Statistical Characterization of Medium-Duty Electric Vehicle Drive Cycles

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Statistical Characterization of Medium-Duty Electric Vehicle Drive Cycles

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Abstract

In an effort to help commercialize technologies for electric vehicles (EVs) through deployment and demonstration projects, the U.S. Department of Energy's (DOE's) American Recovery and Reinvestment Act (ARRA) provided funding to participating U.S. companies to cover part of the cost of purchasing new EVs. Within the medium- and heavy-duty commercial vehicle segment, both the Smith Electric Newton and Navistar eStar vehicles qualified for such funding opportunities. In an effort to evaluate the performance characteristics of the new technologies deployed in these vehicles operating under real world conditions, data from Smith Electric and Navistar medium-duty EVs were collected, compiled, and analyzed by the National Renewable Energy Laboratory's (NREL) Fleet Test and Evaluation team over a period of 3 years. More than 430 Smith Newton EVs have provided data representing more than 150,000 days of operation. Similarly, data have been collected from more than 100 Navistar eStar EVs, resulting in a comparative total of more than 16,000 operating days. Combined, NREL has analyzed more than 6 million kilometers of driving and 4 million hours of charging data collected from commercially operating medium-duty electric vehicles in various configurations.

In this paper, extensive duty-cycle statistical analyses are performed to examine and characterize common vehicle dynamics trends and relationships based on in-use field data. The results of these analyses statistically define the vehicle dynamic and kinematic requirements for each vehicle, aiding in the selection of representative chassis dynamometer test cycles and the development of custom drive cycles that emulate daily operation. In this paper, the methodology and accompanying results of the duty-cycle statistical analysis are presented and discussed. Results are presented in both graphical and tabular formats illustrating a number of key relationships between parameters observed within the data set that relate to medium duty EVs.

Keywords: Medium Duty (MD), Electric Vehicle (EV), Drive Cycle

1 Introduction

The Fleet Test and Evaluation team at the Department of Energy's (DOE's) National Renewable Energy Lab (NREL) in Golden, Colorado, is responsible for conducting real-world performance evaluations of advanced medium-duty and heavy-duty vehicle technologies. These evaluations help manufacturers improve their design, test procedures and ultimately their commercial success while at the same time informing fleet managers to allow them to better select appropriate fuel efficient, low-emission vehicle technologies that fit their operational goals. One such performance evaluation project involves the evaluation of medium-duty electric vehicles (EVs) deployed in commercial operation across the United States. With support from the DOE's American Recovery and Reinvestment Act (ARRA), U.S. companies received incentives to cover a portion of the cost of purchasing new medium-duty EVs. Over a period of 3 years, NREL has collected, compiled, and analyzed data from more than 530 medium-duty ARRA EVs deployed in commercial operation across the contiguous United States. Home terminal locations for these vehicles can be seen in Figure 1.

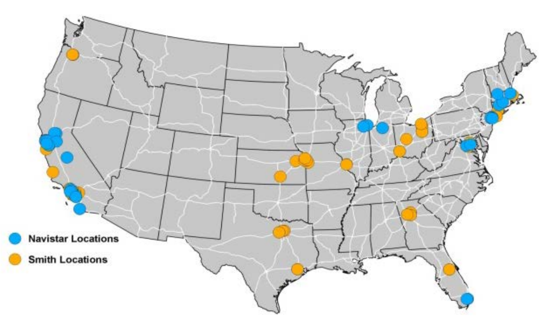

Figure 1: Home locations of Smith Electric Newton and Navistar eStar vehicles

This paper focuses on the analysis of a subset of the projects data. Including more than 109,000 Smith vehicle operating days and 16,000 Navistar vehicle operating days, this analysis examines more than 4.4 million km of EV operational data captured over the course of the project, and the resulting performance and drive cycle characterization.

1.1 Vehicle Overviews

The two types of medium-duty delivery vehicles examined as part of this study are similar in configuration and general operation but do have some unique differences that prevent performing a singular combined analysis; instead, they were investigated separately and then compared and contrasted for a more detailed perspective. The slightly smaller Navistar eStar vehicles are all configured the same, as delivery vans operating in the U.S. class-three vehicle weight rating as seen in Figure 2. Associated vehicle specifications can be found in Table 1.

Figure 2: Navistar eStar, battery electric delivery vehicle [1]

Table 1: Navistar eStar Vehicle Specifications [2]

Navistar eStar Vehicle Specifications	
Curb Weight	3,185 kg
Overall Length	6.47 m
Overall Width	2.0 m
Overall Height	2.69 m
Wheelbase	3.60 m
Peak Motor Power	70 kW
Motor Location	Rear, Fwd of rear axle
Advertised Range	Up to 160 km
Seating	2
Payload	2313.3 kg
Electric Top Speed	80 kph
Battery Capacity	80 kWh
Battery Voltage	300+ V
Charging Standards	SAE J1772
Transmission	Single Speed Reduction
Drive	Rear Wheel Drive
Drag Coefficient	~0.5

The Smith Electric Newton vehicles, on the other hand, are configured to operate in a wider range of applications depending on body type and configuration; vehicle specifications can be seen in Table 2. The Smith vehicles operate in the range of class-four through class-six vehicle weight ratings with the majority of vehicles analysed in this study configured as class-six delivery vehicles as shown in Figure 3, Smith does offer a number of other chassis configurations such as the flat bed shown in Figure 4, other configurations include box truck, step van, refrigerated, aerial lift, utility, flat bed, shuttle bus, and military transport. It is also important to note that Smith has developed multiple generations of Newton's, and the data and analysis included in this paper are for the first generation Smith Newton vehicles only.

Table 2: Smith Newton Vehicle Specifications [5, 6]

Smith Newton Vehicle Specifications	
Curb Weight	4,400 – 4,627 kg
Overall Length	6.8 – 9.3 m
Overall Width	2.21 m
Overall Height	2.39 – 2.51 m
Wheelbase	3.89 – 5.59 m
Peak Motor Power	134 kW
Motor Location	Front, Behind Cab
Advertised Range	Up to 160 km
Seating	3
Payload	5,590 – 7,348 kg
Electric Top Speed	80 kph
Battery Capacity	80 - 120 kWh
Battery Voltage	~ 350 V
Charging Standards	SAE J1772
Transmission	Single Speed Reduction
Drive	Rear Wheel Drive
Drag Coefficient	~0.5

Figure 3: Smith Newton battery electric vehicle [3]

Figure 4: Smith Newton battery electric vehicle with a flatbed configuration [4]

2 Approach

2.1 Data Collection

The data collection performed as part of this research effort focused on capturing in-use operating and charging data for a large number of Navistar eStar and Smith Newton EVs. Data were collected from vehicles deployed across the United States through the use of on-board logging devices connected to the vehicles' controller area network, paired with global positioning system information. These data were then transmitted wirelessly over the cellular network to NREL's secure data server for processing.

2.2 Data Analysis

Having received in-use data, the data are processed using a series of semi-automated routines. These routines include code and calculations specifically tailored for drive cycle analysis, while also incorporating more universal calculations from NREL's Fleet DNA Project. Fleet DNA is NREL's clearinghouse for commercial vehicle operating data and is available for public consumption online as seen in Figure 5 below.

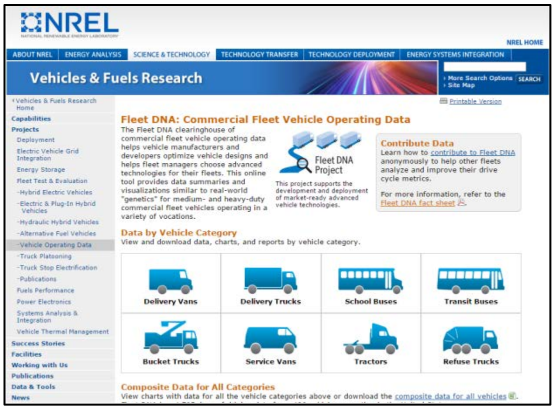

Figure 5: Fleet DNA database public Web portal (www.nrel.gov/transportation/fleettest_fleet_dna.html)

Employing this analysis method allows the performance of these vehicles and vehicle components to be compared not just within the scope of this single project, but across the large number of current and past projects contained within the Fleet DNA database housed on NREL's Commercial Fleet Data Center servers. For additional details about Fleet DNA and the data collection and analysis performed in this paper, please see additional references [7-11].

2.3 Univariate Drive Cycle Statistics

To better understand the in-use driving behaviour of the medium-duty EV's examined in this study, univariate analysis was performed on the aggregated data for each vehicle grouped by manufacturer.

Looking at the typical daily driving duration for each vehicle type as shown in Figure 6, it can be seen that the Navistar daily driving duration is slightly greater than that of the Smith vehicles. The average Navistar driving duration is 4.0 hours whereas the average Smith Electric duration was found to be 1.6 hours. The standard deviations were found to be 2.2 hours and 1.4 hours, respectively. This lower than expected daily driving duration suggests there may be opportunities for optimizing the utilization of the EVs to better take advantage of the fuel saving benefits of these vehicles. Specifically looking at the Smith Newton vehicles' operation, one can postulate that more of the drivers' time per day is spent parked, loading, and unloading the vehicle among other non-driving tasks.

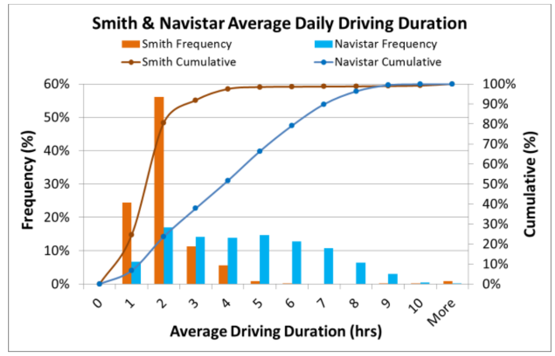

Figure 6: Smith and Navistar Driving Duration

While the daily driving duration is more than double for the Navistar vehicles, the average daily distance travelled helps illustrate their usage pattern more clearly, as seen in Figure 7. The average Navistar distance is found to be 34.9 km, with a standard deviation of 26.0 km, while the average Smith daily driving distance was 41.3 km with a standard deviation of 17.6 km. More than 94% of the Smith Newton trips are less than 67.7 km and, similarly, 91% of the Navistar eStar trips are less than 73.9 km in length. With the majority of trips not exceeding 50 percent of the manufacturers advertised driving range, there may be an opportunity for fleet managers to explore delaying or staggering vehicle charging to minimize peak demand charges at their facilities, as well as either downsizing the battery to better reflect real-world usage and reduce cost. While not directly comparable between the two vehicle platforms, it is interesting to note the overall vehicle efficiency on a kWh/km basis. The larger Smith Electric vehicles averaged a daily driving energy consumption rate of 1.15 kWh/km while the Navistar eStar vehicles averaged 0.52 kWh/km. These two metrics of driving duration and driving distance along with energy efficiency provide a usage basis which may provide guidance to vehicle manufactures as they consider battery pack sizing and range/utilization optimization strategies in the future. For more detailed aggregate energy consumption data, please see references [12, 13].

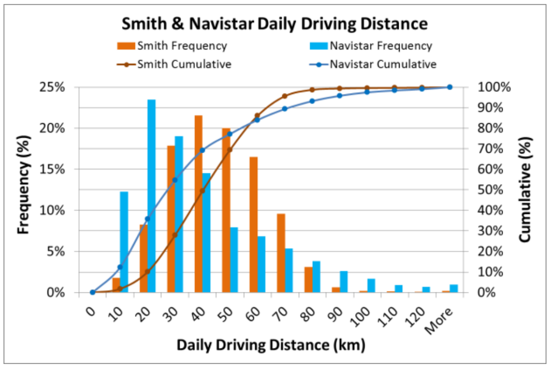

Figure 7: Smith and Navistar Driving Distance

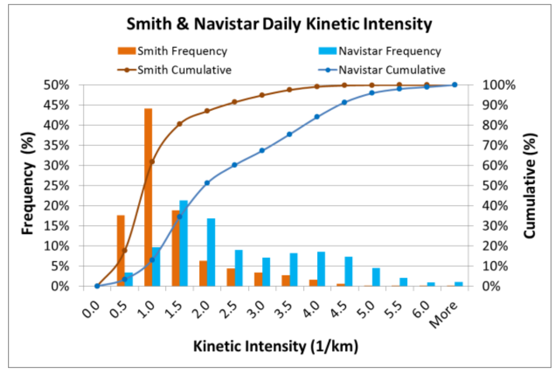

Figure 8: Smith and Navistar kinetic intensity

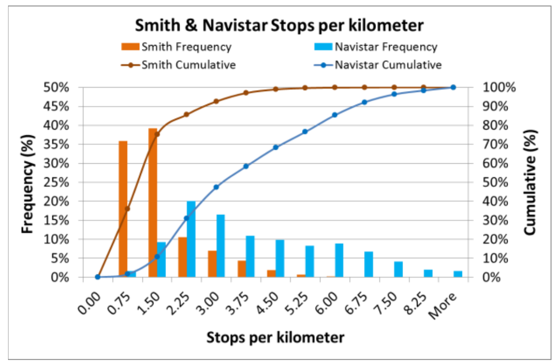

Figure 9: Smith and Navistar stops per kilometer

In terms of on-road driving behaviour, it can be seen in Figure 8 that the smaller and lighter Navistar vehicles have a higher average kinetic intensity [14] when compared to the Navistar vehicles. Kinetic intensity is a measure of the hybrid advantage as a ratio of characteristic acceleration to aerodynamic speed; in the case of EVs, higher values of kinetic intensity generally indicate more stop-and-go driving and therefore more opportunities for regenerative braking. This higher level of kinetic intensity is further reinforced with the examination of the average number of stops per kilometer; the Navistar vehicles average more than twice as many stops per kilometer than the Smith vehicles, as seen in Figure 9. For comparison, the average kinetic intensity of the EPA's HD-Urban Dynamometer Driving Schedule (HD-UDDS) which represents a typical city driving pattern for heavy duty vehicles is just 0.377 per km. The NYC COMP cycle, discussed later in this paper, with an average of 4.96 stops per km has an average kinetic intensity of 2.67 per km whereas the kinetic intensity of a highway driving cycle, such as the CARB HHDDT cycle, is just 0.10 per km.

Reviewing the findings from the combination of Figure 6 – Figure 9, one can see that in a general sense, the Smith vehicles stop less often, for longer durations, with greater distances between stops than the Navistar vehicles. From an operational standpoint, the Navistar eStars were used in a driving pattern with a greater potential for regenerative braking than the Smith Newtons.

It can be seen that the average acceleration and deceleration rates on a per event basis are consistently larger in magnitude for the Navistar vehicles than for the Smith, indicating a greater driving aggressiveness level and further supporting the observation of a higher kinetic intensity. The distributions for the two vehicle types for both acceleration and deceleration rates are shown in Figure 10 and Figure 11. Additional data and statistics further highlighting these trends and observations can be found in [12, 13]. It is also postulated that in addition to the types of drive cycles that the vehicles are deployed on influencing acceleration and deceleration rates, the differences in vehicle mass and motor power may also contribute to the differences in vehicle performance observed. Further analysis of the motor efficiencies and vehicle power demands of both vehicles is required to test this hypothesis.

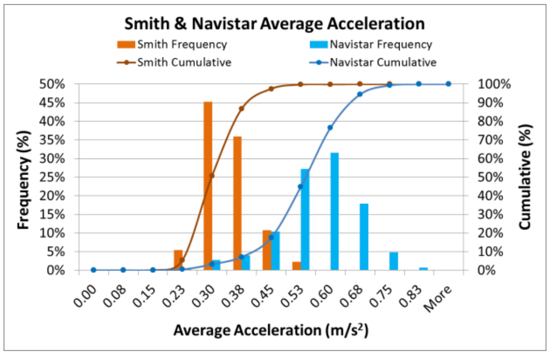

Figure 10: Smith and Navistar average acceleration

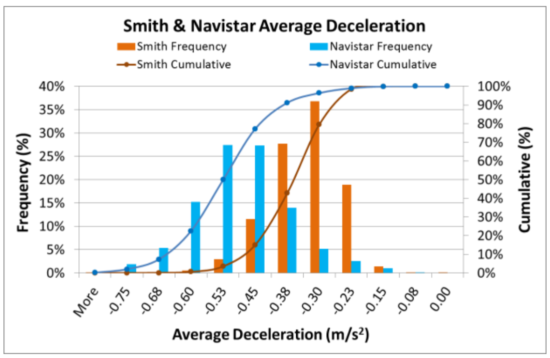

Figure 11: Navistar average deceleration

2.4 Bivariate Drive Cycle Analysis

Further investigation of drive cycle patterns and behaviors from the aggregate data set for all daily driving days using bivariate analysis resulted in additional findings. Examining the relationships, separated by vehicle make, between average driving speed and kinetic intensity, as demonstrated in Figure 12, it can be seen that for a given average speed, the kinetic intensity is consistently greater for the Navistar vehicles than for the Smith vehicles. One can also see that both data sets yield strong correlation values between the two variables, with an R^2 = 0.7789 for the Navistar vehicles and an R^2 = 0.6171 for the Smith vehicles when applying a power fit curve. Evaluating the value of the Pearson's Correlation coefficient for each fit based on the number of data pairs present, it is found that each test produces P-values much less than 0.00001. This extremely small P value allows us to confirm the presence of a strong correlation within both data sets at a significance level beyond one tenth of one percent. Based on this strong correlation between kinetic intensity and average driving speed, one can conclude that average driving speed is a strong indicator of the drive cycle's aggressiveness across the range of vocational applications for these vehicles.

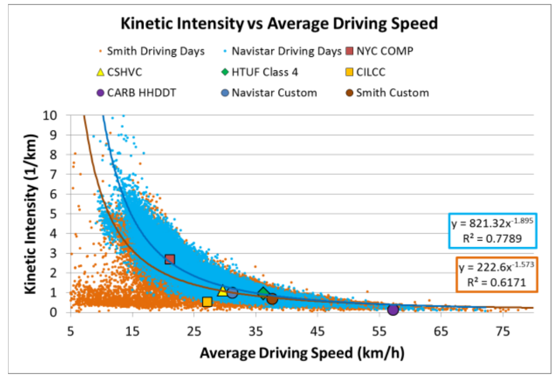

Figure 12: Kinetic intensity vs average driving speed

When exploring the same kinetic intensity variable as it relates to stops per kilometer, as seen in Figure 13, additional insight on driving patterns can be gained. For a given level of kinetic intensity, the Navistar vehicles on average stop more often than the Smith vehicles, which is consistent with the univariate analysis findings mentioned earlier. It should be noted that both vehicle types exhibit a strong linear correlation between kinetic intensity and stops per kilometer and, as such, it can be concluded that stops per kilometer is also a strong indicator of the aggressiveness of the drive cycle for medium duty EVs.

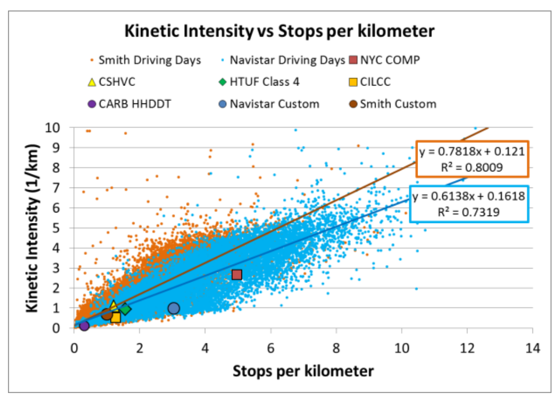

Figure 13: Kinetic intensity vs stops per kilometer

Further examining the relationship between the acceleration rates of these vehicles and the number of stops per kilometer in Figure 14 it is evident that the Navistar vehicles on average have both acceleration and deceleration rates of greater magnitude than the Smith vehicles.

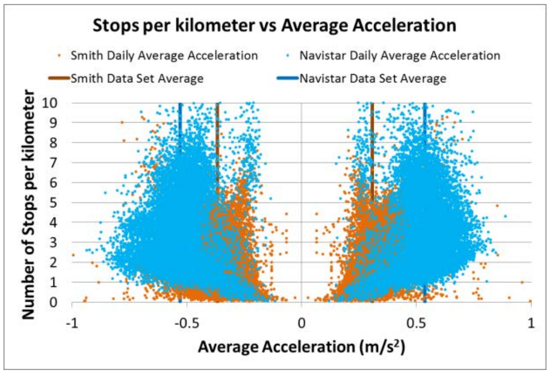

Figure 14: Stops per kilometer vs average acceleration

2.5 Standard Drive Cycle Selection

As part of the drive cycle analysis of these data, representative standard chassis test cycles reflecting the aggregate in-use data were identified and selected using a weighted multivariate least squares method implemented within NREL's DRIVE analysis tool. The NYC COMP cycle was selected to represent the upper bound of driving intensity while the CARB HHDDT cycle was selected as the lower bound for both data sets, with 89% of all combined data points examined falling between the bounds of these two drive cycles. Drive cycles identified as good median fits for the Smith vehicles include: CILCC, CSHVC and HTUF Class 4. The best median fit for the Navistar vehicles was found to be the CILCC cycle. The details of these cycles can be seen in Table 3. See reference [15] for more information on the identified standard chassis test cycles.

Table 3: Representative Standard Drive Cycle Selection Results

Metric	NYC COMP	CSHVC	HTUF Class 4	CILCC	CARB HHDDT
Maximum Driving Speed (km/h)	57.94	70.49	91.08	88.51	95.43
Average Driving Speed (km/h)	21.10	29.68	36.19	27.13	57.27
Standard Deviation of Speed (km/h)	15.23	21.02	22.40	19.98	39.40
Stops per km	4.96	1.21	1.56	1.26	0.31
Characteristic Acceleration (m/s^2)	0.23	0.17	0.17	0.09	0.05
Aerodynamic Speed (m/s)	9.27	12.39	13.57	12.83	22.67
Kinetic Intensity (1/km)	2.67	1.11	0.94	0.52	0.10

2.6 Representative Drive Cycle

NREL's DRIVE tool employs a deterministic multivariate hierarchical clustering method to generate representative drive cycles from source data [16]. Using in-use data, the DRIVE tool processes all data points to build a singular, time-based, weighted, virtual drive cycle that contains the driving profile for each day of in-use data. This composite cycle made up of all data points is then characterized by more than 175 drive cycle metrics. Using these metrics, the tool then deconstructs the composite cycle into numerous micro-trips, which are then used to reconstruct an appropriate representative drive cycle with a user-specified duration. The custom drive cycles generated for this paper are approximately 1 hour in length and are shown in Figure 15 and Figure 16.

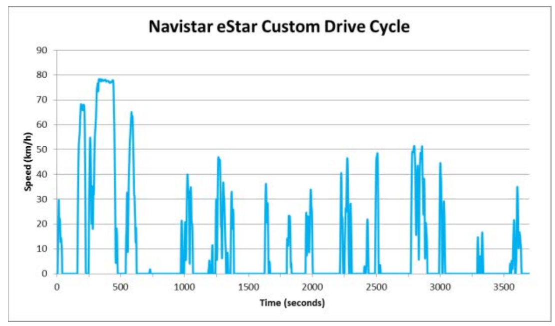

Figure 15: Navistar eStar custom representative drive cycle

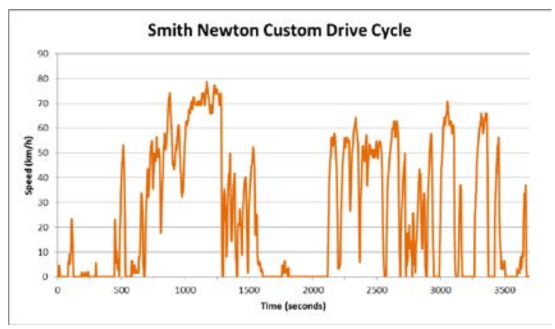

Figure 16: Smith Newton custom representative drive cycle

The speed-time trace data correlating to both of these drive cycles shown in Figure 15 and Figure 16 can be found online [12, 13]. Shown in Table 4 are the in-use averages from each vehicle data set as well as the corresponding statistics from the custom drive cycles generated using NREL's DRIVE tool. The custom drive cycle statistics for both vehicles correlate quite well to the in-use averages from each associated data set, these statistics can be used to better quantify and understand typical medium duty commercial EV operation.

Table 4: Data set average and custom drive cycle statistics

Metric	Navistar eStar		Smith Newton	
	Custom	Average	Custom	Average
Maximum Driving Speed (km/h)	78.4	68.9	78.9	82.5
Average Driving Speed (km/h)	31.3	25.1	36.3	34.8
Standard Deviation of Speed (km/h)	19.7	15.5	25.3	19.9
Stops per km	3.04	3.60	1.00	1.26
Characteristic Acceleration (m/s^2)	0.22	0.23	0.15	0.13
Aerodynamic Speed (m/s)	14.99	11.16	15.05	11.95
Kinetic Intensity (1/km)	2.51	2.37	1.71	1.10

The drive cycles developed as part of this study have shown strong correlation to the average values presented earlier by way of a greater than 90% average match across maximum driving speed, average driving speed, standard deviation of speed, stops per kilometer, and kinetic intensity metrics. Examining the results in greater detail, it can be seen that the Navistar cycle possess a slightly higher average speed than the average day of operation, while the Smith representative cycle has slightly lower stops per kilometer and greater variability in driving speed than average.

3 Summary and Conclusion

This paper has outlined the typical driving patterns and drive cycles of real world medium-duty EVs using a variety of analytical methods and techniques. This paper also examined the differences in vehicle operation and driving behavior within medium-duty EVs by examining several drive cycle characteristics for two separate types of vehicles. One of the major conclusions that can be drawn from this analysis is the opportunity for increased utilization of EV vehicles, and optimization of battery pack size based on real world usage. Also provided in this paper are representative standard chassis dyno test cycles accompanied by custom drive cycles that can be used to explore real world operation of these vehicles either through testing or modelling and simulation activities. By comparing the drive cycle statistics of in-use vehicles to those of standard dynamometer test cycles; one can gain additional insight on medium duty EV driving behavior compared with existing test procedures. Based on the results of the standard drive cycle selection and representative drive cycle generation activities, it can be shown that the vehicles examined as part of this study are being deployed on highly aggressive urban delivery routes with high numbers of stops per kilometer and low average driving speeds. These routes are ideal for EVs given the opportunity to take advantage of regenerative braking and the high energy efficiency of electric motors at low speed. With these findings, vehicle manufacturers will be better able to optimize their designs based on in-use data, and vehicle owners and operators will be well suited to make informed purchasing decisions while improving the utilization of existing EVs within their fleets.

4 Future Work

This rich data set collected as part of this study in conjunction with NREL's existing Fleet DNA database has provided researchers the opportunity to accurately quantify and compare the operational characteristics of both Smith and Navistar electric vehicles, and has created the opportunity for additional in-depth research in the future.

While the analyses performed in this paper have provided a statistical characterization of medium duty electric vehicle drive cycles, further research and investigation is needed to better understand the long-term benefits for fleet owners and operators of operating EVs under a variety of conditions. Given the depth of this dataset, there is also opportunity for additional modelling and simulation activities which will help researchers and manufacturers better understand the effects of changing both vehicle and powertrain characteristics on energy efficiency, and also contribute to optimized vehicle designs on both a component and systems level. Finally, beyond these systems level activities future work will also explore the battery life, utilization, and charging characteristics of Medium-duty commercial electric vehicles.

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Nomenclature

ARRA - American Recovery and Reinvestment Act
CARB HHDDT - California Air Resources Board Heavy Heavy-Duty Diesel Truck Cycle
CILCC - Combined International Local and Commuter Cycle, a composite cycle developed by National Renewable Energy Laboratory, Eaton, and International Truck and Engine
CSHVC - City Suburban Heavy Vehicle Cycle developed by the West Virginia University
DOE - U.S. Department of Energy
DRIVE - Drive Cycle Rapid Investigation, Visualization, and Evaluation tool
EPA - U.S. Environmental Protection Agency
HTUF Class 4 - Hybrid Truck Users Forum Class 4 Parcel Delivery Driving Schedule
NREL - National Renewable Energy Laboratory
NYC Comp - New York City Composite

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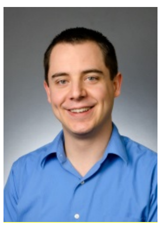
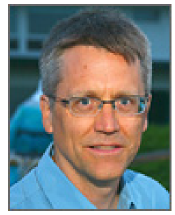


Adam Duran is a senior research engineer working within the Transportation and Hydrogen Systems Center at the National Renewable Energy Laboratory. Adam's work focuses primarily in the areas of drive cycle analysis and characterization, custom drive cycle development, and medium/heavy-duty fleet evaluations. He holds master's and bachelor's degrees in mechanical engineering from the Colorado School of Mines and is currently working on his Ph.D. in mechanical engineering and M.S. in engineering and technology management at the same institution. He may be reached at Adam.Duran@nrel.gov.

Adam Ragatz graduated from the University of Minnesota with a M.S. in mechanical engineering. Adam's graduate work focused on detection and characterization of diesel particulate matter downstream of a failed DPF. He then went on to work at Corning Incorporated, concentrating on in-use emissions from heavy-duty diesel vehicles and the development of advanced aftertreatment solutions. He is now part of the Fuels Performance Group at the National Renewable Energy Lab where he has worked on quantifying the benefits from alternative fuel, and hybrid and electric vehicles.



Kenneth Kelly has more than 20 years of experience working on transportation research and integrated deployment of renewables at National Renewable Energy Laboratory. He currently manages NREL's Fleet Testing and Evaluation activities, assessing the performance of vehicle technologies in medium- and heavy-duty fleets. Ken recently spent 2 years on assignment in Hawaii as NREL's senior project leader of the Hawaii Clean Energy Initiative (HCEI). He holds master's and bachelor's degrees in mechanical engineering from Ohio University.