33nd Electric Vehicle Symposium (EVS33)
Portland, Oregon, June 14 - 17, 2020

Battery Electric Powertrains for Class 8 Regional Haul Freight Based on NACFE Run-On-Less

Rick Mihelic[1], Andrew Kotz[2]

[1]*NACFE, 938 Royal Oaks Drive, Lewisville, TX 75067, mihelic2@verizon.net*

[2]*NREL, 15013 Denver West Parkway, Golden, CO 80401, andrew.kotz@nrel.gov*

Summary

This report evaluates potential Class 8 regional haul commercial battery electric semi-truck performance requirements based on real world diesel and natural gas vehicle duty cycle data. Data was recorded over a 17-day period accumulating 58,633 miles with 10 trucks in a variety of locations as part of the North American Council for Freight Efficiency's (NACFE) Run on Less Regional (ROLR) demonstration of the effectiveness of current production diesel and natural gas tractor technologies in the hands of well-trained drivers. Data was collected with on-board data loggers in concert with the U.S. National Renewable Energy Laboratory (NREL) and Oakridge National Laboratory (ORNL), and independently through use of GEOTAB and LinkeDrive fleet tracking and management systems.

Keywords: Electric Truck, CBEV, Commercial Battery Electric Vehicle, NACFE, Regional Haul, Run On Less, NREL, ORNL, GEOTAB, LinkeDrive

1 Introduction

NACFE created the ROLR demonstration to benchmark fuel and freight efficiency for regional haul of current production diesel and natural gas tractor technologies driven by well-trained drivers in real world operations [1]. The 2019 demonstration followed NACFE's 2017 Run on Less that focused on long haul where seven tractors over a three week period of commercial operations demonstrated that current production technology tractors in the hands of skilled drivers in real-world operations could exceed 10.1 mpg [2].

North American truck freight duty cycles are typically categorized as long haul, regional haul and urban. Regional haul for Class 7 and 8 tractors is defined by NACFE as an operation where the truck stays within a 300-mile radius of a home base. This may include tractors that return to a home base every day or ones on a route for multiple days but that stay within that 300-mile radius trends [3]. There are many permutations of possible duty cycles in this definition. Urban cycles are seeing early deployment of electric trucks as route distances are short compared to long haul routes where range challenges battery capacity and unpredictable routing complicates locating a sufficient number of high power chargers.

Fleets continually innovate to make their operations more efficient, improve market share and reduce their costs in pursuit of improved profitability. NACFE recently identified a trend where freight movement is migrating from long haul operations to regional haul [3]. There are a number of contributory causes of this trend described in NACFE's report, but fundamentally, freight hauling requires the driver, the tractor, the trailer, the load and the route.

The driver is clearly one of the critical components to improving freight efficiency, often considered to be responsible for as much as 30%-35% improvement [4][5]. The ROLR drivers, shown in Figure 1, were selected by their participating fleets as drivers with a cross section of ages, genders and experience.

Figure 1: ROLR drivers (NACFE)

ROLR included production model year 2019 and 2020 tractors from 10 U.S. fleets representing a range of manufacturers as shown in Figure 2. The vehicles included both day cabs and sleepers. Nine of the tractors had diesel powertrains and one used compressed natural gas (CNG). Drivers were dedicated to their tractors for the duration of the demonstration.

Figure 2: ROLR tractors and trailers (NACFE)

Trailers used in this study, as shown in Figure 2, were primarily dry freight and refrigerated 53’ box style. One fleet also ran twin 28’ pup trailers. Trailers were not dedicated to the tractors, but varied from run to run as is typical in many regional drop-and-hook fleet operations [3][6]. The trailers were variously equipped with a range of efficiency improvement devices including skirts, low rolling resistance tires, and/or aerodynamic tail devices, per their fleet’s current operations.

Freight loads varied from zero, termed dead-heading, to maximum allowed vehicle weights. Estimates of real-time freight load during the routes were made to reflect multi-stop deliveries and pick-ups. These were commercial loads determined by the fleets based on their business needs during the demonstration.

Routes used for this study were chosen by the fleets and are illustrated in Figure 3 spanning a variety of locations in the U.S. The routes were based on fleet commercial operating demands. Some of the routes were predictable and repetitive, while others varied considerably from day to day. NACFE sub-classifies regional routes as A-B-A, A-B-C-D-A, or hub-and-spoke [3].

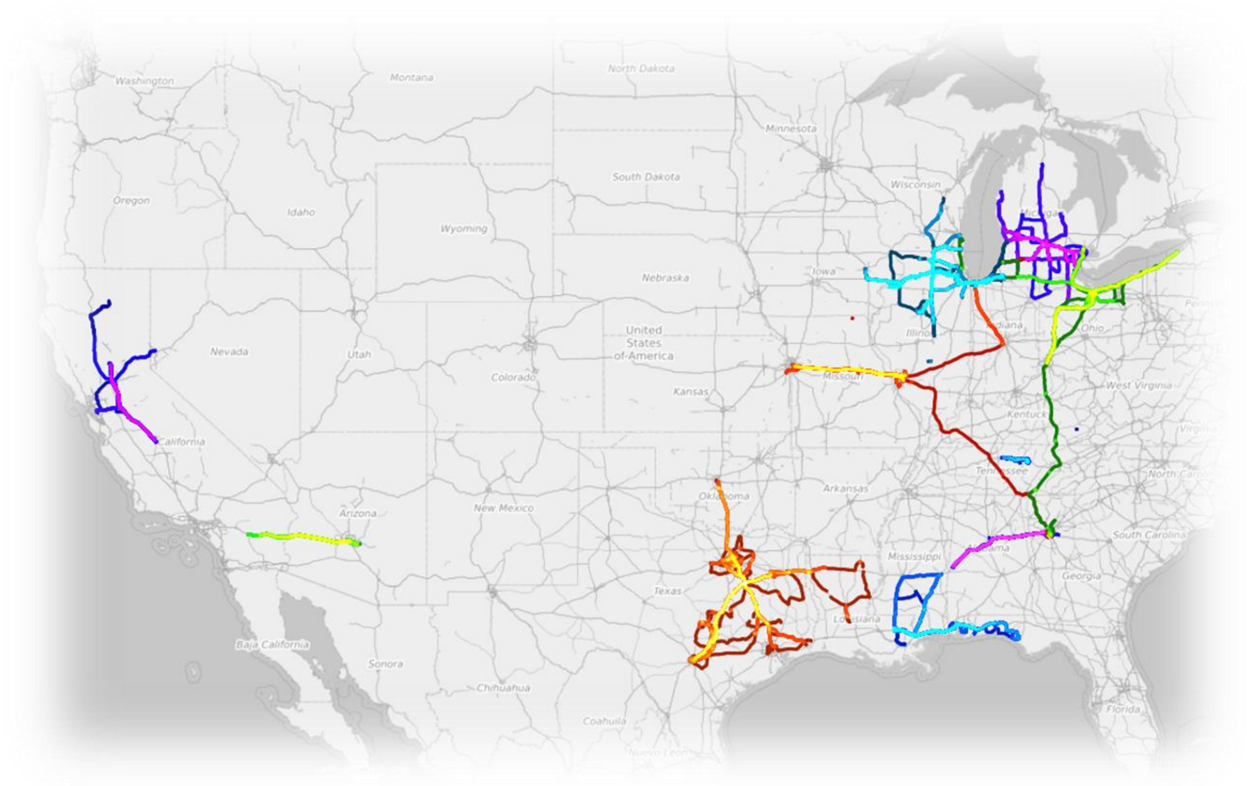

Figure 3: ROLR routes over 17 days (NREL)

Throughout the duration of the test, NACFE posted daily website updates on each of the trucks during the 17 days [1]. The data provided publicly by NACFE is summarized in Table 1. Daily ranges when the trucks were in motion varied from 75 miles to 816 miles, with a group average of 434 miles per day and a standard deviation of 126 miles. Some of the routes were consistent in daily mileage, whereas others varied significantly from day to day. For example, the daily mileage standard deviation for Fleet 10 and fleet 6 were respectively 12 and 35 miles, while the daily mileage standard deviations for fleets 1, 5 and 7 were 158, 196 and 163 miles respectively.

Table 1: ROLR Summary Daily Mileage over 17 days (NACFE)

	Fleet 1	Fleet 2	Fleet 3	Fleet 4	Fleet 5	Fleet 6	Fleet 7	Fleet 8	Fleet 9	Fleet 10
Max	816	491	485	594	776	429	559	528	560	586
Min	373	190	222	275	131	281	75	218	307	541
Ave	509	397	369	453	452	397	398	407	426	545
Std Dev	158	79	93	95	196	35	163	78	62	12

The cross section of ROLR vehicle types, regions, routes, drivers, loads and operations is representative of subsets of the regional haul market. The data is not intended to define the entire regional haul space. The average daily distance is, however, typical of a large percentage of Class 8 freight vehicles. An average of 435 miles per day translates to 108,750 miles per year, assuming five days per week and 50 weeks per year. The 2019 American Transportation Research Institute's (ATRI) annual Operational Costs of Trucking report states 37% of respondents had daily ranges from 100 to 500 miles, and the average miles per year for all respondents was 91,506 miles [7]. Using the same definition of a year of driving, that translates to an ATRI all truck daily average of 366 miles for all trucks in the ATRI survey. The ROLR mileage is more challenging. Averages can be misleading without knowing the details of the mileage and distribution of the data.

A more detailed evaluation of daily miles for some of the fleets highlights that each day may have multiple trips, so where the daily mileage might average 397 miles, as in the Fleet 6 example shown in Figure 4, that mileage is made up of three identical round trips, each trip going 70 miles from base and then 70 miles back. This more granular detail is critical in evaluating routes for potential replacement by commercial battery electric vehicles (CBEVs).

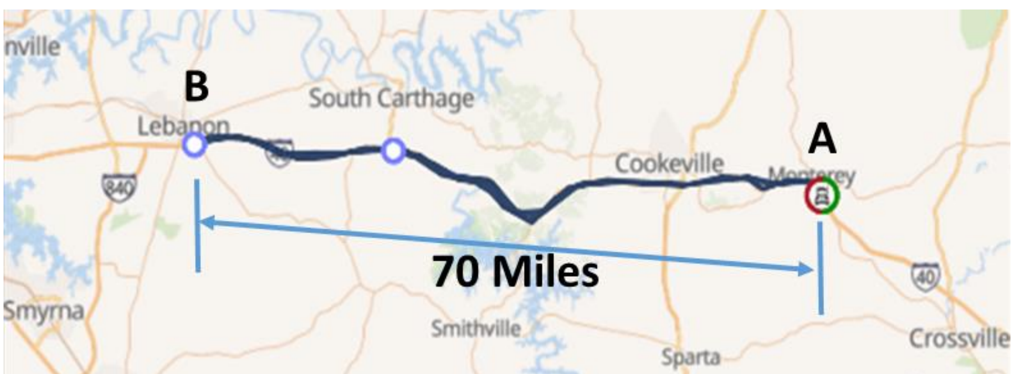

Figure 4: ROLR Fleet 6 A-B-A Trip (NACFE/LinkeDrive)

In evaluating ROLR routes for potential replacement by CBEVs, depending on how you define terms like "trip," "drive cycle," and "duty cycle," you can skew the analysis considerably. A one-way trip may be 70 miles, a round trip is 140 miles, and a day's legal hours-of-service driving for this particular driver is 400 miles. If that truck has a second shift driver, the truck might see 800 miles in that day. A three shift operation might see 1,200 miles per day for that specific truck. A week of one shift driving may be 2,000 miles.

Further, the ROLR analysis highlighted that refrigerated trailers also need to be fueled. If these units are replaced with alternative power systems additional charging times and charging systems may be required. As a result, the discussion on CBEV charging needs to include a plan for refueling refrigerated trailers during the course of operations, or replacing them with alternative power systems that may also require charging times and charging systems.

Therefore, duty cycle descriptions used in evaluating CBEVs need to consider the tractor, driver, route(s), load and even the trailers used to ensure there is enough battery range and availability for charging the vehicle.

1.1 Test and Analysis

Each ROLR tractor was instrumented by NREL with Vector GL2000 data loggers with global positioning systems and wireless data transfers as shown in Figure 5. Data was recorded between 1 Hz to 10 Hz data rates, capturing as many as 700 channels of data from the vehicle controller area network (CAN) data bus. In total, seven million seconds of data were collected over 58,000 vehicle miles. The data was then parsed by NREL at 1 Hz for further analysis by ROLR team members [8].

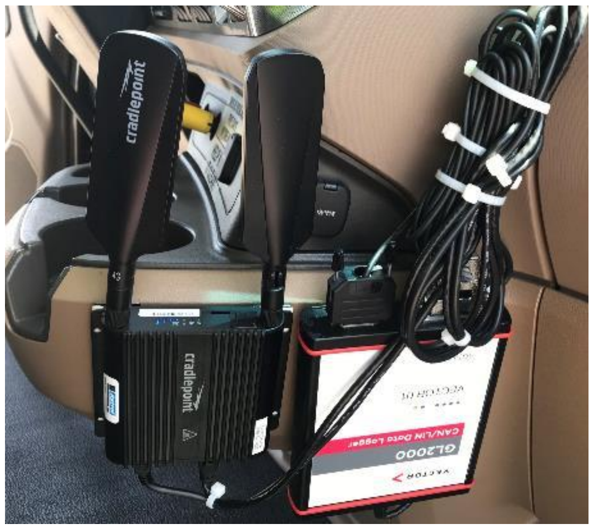

Figure 5: NREL data logger and GPS (NREL)

1.1.1 Vehicle Speeds

The daily distribution of time the ROLR tractors spent at speed is shown in Figure 6 with lightly shaded lines being an individual vehicle day and the dark line being the mean distribution. The results show the ROLR tractors vehicles were moving at highway speeds — 50 mph and above — nearly 80% of the time they were in motion. This is consistent across all the duty cycles. The bimodal peaks at 55 and 65 mph are likely due to posted max road speeds that vary by region.

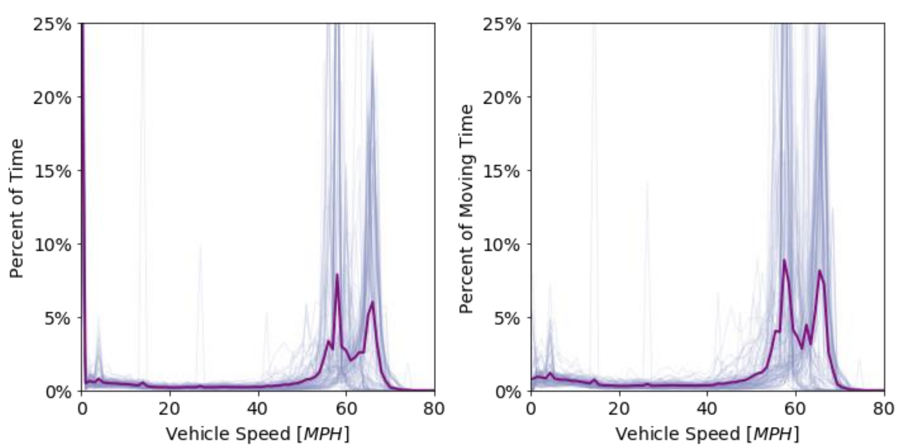

Figure 6: Vehicle speed vs time (NREL)

1.1.2 Vehicle Distance

The distribution of daily distances for the ROLR tractors is shown in Figure 7. Daily ranges when the trucks were in motion varied from 75 miles to 816 miles, with a group average of 434 miles per day and a standard deviation of 126 miles. The ranges above 600 miles highlight that designing a CBEV for average range conditions would preclude the occasional long trips, assuming no charging takes place during the daily operation, requiring some alternative transport to be available.

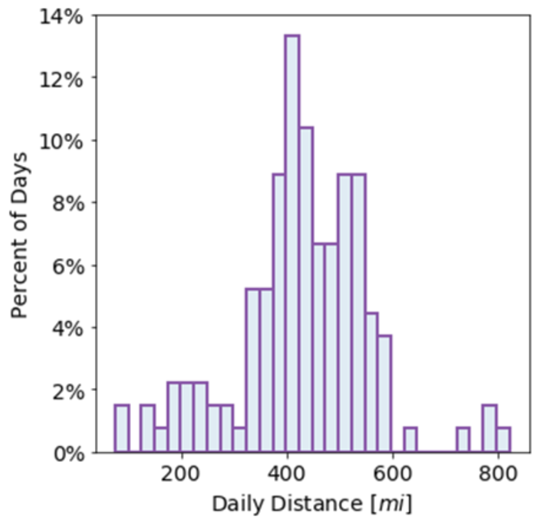

Figure 7: Vehicle daily distance (NREL)

1.1.3 Vehicle Route Type Speed and Distance

Reviewing GPS tracking data, Fleets 2, 4 and 9 were categorized as hub and spoke type duty cycles. Fleets 3, 5 and 8 were classified as A-B-C-D-A type duty cycles. Fleets 1, 6, 7 and 10 were grouped as A-B-A duty cycles. Summarizing speed and distance for those groups shows primarily bi-modal distributions on speeds with generally lower speeds on multi-stop A-B-C-D-A and hub and spoke cycles. Distance distributions for all three groups of duty cycles however remain narrowly distributed around the 434-mile average as seen in Figure 8.

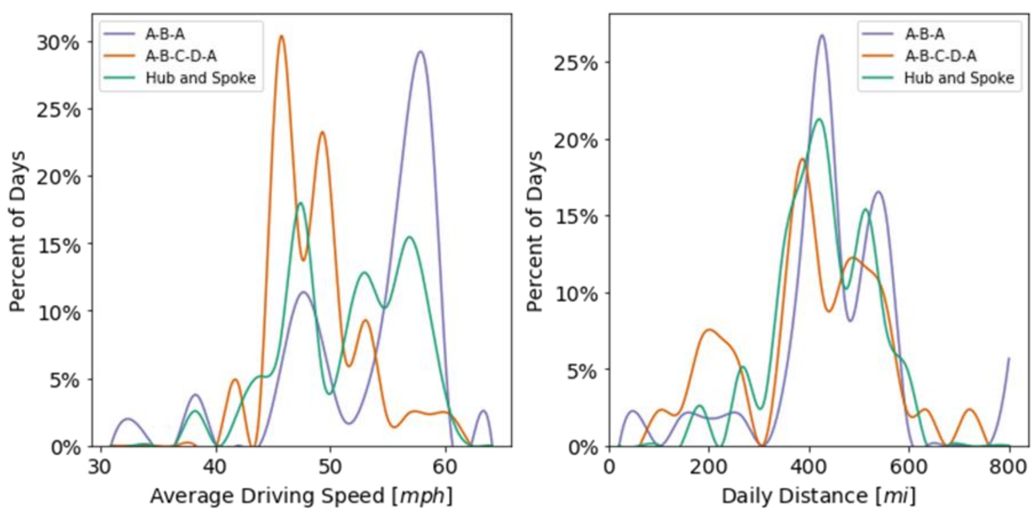

Figure 8: Vehicle daily speed and distance by duty cycle type (NREL)

Regardless of trip segment length, and within the constraints of their operating needs and the constraints of the hours of service for the driver, these ROLR tractors were all averaging similar daily net miles per truck and driver. Any CBEV specified for regional haul operation needs to consider not just the miles per trip segment, but the entire daily freight-miles to ensure distribution networks are not disrupted, including considering the miles possible per driver per truck per day for that operation. A review of public sources, press releases, media, etc. on commercial battery and fuel cell electric tractors highlights standard condition vehicle ranges as shown in Figure 9 [9]. Note that more current 2020 manufacturer specifications show the Tesla Semi range as 300 or 500 miles [10] and Nikola One as 500 to 750 miles [11] under nominal conditions, versus the data shown in the ICCT graph.

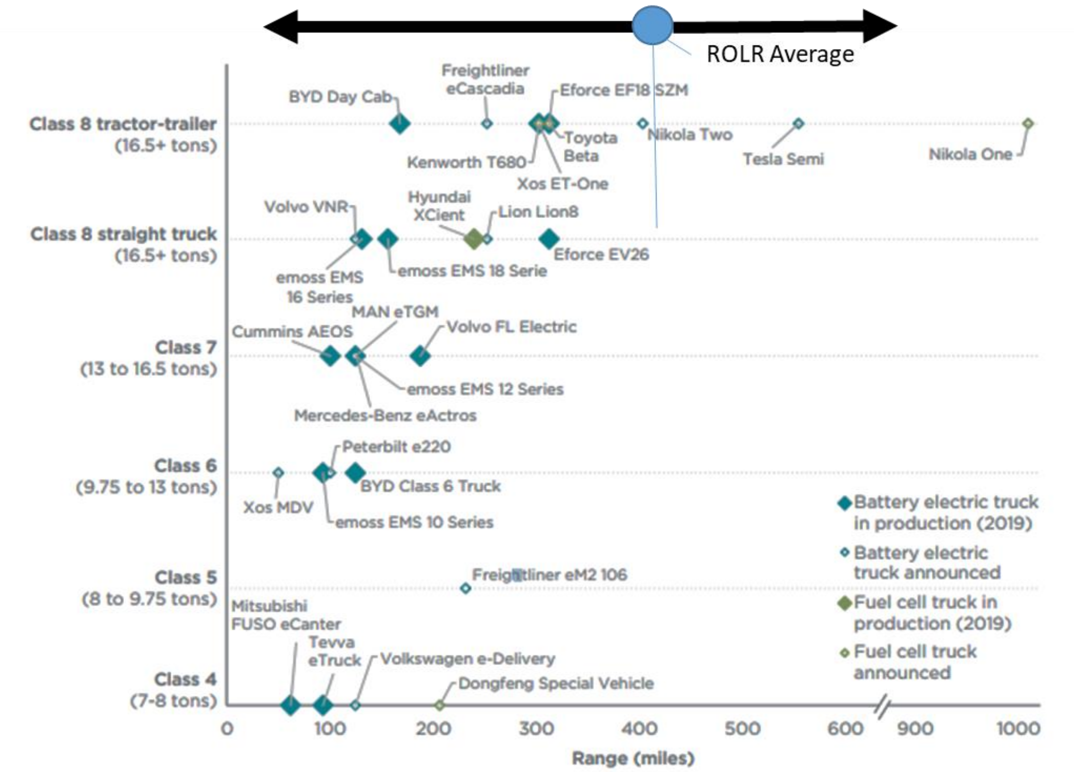

Figure 9: Range and GVWR class of announced or in-production zero-emission trucks (ICCT/NACFE)

The ROLR daily duty cycles exceed published ranges for today’s electric tractors meaning they may require mid-route recharging, or additional battery packs that could reduce freight payload per trip, or operational changes involving additional vehicles and/or drivers. Fuel cell variants, shown in the chart, may also be challenged with the longest ranges encountered in ROLR, and may require mid-trip refuelling stops to cover all of the current ranges.

The upcoming Tesla Semi specifications indicate it could come close to accomplishing the average daily trips. The Nikola One specifications are close to being able to accomplish the maximum daily recorded trip. However, as of writing, these vehicles are not yet commercially available and nation-wide commercial truck charging/fuelling infrastructure has yet to be installed. Further, these range estimates do not consider the ambient conditions, payloads and grades experienced by the ROLR vehicles making the real-world range estimates of these trucks uncertain on the ROLR duty cycles.

1.1.4 Dwell Time

Dwell is that time that the vehicle is at rest and could be charging, either during the day's duty cycle or when the vehicle is parked after a shift. The ROLR fleet dwell times were generally short, with most dwell periods falling in the 30-second to 30-minute range as shown in the distribution graphed in Figure 10. Captured dwell periods were categorized into four distinct bins based on charging time potential including "none" (less than 6 minutes dwell), "fast charge" (6 minutes to 1 hour dwell), "slow charge" (1-10 hours dwell) and "delayed charge" (over 10 hours dwell). Note that in the case of some of the fleets, the vehicles were used in second shift operations, further challenging available dwell times for charging while increasing range demands. With current CBEV technology, any operation looking to utilize battery electric tractors needs to have enough dwell time at predictable locations to minimize infrastructure and ensure adequate energy is added to the battery. Each additional mid-route charger needed to complete a segment of work multiplies capital investment over a single depot charging system. However, short en route charging from one or more high power rapid charging systems may be necessary to complete the duty cycle with current technology. These en route charging stations may only be utilized for a small number of trucks per day, and possibly as few as one truck per day.

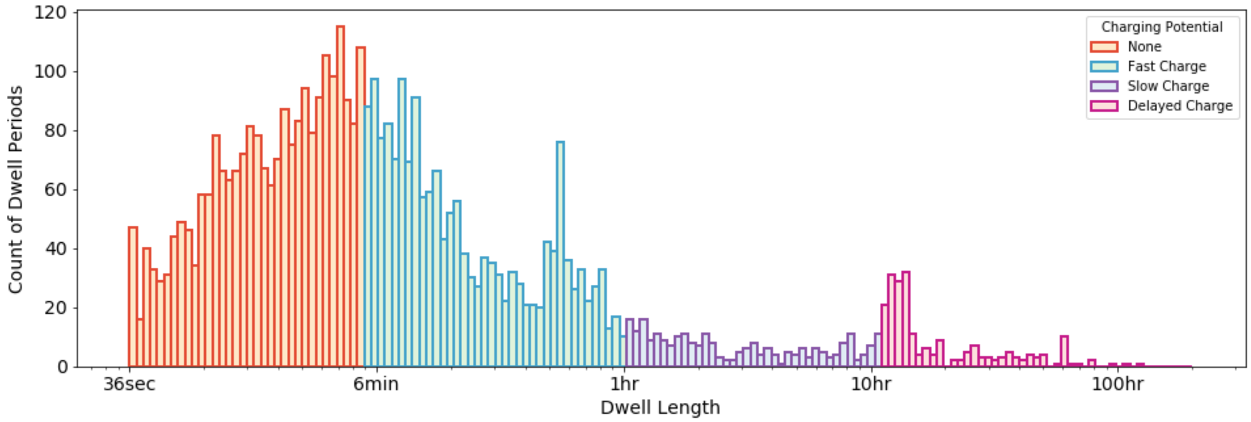

Figure 10: ROLR vehicle dwell times (NREL)

The daily ranges — averaging 434 miles — combined with the minimal times the vehicles were at rest highlights that rapid en route opportunity charging is needed for all 10 fleets with respect to current CBEVs. While overnight charging is possible in most of the ROLR vehicles, that is insufficient to cover the required daily ranges without increasing battery capacity and/or improving battery efficiency than seen in the currently planned or prototype heavy-duty CBEV vehicles shown in Figure 9.

1.1.5 Weight and Range

Assuming a CBEV consumes energy at 2 kWh/mi and operates in nominal ambient conditions and flat terrain, a 600-mile range would require 1,200 kWh of energy. Additional kWh margin would be required to address real world conditions including winds, winter and summer variable conditions, terrain grade changes, freight loads, and considering battery degradation effects over time [12][16]. Battery weights described by CBEV OEMs vary from 14 to 25 lb/kWh. A 1,200 kWh battery pack optimistically could weigh 16,800 lbs.

As of early 2020, there are few production representative Class 8 semi tractors in existence to measure actual weights. One example is the Daimler Freightliner e-Cascadia day cab in testing with NFI in drayage operation, shown in Figure 11. NACFE's assessment of weights compared to an equivalent diesel day cab shows a difference of ~4,000 lbs. in maximum freight capacity for the 250-mile range with the 550 kWh of battery pack. Doubling the range to 500 miles by doubling the battery pack to 1,100 kWh may add 7,700 lbs. of tare weight, reducing the max payload to 37,300 lbs. Further, a 750-mile range might increase tare weight 15,400 lbs., reducing max payload to 29,600 lbs. NACFE estimates ~7,800 lbs. of diesel related equipment and fluids are removed from a tractor before making it electric [12]. These are directional numbers for the purposes of discussing the scale of battery weight trade-offs.

Drayage Day Cab

(Weight in lbs)

	eCascadia	Diesel
GVWR	82,000	80,000
Tractor	23,000	15,400
Fuel	0	1,296
Trailer	14,000	14,000
Freight Max	45,000	49,304

eCascadia Day Cab
Tare 23,000 lb
Range 250 miles
Battery 550 kWh

Typical Freight Below 45,000 lbs.

Figure 11: Example Class 8 CBEV weight comparison (Daimler photo/NACFE analysis)

1.1.6 Long Duration Charging

The dwell time analysis from Section 2.1.4 of the ROLR duty cycles highlighted that sufficient overnight charging opportunities exist, assuming CBEV tractors were equipped with sufficient on-board battery capacity to accomplish the variety of daily ranges. Using dwell time information, a simplified vehicle model was developed that estimates electric vehicle energy consumption from engine produced power and assumes charging occurs when the vehicle is stopped for more than two hours which is end of shift for the ROLR duty cycles. The analysis assumed a 90% conversion efficiency of energy from the batteries to the wheels; no energy use occurred when the vehicle was key-off, i.e. no hotel loads; and conservatively that there was no energy recapture through regenerative braking. Ambient conditions were also not considered. Using this vehicle model various battery sizes up to 2,000 kWh and charge rates up to 1,000 kW were tested to identify what would enable the vehicle to complete its work without any state of charge violations (i.e. battery at 0% — note that NACFE has reported that most EV battery systems have low thresholds of 10% - 20% state of charge [12][16]). The graph in Figure 13 plots a line for each vehicle where those combinations of battery size and charge rate are the minimum requirements to complete the work for eight of the 10 ROLR vehicles. A usable battery capacity of 1,000 kWh was the lowest battery size where one of the tractors was able to complete its work under the two-hour or greater stopped time assumption. A 1,000 kWh pack is larger than current and planned battery sizes from Figure 10, except perhaps for the 500 mile range Tesla. Only six vehicles had sufficient dwell time en route for this charging. However, all six of those vehicles were able to complete their work with a charge rate less than the currently available 350 kW levels.

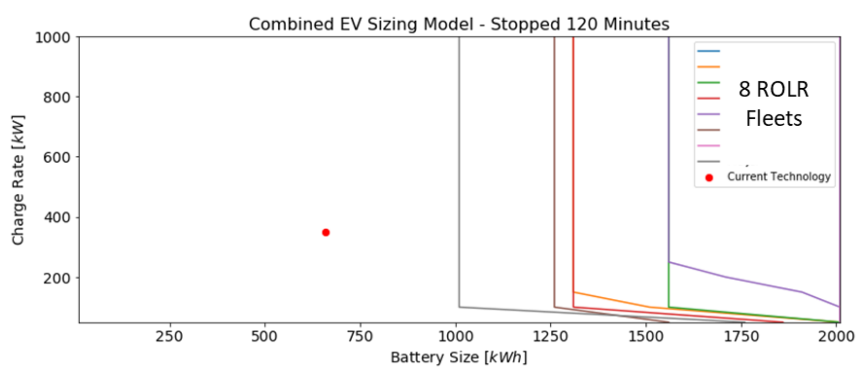

Figure 12: Long Duration Charging (NREL)

1.1.7 En route Opportunity Charging

Analysis of the ROLR duty cycles shown in Figure 10 highlights that mid-cycle opportunity charging exist with stops greater than 50-minutes, suggesting rapid charging capabilities combined with less on-board battery storage may suffice. Using the same analytical model, Figure 13 then assumes charging occurs when a vehicle is stopped en route for greater than 50 minutes, with 90% conversion efficiency and conservatively no regeneration recovery during travel along with the previous assumptions. The analysis again concludes that all vehicles need a battery size of 1,000 kWh or greater, however, overall battery size requirements decreased, and six of seven vehicles showing on this plot could be sustained with en route charging using currently available 350 kW level chargers located at mid-route stops greater than 50 minutes in addition to the home base charger.

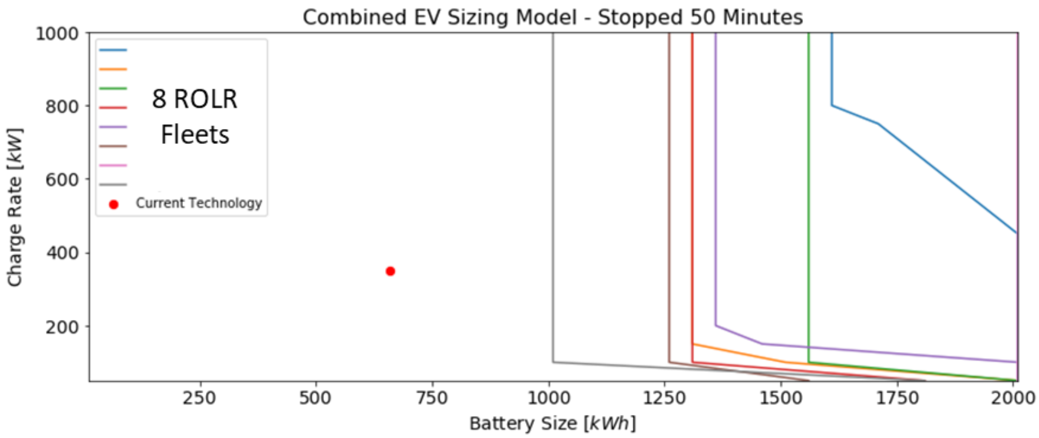

Figure 13: En route Opportunity Charging (NREL)

1.1.8 Future Rapid En Route Opportunity Charging

Dwell time analysis of the ROLR duty cycles shown in Figure 10 highlights that mid-cycle charging opportunities are brief, requiring rapid charging capabilities if less on-board battery storage is used. The CharIn industry group is projecting need for 1 MW or greater chargers to provide rapid charge times [13][14][15]. The analysis summarized in Figure 14 assumes en route charging occurs when vehicles are stopped for longer than 20 minutes. Under this assumption, all eight vehicles could complete their work with battery sizes less than 1,400 kWh with charge rates less than 500 kW and one vehicle could be electrified under current technology.

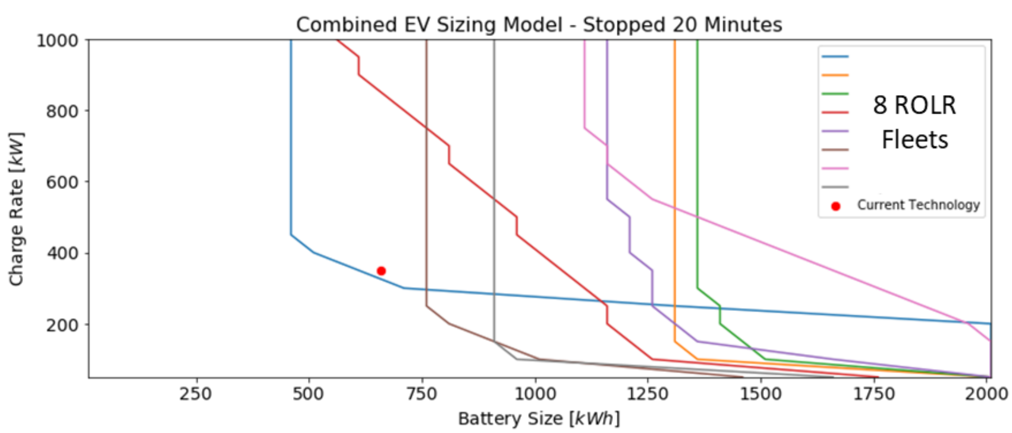

Figure 14: Future Rapid en route opportunity charging (NREL)

Infrastructure demands for putting future high power charging at multiple locations en route imply significant greater capital investment compared to overnight charging with currently available 350 kW charging combined with large capacity batteries on board the tractor. There is a trade-off analysis needed between spending on battery capacity in a fleet's quantity of CBEV tractors versus spending on charging capability at all the short stops on routes. Likely that analysis would favor increasing battery capacity in the tractors for overnight charging since the daily utilization rate of the expensive en route charging facilities for the fleet would be low.

2 Conclusions

Regional haul encompasses a wide range of potential duty cycles. The ROLR demonstration focused on 10 specific fleets that saw on average 434 miles. These 10 do not define the entire regional segment, but are representative of a significant number of operating vehicles in the segment. There are other fleet operations with shorter daily mileage in regional haul. The ROLR fleet data highlights 10 example fleet operations where it is challenging for near-term planned CBEV tractors. Battery packs are the equivalent of diesel fuel tank size, and just as tractors needing longer range may have larger fuel tanks, CBEVs for the ROLR fleets would need to have significantly larger capacity than the current examples shown in Figure 10. En route charging helps, but future higher power charging is required for the ROLR examples to allow smaller battery pack capacity. The trade-off between having multiple high-power chargers en route versus larger battery pack capacity is economically biased toward using higher capacity battery packs due to the multitude of short stops encountered by ROLR fleets and limited dwell times on duty cycles. Operational changes may need to be considered when replacing diesel tractors with CBEVs on these ROLR example duty cycles.

Acknowledgments

NACFE is indebted to the support from the U.S. Department of Energy NREL and ORNL labs in providing instrumentation, data collection and analysis support for the ROLR demonstration.

Sponsors for the NACFE ROLR event included Rocky Mountain Institute (RMI), Shell, Peterbilt, Strick, Dana, Great Dane, the National Renewable Energy Laboratory (NREL), the Oak Ridge National Laboratory (ORNL), GEOTAB, LinkeDrive, SmartWay, Michelin, Meritor, PepsiCo, Peloton, Cummins and Noodle.ai.

NACFE is indebted to the professionalism of the 10 ROLR volunteer fleet drivers and fleets shown in Figure 1, who were critical to the successful collection of information.

References

[1] NACFE Run On Less Regional website, https://runonless.com/regional, accessed on 2020-14-02

[2] Y. Park, et. al., *Run On Less*, NACFE, February 28, 2018, https://nacfe.org/run-on-less-report/ accessed on 2020-14-02

[3] R. Mihelic, M. Roeth, *More Regional Haul: An Opportunity for Trucking?* NACFE, April 8, 2019, https://nacfe.org/regional-haul/ accessed on 2020-14-02

[4] American Trucking Association (ATA) Technology & Maintenance Council (TMC), *Driver Effects on Fuel Economy*, ATA TMC RP1114A 2015

[5] Mihelic, R., *Fuel and Freight Efficiency - Past, Present and Future Perspectives*, SAE Int. J. Commer. Veh. 9(2):120-216, 2016, https://doi.org/10.4271/2016-01-8020 accessed on 2020-14-02.

[6] Mihelic, R., Roeth, M., Schaller, D., *The Feasibility of Intentional Pairing Heavy-Duty Tractors and Trailers*, NACFE, July 30, 2019, https://nacfe.org/report-library/intentional-pairing/ accessed on 2020-14-02

[7] Murray, D., Glidewell, S., *An Analysis of the Operational Costs of Trucking: 2019 Update*, American Transportation Research Institute (ATRI), November 2019, https://truckingresearch.org/2019/11/04/an-analysis-of-the-operational-costs-of-trucking-2019-update/ accessed on 2020-14-02

[8] Kotz, A., Walkowicz, K., Kelly, K., Miller, E., Payne, G., NACFE Run On Less Regional, U.S. D.O.E. NREL, ROLR proprietary analysis results presented at NACFE Workshop, Gulf Shores, AL, 2020-21-02

[9] Hall, D., Lutsey, N., *Estimating the Infrastructure Needs and Costs for the Launch of Zero-Emission Trucks*, ICCT, August 2019, https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf accessed on 2020-14-02

[10] Tesla Semi website https://www.tesla.com/semi accessed on 2020-14-02

[11] Nikola One website https://nikolamotor.com/one accessed on 2020-14-02

[12] R. Mihelic, M. Roeth, *Electric Trucks Where They Make Sense*, NACFE, May 1, 2018, https://nacfe.org/future-technology/electric-trucks/ accessed on 2020-14-02

[13] Kane, M., *CharIN Develops Super Powerful Charger With Over 2 MW Of Power,* InsideEVs, September 26, 2019, https://insideevs.com/news/372749/charin-hpccv-over-2-mw-power/ accessed 2012-14-02

[14] *CharIN High Power Commercial Vehicle Charging Task Force Aggregated Requirements, CharIn*, February 18, 2019, https://www.charinev.org/fileadmin/HPCCV/High_Power_Commercial_Vehicle_Charging_Requirements_v2.0.pdf accessed 2012-14-02

[15] J. Lund, et al, *Amping Up: Charging Infrastructure for Electric Trucks*, NACFE, March 1, 2019, https://nacfe.org/report-library/guidance-reports/ accessed on 2020-14-02

[16] R. Mihelic, M. Roeth, B. Ballschmidt, J. Lund, *Medium Duty Electric Trucks Cost of Ownership*, NACFE, October 7, 2018, https://nacfe.org/report-library/guidance-reports/ accessed on 2020-27-02

Authors

Rick Mihelic has been NACFE's Director Future Technology Studies for five years, authoring Guidance Reports on electric medium and heavy-duty trucks, Confidence Reports on Determining Efficiency, Tractor Aerodynamics, Trailer Aerodynamics, and Two Truck Platooning. President of Mihelic Vehicle Consulting LLC, Mihelic has 38 years' experience in the trucking industry including 20 years in commercial vehicle development for Peterbilt developing aerodynamic vehicles and ground breaking systems including the Peterbilt/Cummins DOE SuperTruck, compliance with the EPA Green House Gas Standards. He is active in SAE Commercial Vehicles, ATA TMC Future Truck task forces and committees. Mihelic was awarded the prestigious SAE L. Ray Buckendale Award in 2016 including publishing Fuel and Freight Efficiency – Past, Present and Future Perspectives. He spent 12 years in advanced technology R&D programs for Lockheed with DOD, NASA and DOE. Mihelic is board member of the ISEEK Corporation.

Andrew Kotz received his Ph.D. in Mechanical Engineering from the University of Minnesota. He is now a Commercial Vehicle Research Engineer at the National Renewable Energy laboratory. His research focuses on real-world testing and big data analytics of heavy-duty vehicles to understand both energy consumption and emissions.