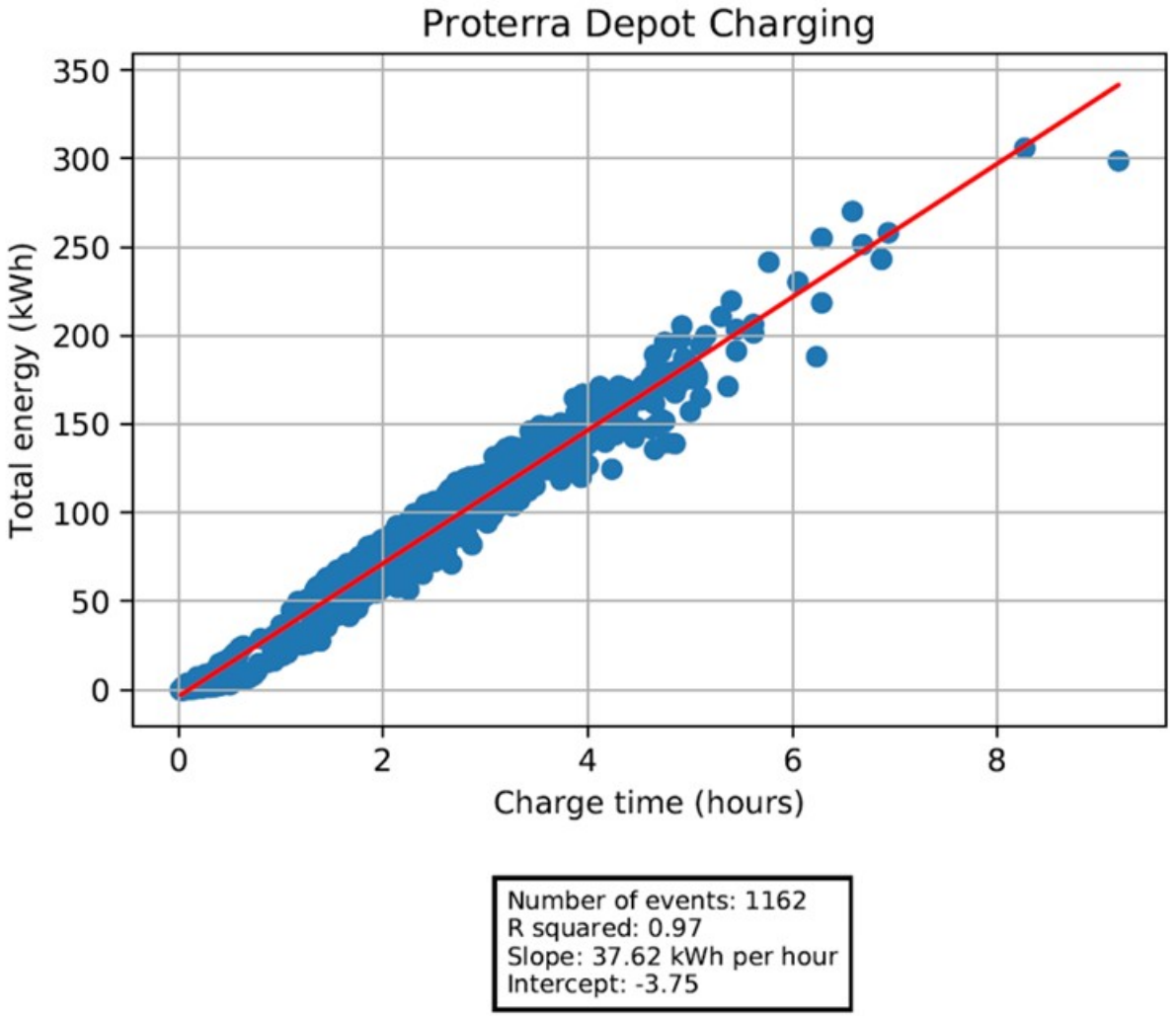
Proterra Depot Charge Duration and Energy Data





Number of Events: 1650
Maximum Active Peak Power: 88.2 kW
Average Active Power: 28.1 kW
Maximum Active Energy Delivered: 305.9 kWh
Average Active Energy Delivered: 73.6 kWh
Average Charging Duration: 2.3 hours

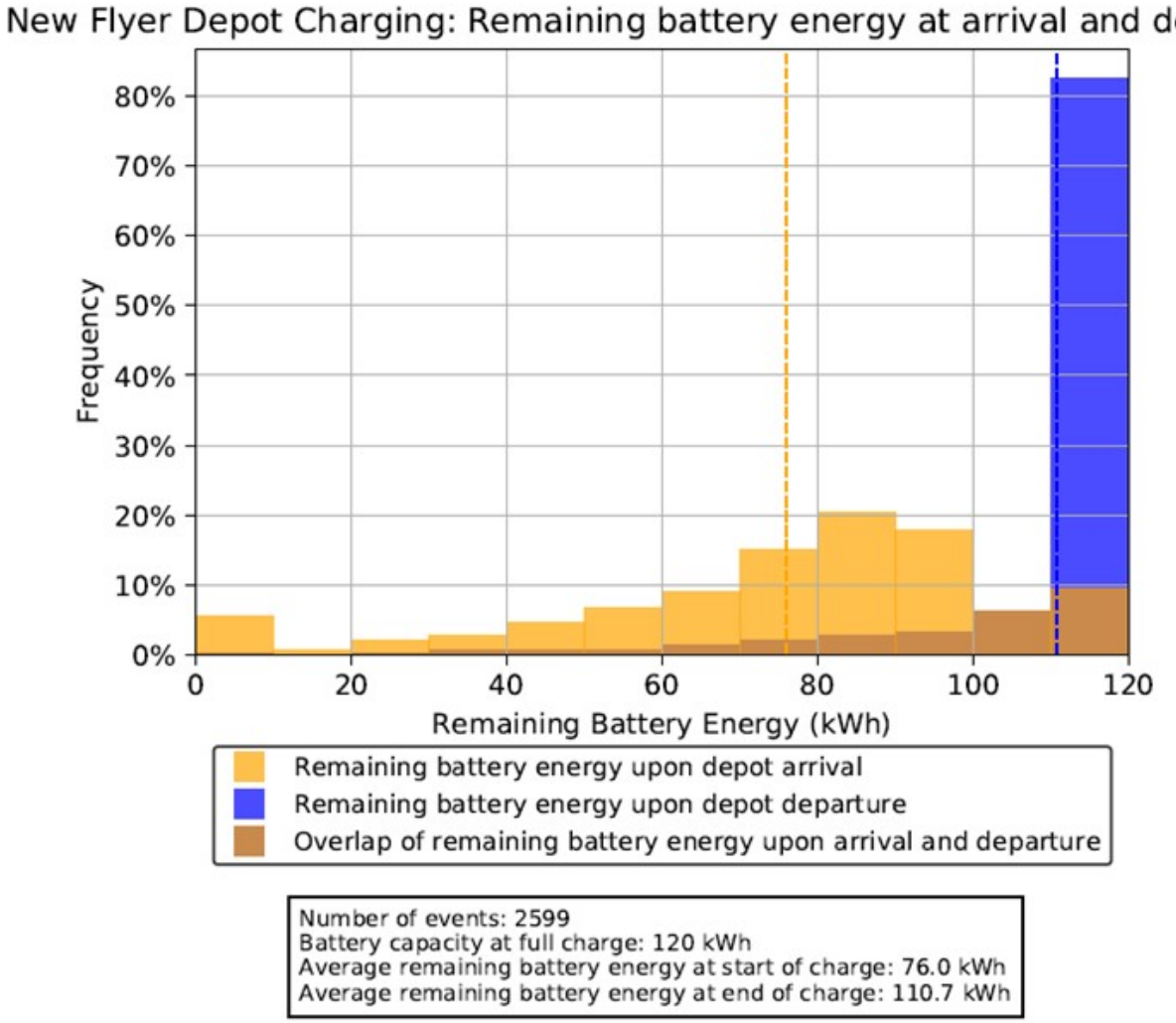
Proterra Depot Charge Delivery



Charge Delivery = 37.6 kWh/hour
With good correlation

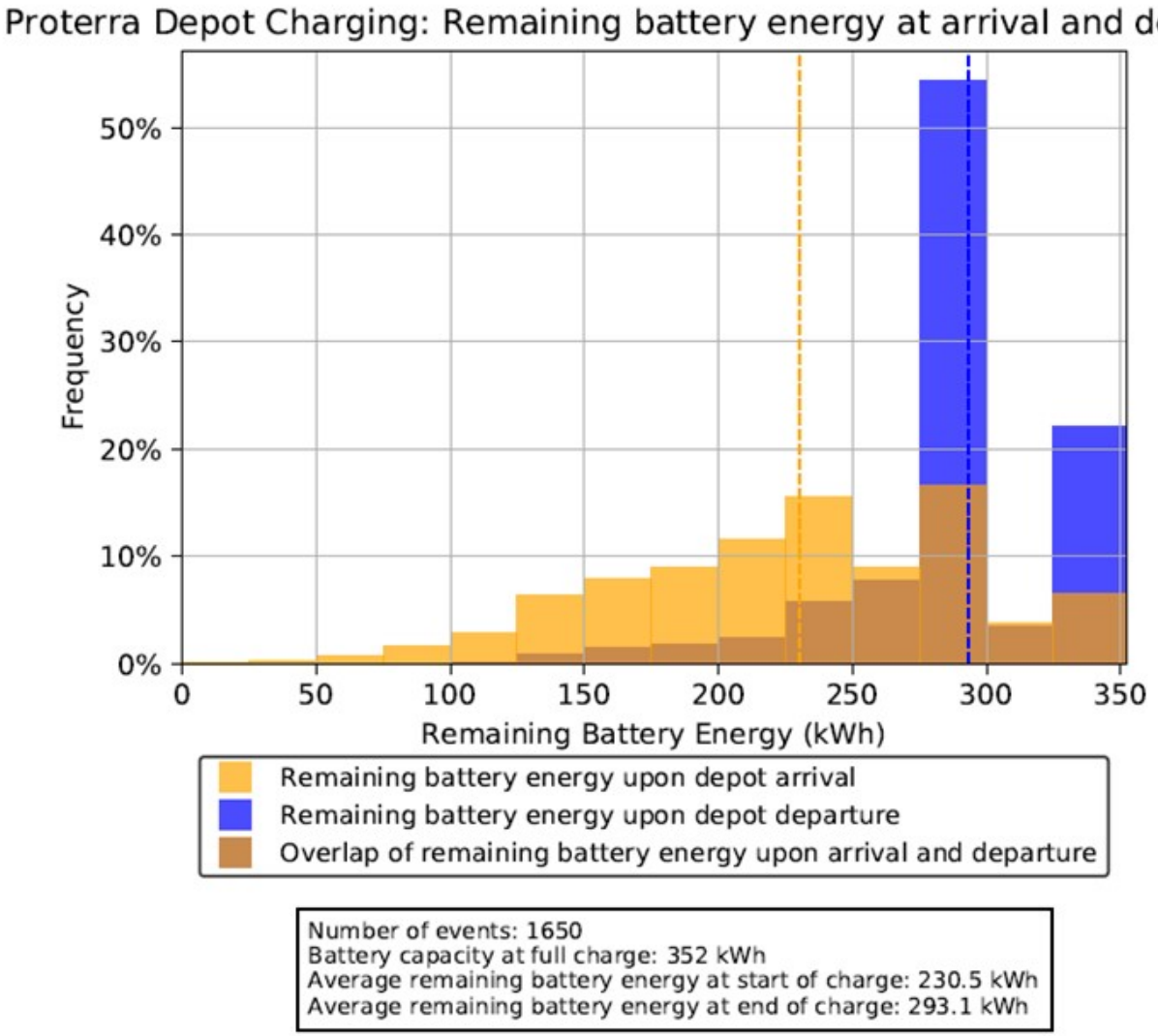
New Flyer data was not a good correlation

New Flyer Depot Remaining Energy



- New Flyer began depot charging with an average of 76 kWh remaining available battery energy and
- Completed the charges at an average of 111 kWh.
- More than 80% of the charges ended with a full charge. In general, the New Flyer buses had more than enough capacity.
- In theory, it would be more efficient to return to the depot with nearly an empty battery. On average, the buses returned with 63% of its capacity remaining with very few near the empty level.

Proterra Depot Remaining Energy



- Proterra began depot charges with an average of 230 kWh remaining energy
- Completed the charges at an average of 293 kWh
- On average the buses were returned to the depot with 65% of the battery capacity remaining.
- Ideally, it would be better to return the buses to the depot with nearly an empty battery as long as there is enough to complete the task.

For both New Flyer and Proterra, it may have been more practical to have a smaller battery or be able to optimize the bus schedule to use a significant portion of the battery energy.

On-route Charging Data Summary

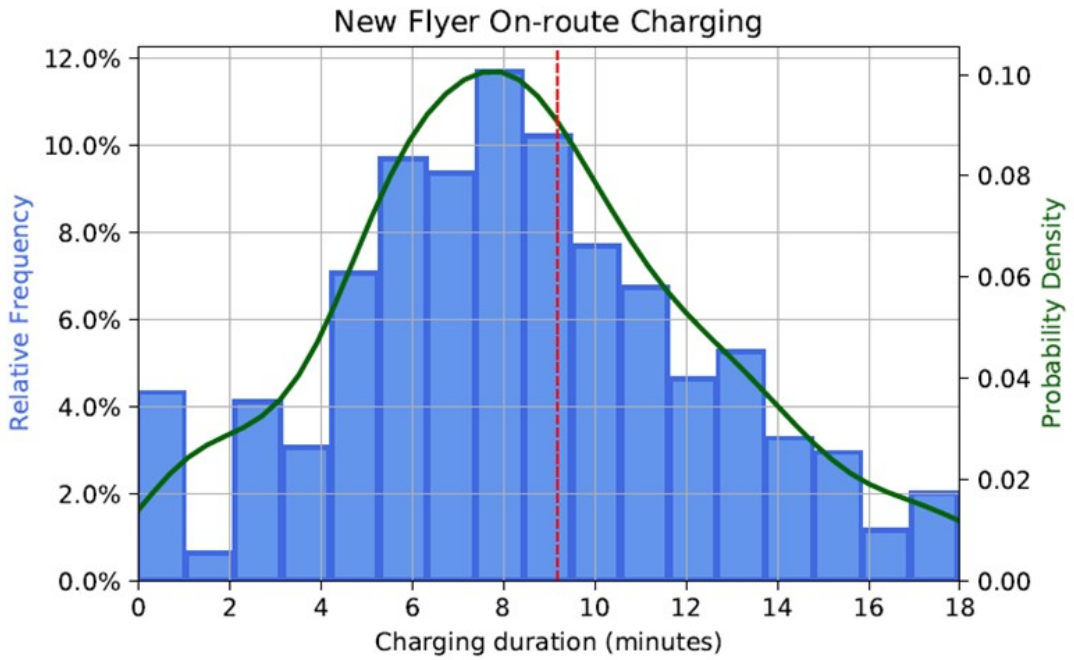
On-Route Charging	# of Charges	Total Charging Duration (h)	Total Delivered Energy (kWh)	Average Charge Duration* (min)	Average Charge Energy** (kWh/min)
New Flyer	949	145.2	21,929.7	9.2	2.8
Proterra	26	4.7	581.2	3.1	NA
Total	975	166.6	22,511		

New Flyer includes 2/1/2018 to 4/4/2019

Proterra includes 12/26/2017 to 6/14/2019

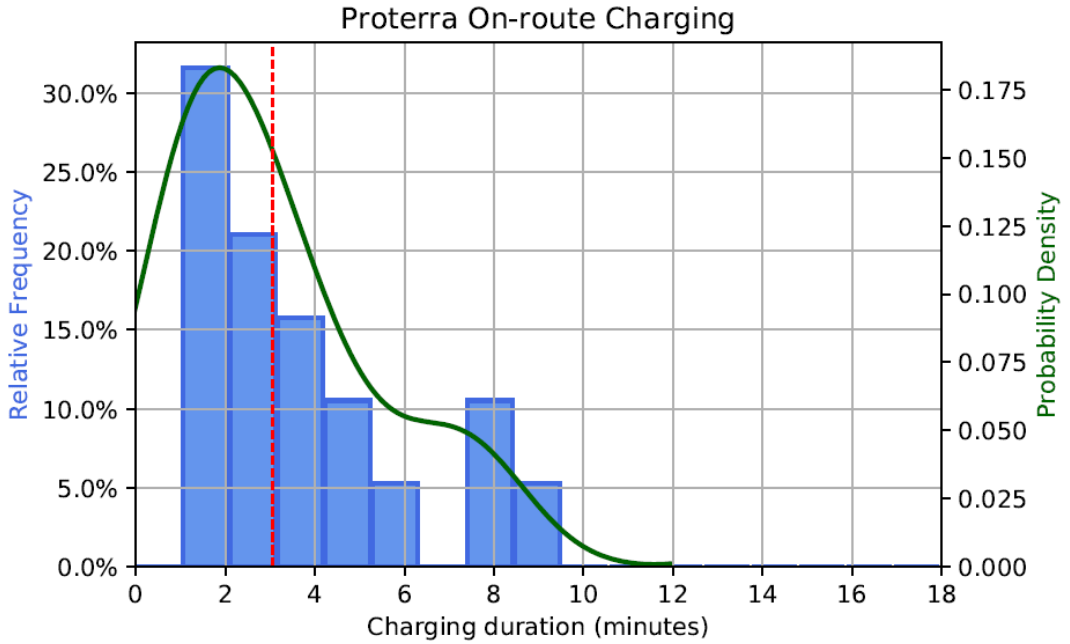
- Proterra mainly used the depot charging and not on-route charging

On-route Charge Duration Data



Number of Events: 949
Maximum Active Peak Power: 278.8 kW
Average Peak Power: 208.7 kW
Maximum Battery Energy Delivered: 125.4 kWh
Average Battery Energy Delivered: 23.1 kWh
Average Charging Duration: 9.2 minutes

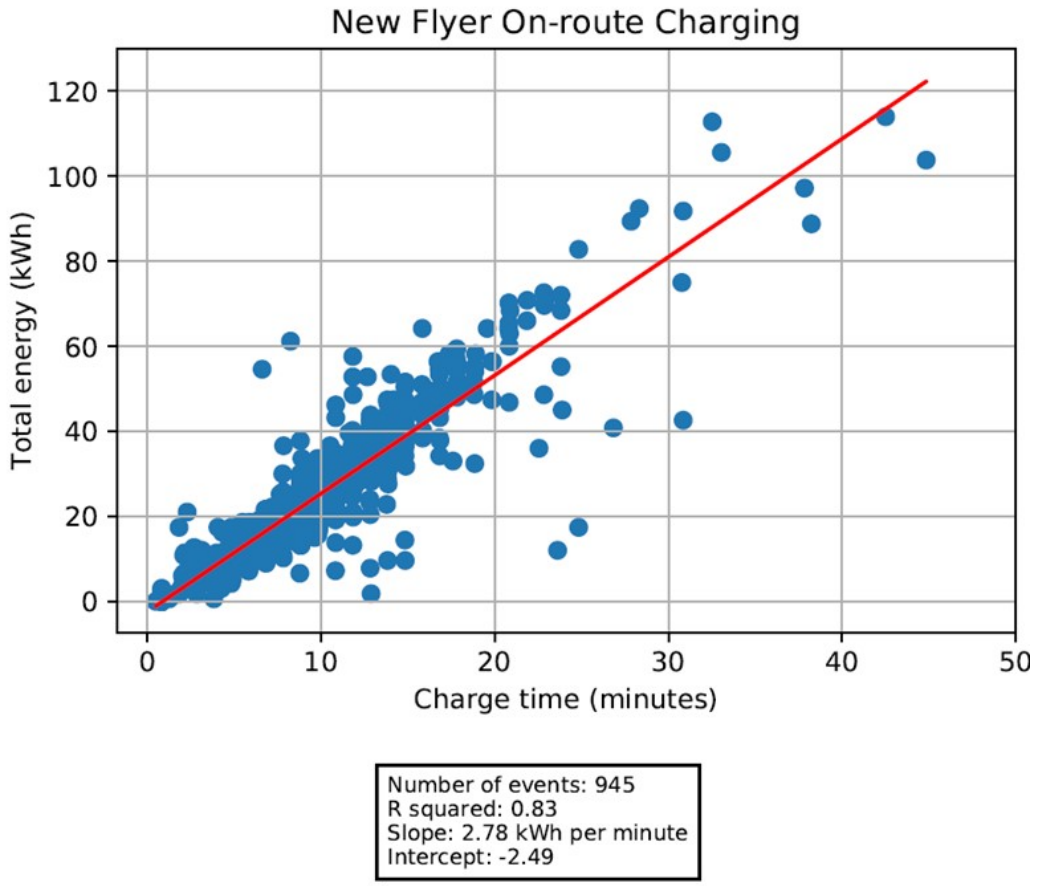
New Flyer On-route Average Charge Duration = 9.2 minutes



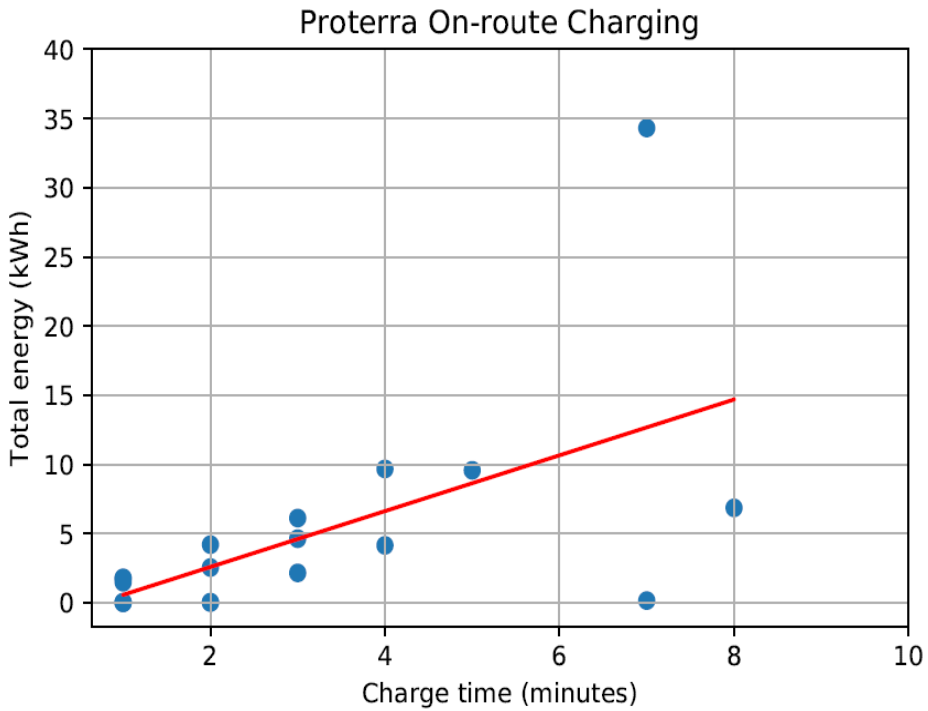
Number of Events: 19
Maximum Active Peak Power: 349.9 kW
Average Active Power: 71.5 kW
Maximum Energy Delivered: 34.3 kWh
Average Energy Delivered: 4.7 kWh
Average Charging Duration: 3.1 minutes

Proterra On-route Average Charge Duration = 3.1 minutes

On-route Charge Duration Data

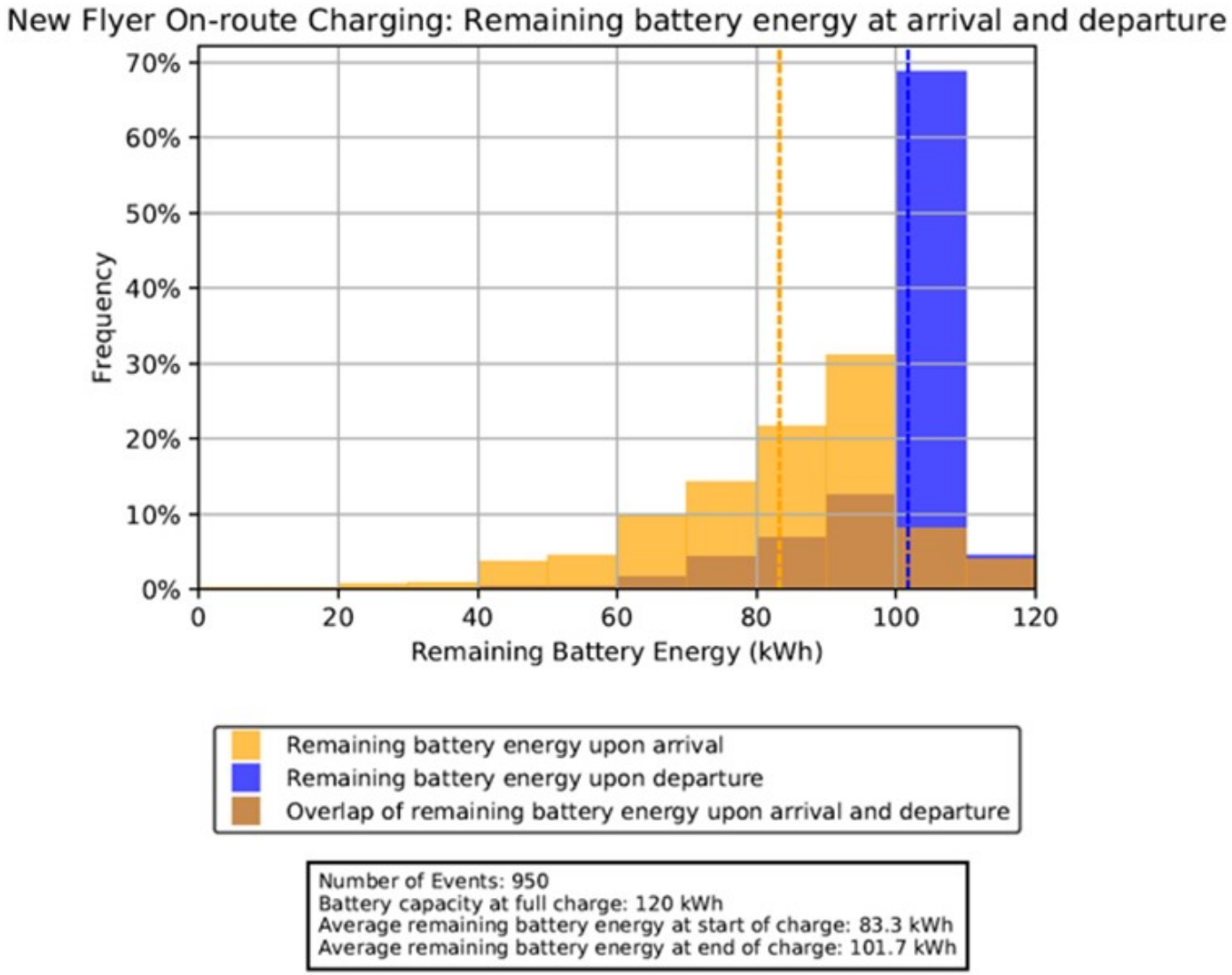


Number of events: 945
R squared: 0.83
Slope: 2.78 kWh per minute
Intercept: -2.49



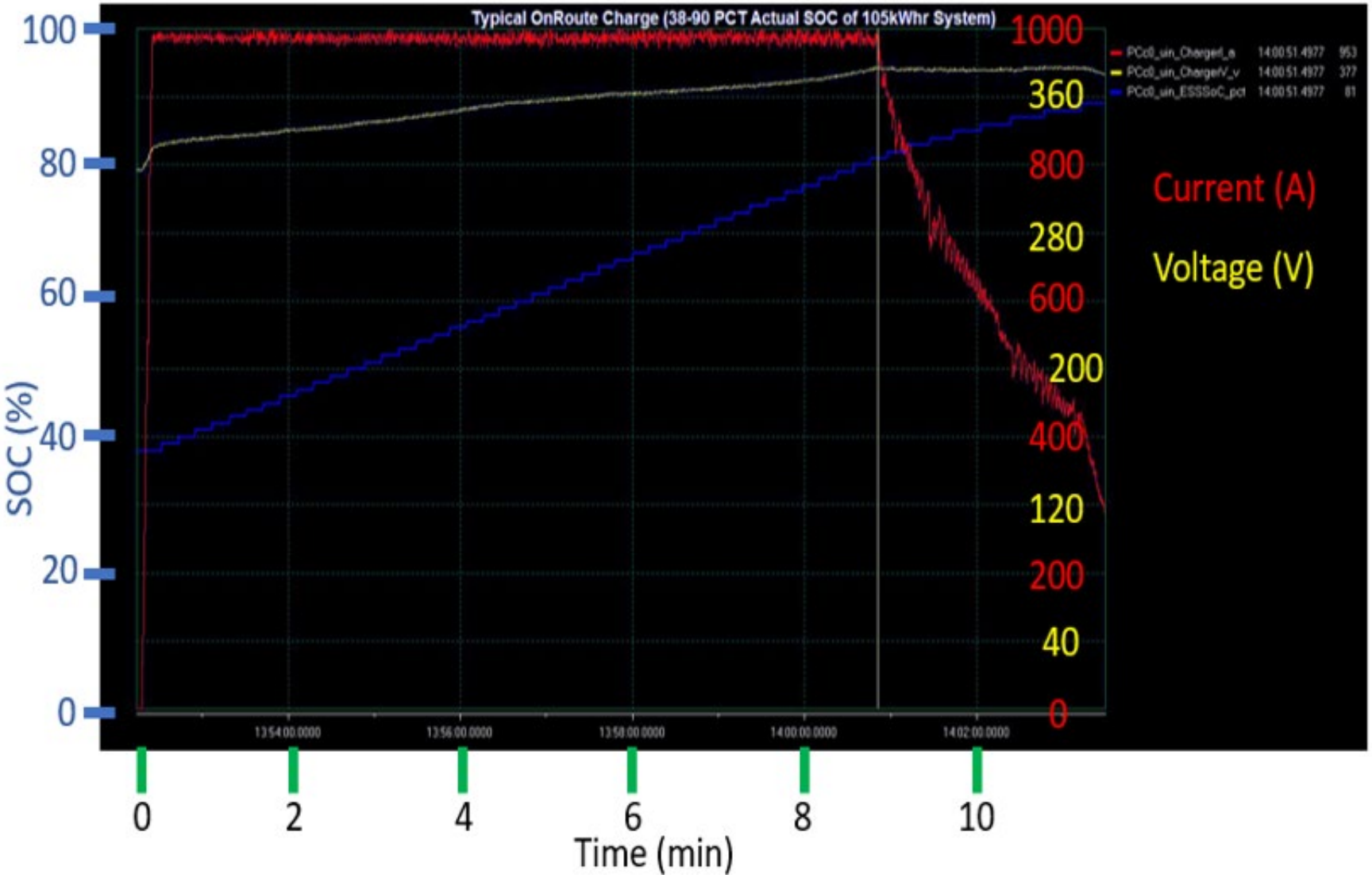
Number of events: 19
R squared: 0.34
Slope: 2.02 kWh per minute
Intercept: -1.44

New Flyer On-route Remaining Energy



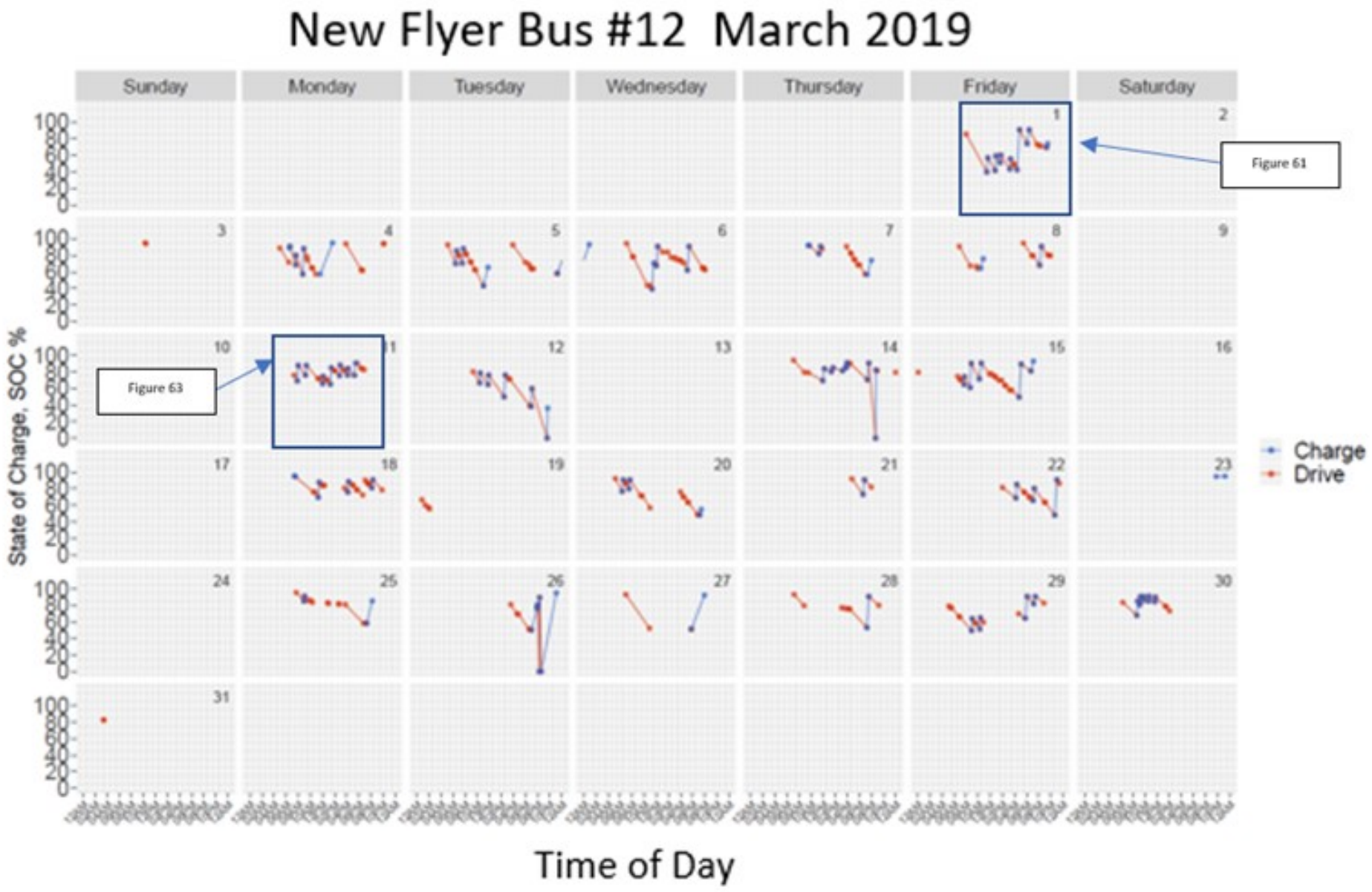
The New Flyer on-route charging on average began charging at 83 kWh and completed charge at an average of 102 kWh.

Proterra Typical On-route Charge Profile



- The battery is charged from 38 to 90% in less than 12 minutes.
- During that time 105 kWh were charged.
- Immediately, the current goes to maximum (1000 A) and remains until the SOC reached about 80% then the current begins to drop.
- The voltage of the battery is in the 340 - 380 V range.
- The inflexion point is 953 A, 377 V (359 kW) and 81% SOC.

New Flyer Monthly Discharge and Charge Patterns

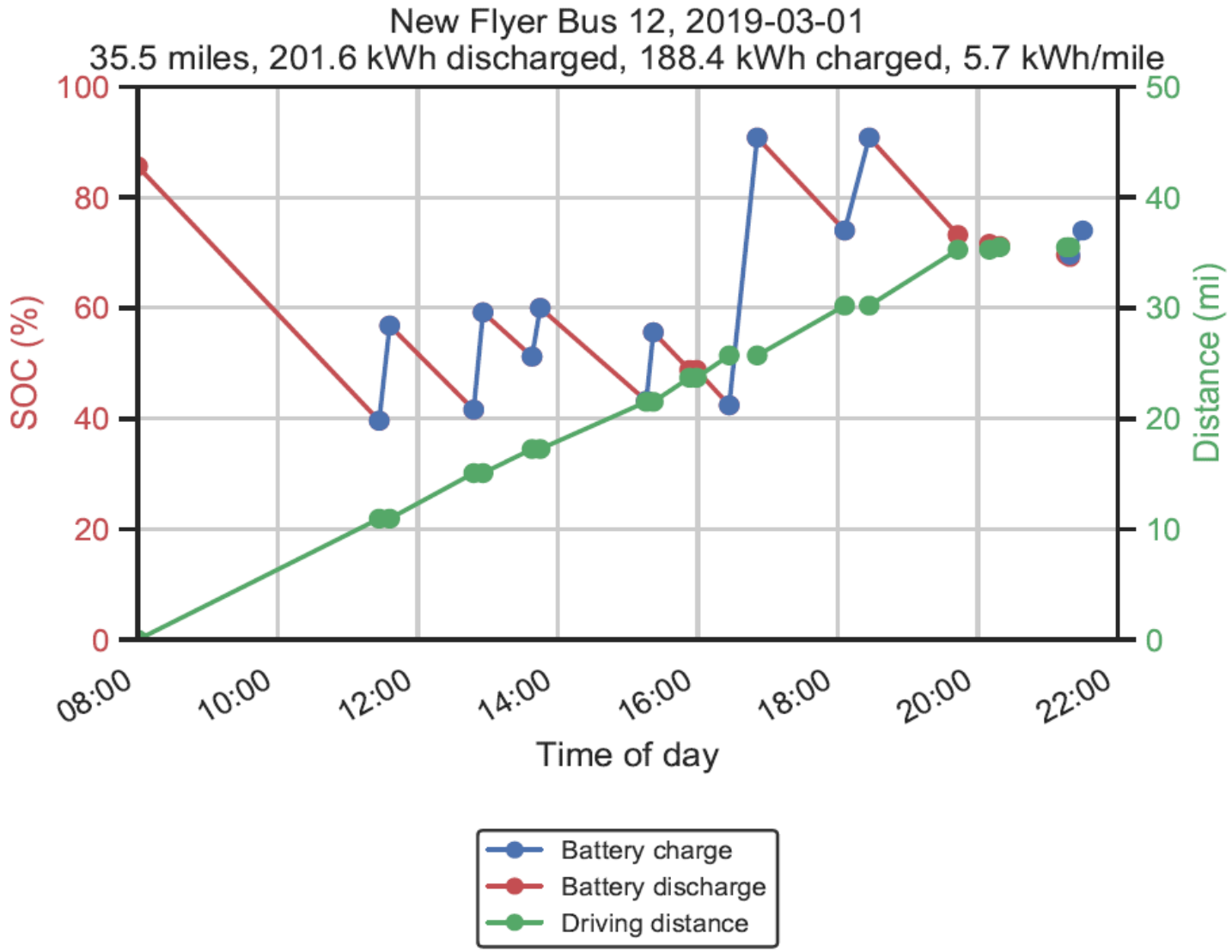


Each day of the March 2019 is shown with the discharge (red-drive) and charge patterns (blue-charge)

Buses were not used on Sundays. Typically, the buses began to drive in the early morning.

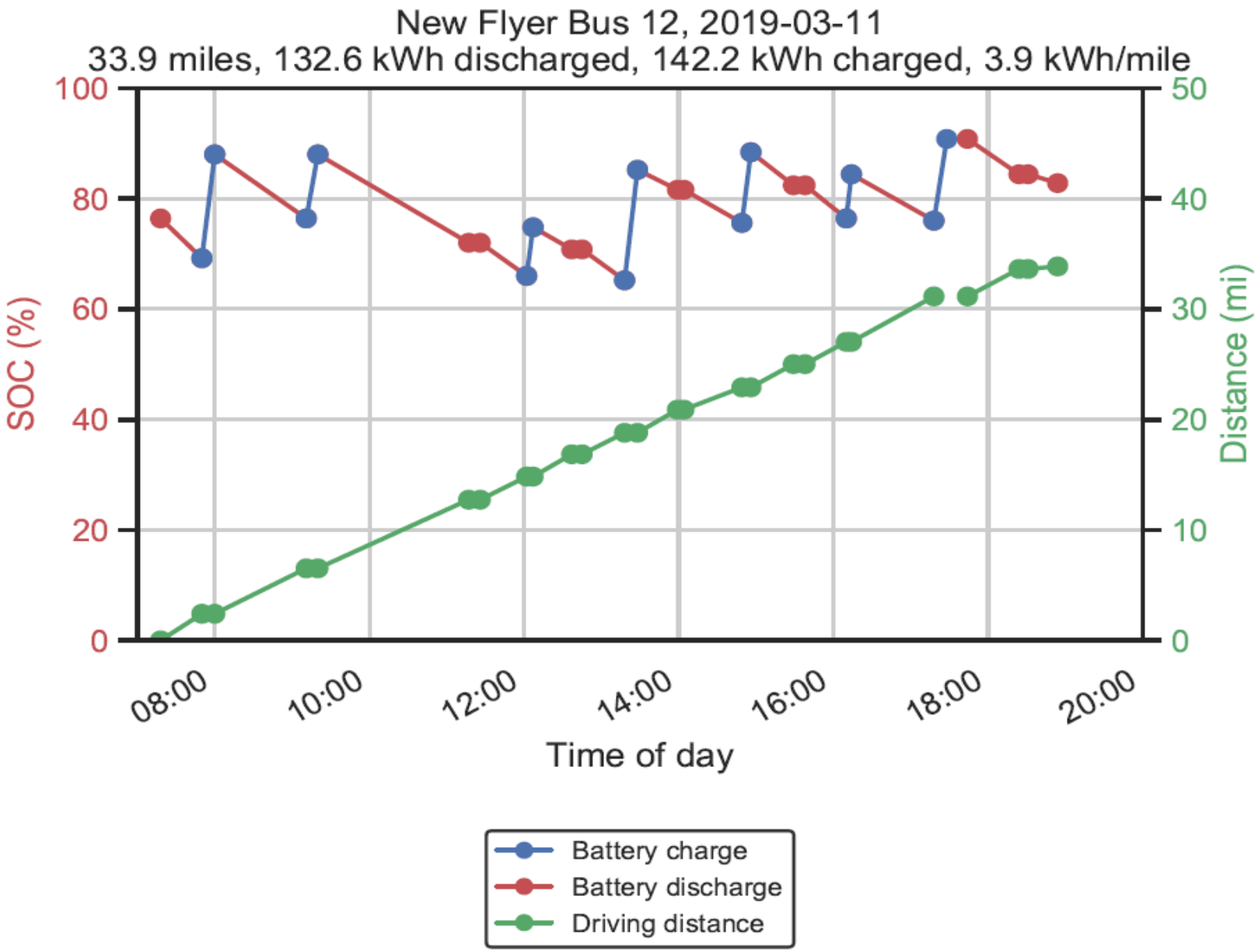
The New Flyer bus was usually on-route charged as shown. Two days referenced are detailed

New Flyer Charge Pattern- March 3



- New Flyer bus being charged 7 times over a 12-hour period.
- Initially, the bus starts out at 8:00 am with an 85% SOC. The bus drives about 21 miles using about 45% SOC until about 11:30 am.
- Then the bus charges for a short time and recaptures 18% SOC. The bus drives again for about 15 miles using 17% SOC.
- The bus begins another charge about 1:00 pm. The bus continues and accumulates 7 charges that day driving a total of 35.5 miles.

New Flyer Charge Pattern- March 11



New Flyer's daily pattern with 7 charges over a 12-hour day traveling 34 miles.

Discharge and Charge Patterns Examples

	Bus #	Date	# of Charges	Event Distance (mi)	Event Discharge (kWh)	Event Charge (kWh)	Net Charge (kWh)	Event Consumption (kWh/mi)	Event Start	Event Duration (h)	Charge Duration (h)	Percent Charge Duration
New Flyer	12	3/1/2019	7	35.5	202	188	(14)	5.7	8:00 AM	12	1.2	10%
New Flyer	12	3/6/2018	1	23.3	104	116	12	4.5	4:30 AM	12	5.5	46%
New Flyer	12	3/11/2019	7	33.9	133	142	9	3.9	7:30 AM	12	1.2	10%
New Flyer	15	2/17/2019	16	71.1	292	265	(27)	4.1	6:00 AM	19	1.3	7%
New Flyer	15	2/28/2019	11	59.8	298	309	11	5.0	7:00 AM	21	3.3	16%
Proterra	17	4/12/2019	1	66.5	229	183	(46)	3.4	4:00 AM	22	7.0	32%
Proterra	17	5/21/2019	3	136.7	427	305	(122)	3.1	5:00 AM	31	8.0	26%
Proterra	17	6/17/2019	5	172.3	530	396	(134)	3.1	3:30 AM	44	16.0	36%
Proterra	18	4/16/2019	1	46.3	157	131	(26)	3.4	4:00 AM	19	7.0	37%
Proterra	18	5/23/2019	1	46.7	162	132	(30)	3.5	4:00 AM	19	7.0	37%
Proterra	19	4/23/2019	1	40.3	127	118	(9)	3.2	7:00 AM	16	4.0	25%
Proterra	19	5/10/2019	2	101.9	304	218	(86)	3.0	8:30 AM	29	11.0	38%

The report contains many more examples of the different patterns.

EPRI Report: 3002017813

https://membercenter.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002017813