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Characterization of In-Use Medium Duty Electric Vehicle Driving and Charging Behavior

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Characterization of In-Use Medium Duty Electric Vehicle Driving and Charging Behavior

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***Abstract* — The U.S. Department of Energy's American Recovery and Reinvestment Act (ARRA) deployment and demonstration projects are helping to commercialize technologies for all-electric vehicles (EVs). Under the ARRA program, data from Smith Electric and Navistar medium duty EVs have been collected, compiled, and analyzed in an effort to quantify the impacts of these new technologies. Over a period of three years, the National Renewable Energy Laboratory (NREL) has compiled data from over 250 Smith Newton EVs for a total of over 100,000 days of in-use operation. Similarly, data have been collected from over 100 Navistar eStar vehicles, with over 15,000 operating days having been analyzed. NREL has analyzed a combined total of over 4 million kilometers of driving and 1 million hours of charging data for commercial operating medium duty EVs.**

In this paper, the authors present an overview of medium duty EV operating and charging behavior based on in-use data collected from both Smith and Navistar vehicles operating in the United States. Specifically, this paper provides an introduction to the specifications and configurations of the vehicles examined; discusses the approach and methodology of data collection and analysis, and presents detailed results regarding daily driving and charging behavior. In addition, trends observed over the course of multiple years of data collection are examined, and conclusions are drawn about early deployment behavior and ongoing adjustments due to new and improving technology. Results and metrics such as average daily driving distance, route aggressiveness, charging frequency, and liter per kilometer diesel equivalent fuel consumption are documented and discussed.

Keywords — Medium Duty (MD); Electric Vehicle (EV); Charging Behavior; Driving Behavior; Smith; Navistar; Commercial Vehicle

I. Introduction

Starting in 2011, the Fleet Test and Evaluation Team at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) has been working on a large scale vehicle technology evaluation project documenting and evaluating the performance of electric and plug-in hybrid electric drive systems in medium duty trucks operating across the United States. As part of this project, under the American Recovery and Reinvestment Act, participating U.S. companies received funding to cover part of the cost of purchasing new electric vehicles (EVs). To meet the new demand for all-electric medium-duty delivery vehicles, Smith Electric Vehicles and Navistar built and deployed a combined total of nearly 500 medium duty electric trucks. These vehicles have been deployed in commercial service across the United States in a range of diverse climates and applications from Southern California to New York.

To date, limited research has been completed characterizing the performance of modern medium duty electric delivery vehicle technology [1-4]; however initial research and studies have been performed which explore the economic potential and viability of the technologies discussed in this paper [5-8]. Along with the information presented in this paper, additional supplemental data for further study can be found in publicly available published reports hosted online [9,10].

A. Vehicle Overviews and Specifications

The vehicles examined as part of this study operate as medium-duty delivery vehicles within the United States. The Navistar eStar vehicles examined in this study are configured as smaller delivery vans with a chassis weight capacity designed for U.S. class three and European Union N1 gross vehicle weight ranges (4,536–6,350 kg). Figure 1 shows a visual representation of the Navistar eStar vehicle configuration.

Fig. 1. A Navistar eStar battery electric delivery vehicle [11].

On the other hand, the Smith Newton vehicle chassis can be adjusted for vehicle applications ranging from U.S. class three to class six and European Union N1 to N2 weight classifications depending on body build (e.g. delivery van, school bus, or stake truck). Figure 2 shows a Smith Newton vehicle configured as a delivery vehicle.

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Fig. 2. A Smith Newton Vehicle operating in New York City [12].

In addition to the basic gross vehicle weight ratings mentioned previously, additional detailed vehicle specifications are shown in Table I. It is interesting to note that while the vehicles examined in this paper operate in two different weight classes; both were designed with the same battery capacity, 80 kWh. As will be seen in the analysis of the energy consumption rate of these vehicles, the difference in vehicle mass has a significant influence on energy consumption per 100 kilometers traveled; therefore, due to the vehicles possessing the same energy storage capacity we find that there is a significant difference in the estimated maximum vehicle operating ranges.

TABLE I. VEHICLE SPECIFICATIONS

	Smith Newton	Navistar eStar
Weight Class	Class 6 / N_2	Class 3 / N_1
GVWR (kg)	~9,980 - ~11,793	~5,488
Payload (kg)	~5,590 – 7,348	~2,313
Drag Coefficient	~0.5	~0.5
Charging Standard	J1772 or 3-phase	J1772
Battery Capacity (kWh)	80	80
Motor Power (kW)	134	70
Top Speed (km/h)	80.5	80.5
Advertised Range	Up to 160 km	Up to 160 km

[a] The specifications shown in this table are drawn from [13-15], with additional charging standard information available via [16]

II. APPROACH

A. Data Collection

The data collection approach in this study focused on the capture of in-use operating and charging data for a large study population of Navistar and Smith EVs. The sample population examined in this study, contained vehicles operating in a variety of unique geographic locations, allowing for the exploration of the influences of geography and climate on operating behavior and performance. In addition to capturing data from a large sample population, the data collection occurred over a period of three years, with overlapping operation between the Smith and Navistar vehicles. The collection of multiple years of operating and charging data, coupled with the breadth of geographic deployment of the subject vehicles provided the opportunity for the higher level analysis of trends over time and through geography presented in this paper. As shown in Table II, a combined total of 360 total vehicles, operating in 126 unique deployment locations from 2011 to 2014 contributed data to this study.

TABLE II. PROJECT OVERVIEW

	Smith Newton	Navistar eStar
Reporting Period	11/1/2011 – 9/30/2014	7/1/2012 – 6/30/2014
Number of Vehicles	259	101
Operating Cities	81	35
Vehicles Days Driven	108,668	17,447
Total Distance Traveled (km)	4,407,127	569,279
Total Charge Delivered (kWh)	5,032,809	298,260

To better visualize the information contained within Table II, the map in Fig. 3 shows the home charging location of each vehicle which provided data to this project. Note the wide range of geographic regions covered by the vehicles. In particular there were a number of vehicles deployed to the densely populated east and west coasts, with another large set being deployed in the central United States, an area with typically lower population density. In addition to collecting data in geographic areas with ranges in population density, examining Fig. 3 one can see that the vehicles also cover a wide geographic range north and south within the United States. This provides the opportunity to examine the effects of operating climate on vehicle performance and charging behavior.

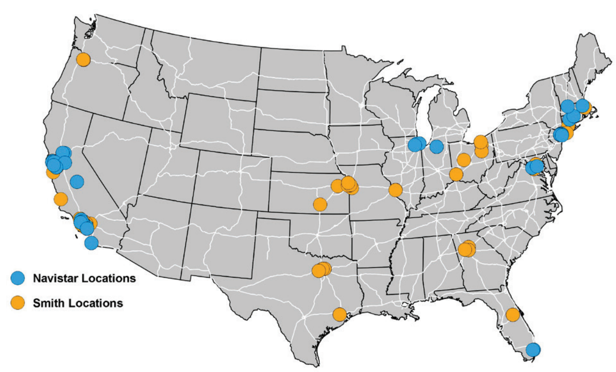

Fig. 3. Home locations of Smith Newton and Navistar eStar vehicles.

As part of the study, on-board diagnostic data were collected via onboard data logging devices, typically capturing data from the controller area network along with global positioning system information. Once captured via onboard logging device, the data were then transmitted wirelessly back over the cellular network and eventually on to the original equipment manufacturer (OEM). Once received by the OEM,

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the data were then transferred to NREL via a secure File Transfer Protocol (FTP) site, usually as a text file. Having arrived at NREL, a number of automated processes handled downloading, filtering, sorting, and processing of the OEM supplied data. During analysis, the raw and processed data were stored in NREL's Commercial Fleet Data Center (CFDC) PostgreSQL central database. Once the data have been processed and stored in the datacenter, additional analysis and reporting routines are then used to generate vehicle operating reports for public consumption. This process is outlined in the schematic shown in Fig. 4.

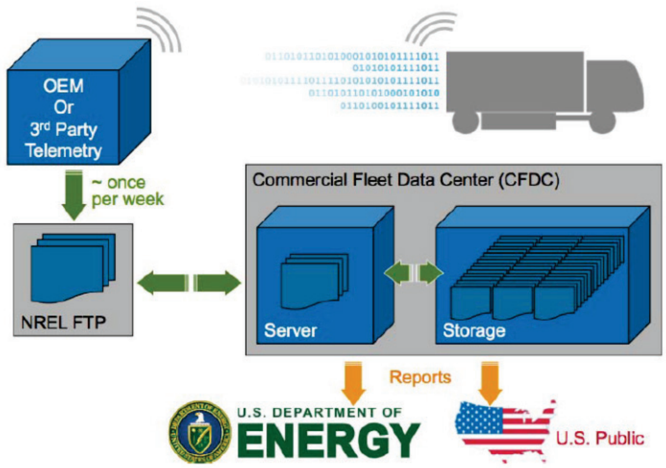

Fig. 4. Illustration of project data storage mechanism via onboard data collection and FTP data transfer.

B. Data Analysis

For data processing, two primary software packages were used for calculations and analysis, MATLAB and Python. Examining the data processing approach on a detailed level, the data analysis process can be broken down into a number of sequential steps. First, raw data are loaded directly from individual files or read from the CFDC PostgreSQL central database. During this step, all data received by the secure FTP site are stored; and if data are found to be erroneous or corrupt during the filtering process, they are flagged and are not included in subsequent processing steps. From this initial loading step, the original Greenwich Mean Time (GMT) reference time and date information within each file are adjusted for the local geographic operating location, and then binned into "driving days" that capture one full day of driving and any subsequent charging, even if the charge cycle goes past midnight. Subsequent sub-analyses are then carried out on individual areas of interest including drive cycle, powertrain, power electronics, batteries, and any individual vehicle components of interest. These routines include code and calculations specifically designed for each specific area of interest, while also incorporating more universal calculations from NREL's Fleet DNA Project [17]. Employing this analysis method allows the performance of these vehicles and vehicle components to be compared across the large number of current and past projects contained within the Fleet DNA database housed on the CFDC. Finally, analysis results can be combined with both demographic and geographic data to better understand localized trends and markets. Final data products are then published for public comment. The process for data analysis is outlined in the schematic in Fig. 5.

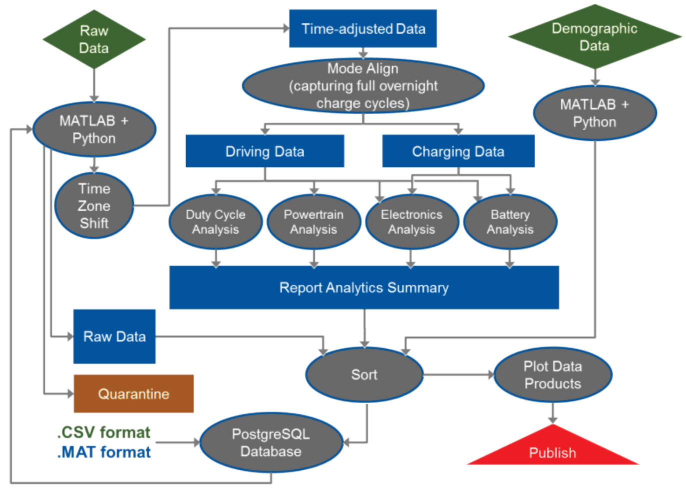

Fig. 5. Flow diagram of data analysis approach.

For more in-depth discussion of the analysis performed in this paper, please see additional references [18-19] for specific statistics, methods, and approaches.

III. RESULTS

A. Driving Behavior

Understanding vehicle operation is paramount to improving existing technology and future vehicle deployment. In an effort to better understand the typical daily operation of the vehicles examined in this project, researchers summarized the hundreds of thousands of vehicle days of operation collected, calculating the percentage of overall vehicle operating time spent at each hour during the day. Fig. 6 illustrates the results of this effort, showing the typical time of day when both the Navistar and Smith vehicles are being driven.

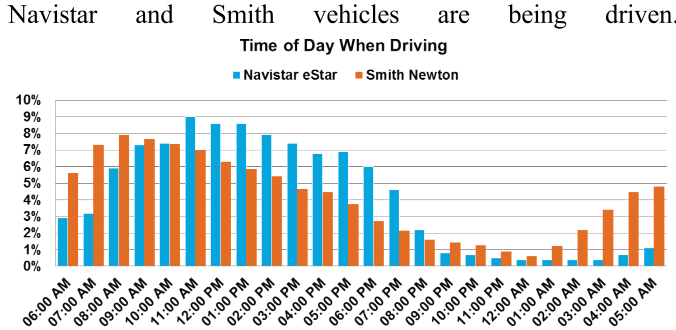

Fig. 6. Comparison of Smith Newton and Navistar eStar operating times.

The driving pattern developed as a result of this analysis follows typical "daytime" operation, with the majority of vehicle operation occurring between roughly 5 a.m. and 7 p.m. local time. In particular, the Smith vehicles seem to operate between 6 a.m. and 4 p.m. while the Navistar vehicles peak operating time is later in the day from 8 a.m. to 7 p.m.

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In addition to examining the typical operating times for each of the two vehicles contained within this study, additional analysis was performed to characterize the typical daily drive cycles associated with typical operation. Table III lists a number of drive cycle statistics which describe the average daily operation of the vehicles examined.

TABLE III. DRIVE CYCLE STATISTICS

	Smith Newton	Navistar eStar
Average Daily Driving Distance (km)	40.4	32.7
Average Driving Speed (kph)	34.3	22.9
Average Daily Max Speed (kph)	81.4	81.1
% of miles City (<48 kph) | Hwy	~ 65 | 35	~ 76 | 24
Average Stops per Day	60.2	123.7
Average Stops per Kilometer	1.18	3.79
Average Daily Max Acceleration (g)	0.33	0.39
Average Brake Regen Events (1/km)	5.7	10.1
Median Driving Aggressiveness Kinetic Intensity (1/km)	1.1	3.5

b. Kinetic Intensity describes the ratio of aerodynamic energy to kinetic energy over a drive cycle [19].

Examining the average daily operation of the two vehicle types, a number of conclusions can be drawn regarding operating behavior. The first major conclusion, is that the Navistar vehicles, being smaller and possessing less mass operate on much more intense urban delivery drive cycles than their larger Smith counterparts. This conclusion is supported by the median Kinetic Intensity of the Navistar vehicles being 3.5, while the Smith's is 1.1. This three times larger intensity is the result of the much greater number of stops per kilometer, higher acceleration rate and much lower average driving speed for the Navistar vehicles compared to the Smith's. This conclusion is further supported upon further examination of daily vehicle driving distance. The Navistar vehicles travel much less distance on a typical day when compared to the Smith vehicles, and have a much higher percentage of their distance traveled occurs at city speeds. Fig. 7 shows the distribution and average daily driving distance for each vehicle.

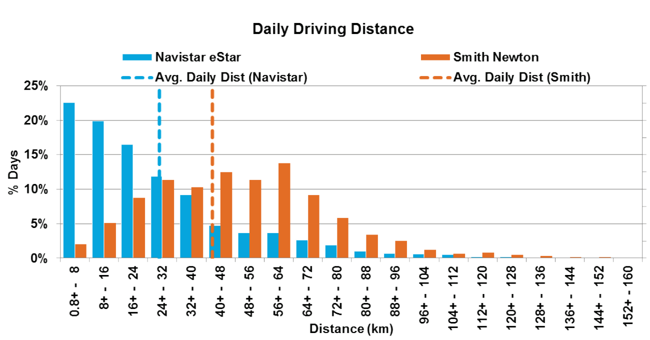

Fig. 7. Distribution of daily driving distances for Smith and Navistar.

As shown in the figure, the Navistar vehicles consistently accumulated lower daily driving distances than the Smith vehicles, with approximately 42% of Navistar vehicles accumulating fewer than 16 km on a daily basis. This is in contrast to the Smith vehicles whose average daily driving distance was 11.4 km farther than those of the Navistar's.

Examining the daily operation of the Smith and Navistar vehicles at a more detailed level, a number of additional trends can be identified. When examining daily Kinetic Intensity and average driving speed metrics as shown in Fig. 8, a strong exponential correlation is found to occur. Based on this correlation, it is concluded that for the electric vehicles examined in this study, average driving speed can be considered a strong indicator of the aggressiveness of the drive cycle. For additional reference, typical medium-duty drive cycles are plotted along with the daily data points to illustrate the wide range of vehicle operation. The standard United States chassis test cycles - HTUF 4, Orange County Bus, and NY City Composite Cycle, appear to be representative of the range of typical daily driving for the Navistar vehicles across all applications. The Manhattan Bus and West Virginia University 5 Peak cycles bound either end with nearly 85% of the drive cycle kinetic intensities falling between these points. See ref [20] for more information on the identified standard chassis test cycles.

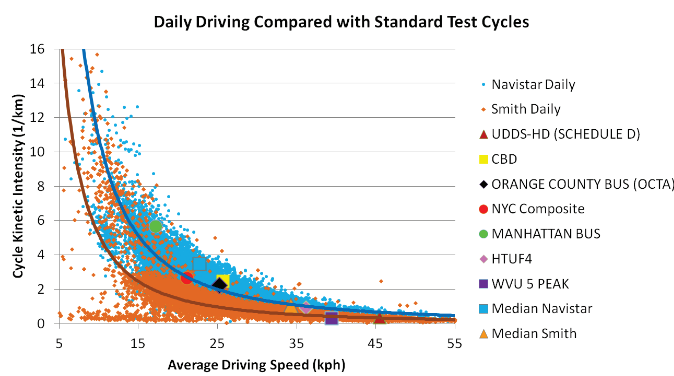

Fig. 8. Daily driving compared with standard drive cycles.

In an effort to explore the effects of drive cycle on energy consumption, additional analyses were performed on the daily data to examine the potential for any trends within the data. Energy consumption was plotted against the primary drive cycle metrics contained within Table III and a relationship betweend driving agressiveness and energy consumption was observed. Fig. 9. shows the effect driving aggressiveness as measured by kinetic intensity, has on energy consumption displayed as equivalent fuel consumption. In addition, for reference a number of standard chassis test cycles are also plotted along with the vehicle source data. The trend lines illustrate the cycle dependency of electric equivalent fuel consumption.

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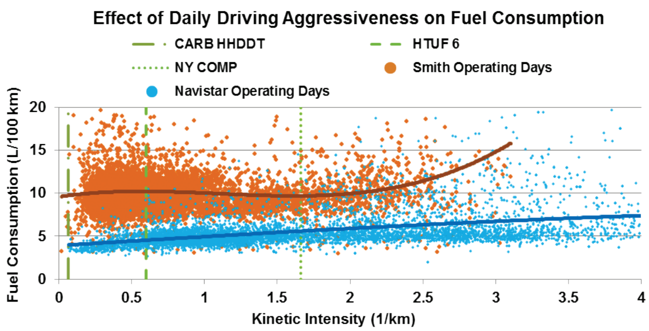

Fig. 9. Effect of driving aggressiveness as measured by kinetic intensity on equivalent fuel consumption.

Examining Fig. 9, it appears as though the minimun energy consumption rate for the Smith Newton vehicles occurs when operating on a moderate aggressive drive cycle around 1.6. When examining standard chassis test cycles with aggressiveness values in the same range, we find that the NY Comp cycle which is representative of dense urban driving is very close to the type of cycle that would have the lowest energy consumption per kilometer. This discovery is somethwat contrary to what one may expect, which would be lowest energy consumption per kilometer to occurt on the least aggressive cycles. It is posited that due to their limited stop and go behavior, and generally higher operating speds, passive drive cycles do not possess enough opportunity for regenerative braking. On the opposite end of the spectrum, it is posited that the most aggressive cycles, characterized by by a high energy consumption rate per kilometer due to typically higher acceleration rates, larger number of stops per kilometer, and lower operating speed suffer from the limited ability to fully capture regenerative braking energy due to inefficiencies within current regenerative braking systems which are only magnified due to the large mass of the vehicles examined. It is posited that this trend is not observed in the Navistar vehicles due to their much smaller vehicle mass, and thus greater opportunity to capture regenerative braking energy. Were the Navistar vehicles to be operated on even more intense cycles than those observed in the field, it is proposed that a similar trend as to what is seen with the Smith vehicles would be discovered.

B. *Charging Behavior*

As was the case with driving behavior, understanding vehicle charging behavior is fundamental in improving existing technology and optimizing charging strategy. In an effort to better understand the typical daily charging behavior of both the Smith and Newton vehicles examined as part of this study, researchers summarized the over one million hours of vehicle charging collected to identify periods of time during which the vehicles were plugged in as well as when they were charging their battery packs. Figure 10 illustrates the typical daily time when the vehicles plug-in to charge.

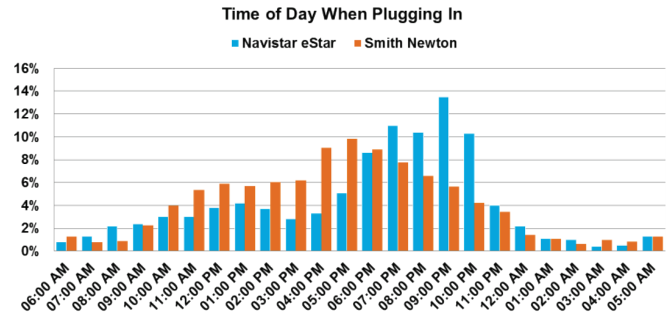

Fig. 10. Comparison of plug-in times by vehicle type.

This pattern shown in Fig. 10 follows typical "daytime" operation, with the majority of vehicle plug-ins occurring between roughly 5 p.m. and 10 p.m. local time. Examining the plug-in behavior in greater detail, one notices that the Navistar vehicles appear to have a bimodal distribution in their plug-in behavior with one peak occuring between 10 a.m. and 2 p.m. and another occuring between 4 p.m. and 6 p.m. This suggest the vehicles are plugging in during lunch breaks and at the conclusion of the typical operating day. This trend appears to also be present within the Smith vehicles, albeit on a much less visually apparent level.

Examining daily charging behavior, we see that vehicle peak charging occurs during the middle of the night as expected. The peak charging time for Navistar occur between 7 p.m. and 12 a.m, while the peak charging for Smith occurs between 10 p.m. and 3 a.m. as shown in Fig. 11. As was the case with the plug-in time distribution, there appears to be bimodal distribution within the charging behavior.

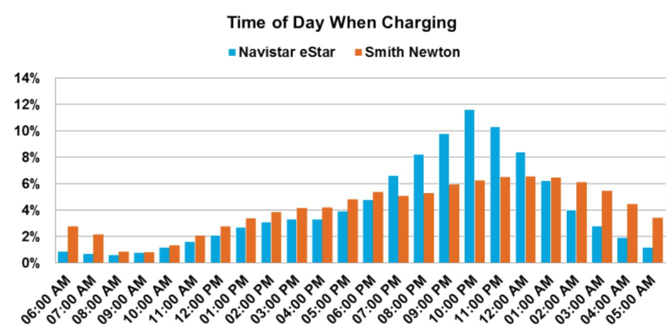

Fig. 11. Comparison of Navistar and Smith charging times.

In addition to examining typical plug-in and charging times for each of the vehicles contained within this study, analysis was performed characterizing charging behavior. Table IV presents a number of statistics which describe the results.

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TABLE IV. CHARGING STATISTICS

	Smith Newton	Navistar eStar
Overall AC Energy Charged (Wh/km)	1,144.9	554.4
Overall DC Energy Charged (Wh/km)	1006.1	523.9
Overall DC Energy Discharged (Wh/km)	938.8	505.4
DC Driving Energy Consumed (Wh/km)	873.4	458.1
Overall Diesel Equivalent Fuel Consumption (km/L)	10.6	19.6
Average Energy per Charge (kWh)	21.8	18.5
Average Charge Duration (hr)	6.4	3.5
Average Charges per Day	1.9	0.93

When examining the charging behavior of the two different vehicles, a number of conclusions can be drawn regarding the overall energy consumption and charging behavior. The first major conclusion, is that the eStar vehicles, being smaller and possessing less mass consume significantly less energy per kilometer than their larger Smith counterparts. This is to be expected, and is illustrated by the almost value of equivalent fuel consumption per one hundred kilometers for Navistar being half that of Smith. However, if base vehicle mass and maximum payload capacity values are used to normalize the energy consumption rate results on a L/km-tonne basis, it is found that the Smith vehicles display a higher freight efficiency than the Navistar vehicles. Based on a freight analysis, it is theorized that the observed Smith advantage is the result of operating on a less aggressive drive cycle in addition to technology differences between the two manufacturers. Further analysis comparing the mass normalized energy consumption rate of both vehicles types operating on similar drive cycles is required to evaluate this hypothesis.

C. Geographic and Seasonal Effects

One of the biggest advantages of having a broad long-term data collection project is the opportunity to explore and observe trends within data through time and with reference to location. In this particular study, driving and charging data were collected over multiple years of operation across the United States, providing the opportunity to examine the effect geographic and seasonal influences have on energy consumption and operating behavior for EVs. As shown in Fig. 12 and Fig. 13, this data provides the opportunity to examine energy consumption rates for both the Navistar and Smith vehicles over the course of the study.

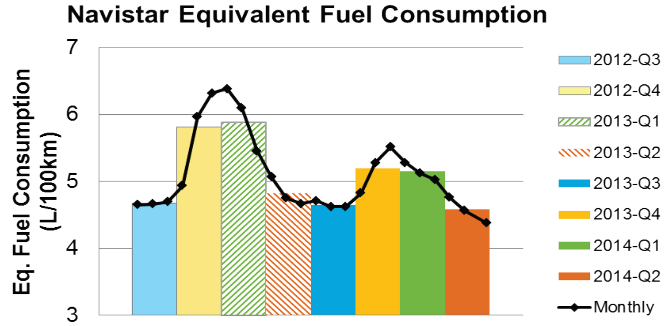

Fig. 12. Seasonal and monthly fuel consumption rates for Navistar eStar.

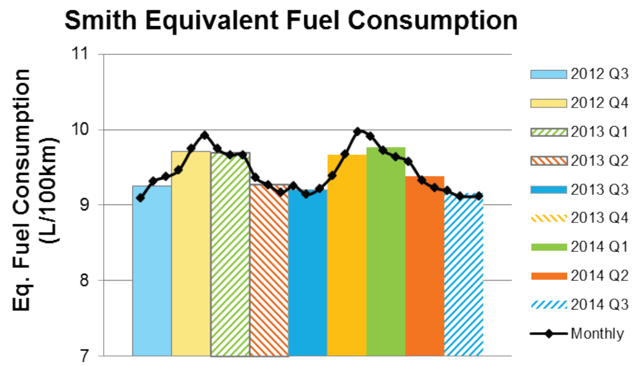

Fig. 13. Seasonal and monthly fuel consumption rates for Smith Newton.

Upon closer examination of both the quarterly and monthly energy consumption rates, a trend of higher energy consumption during quarters 1 and 4 is observed. It was posited that since these vehicles operate in the nother hemisphere, the months identified correlate to the winter season and therefore the increase in energy consumption is due to the non-tractive energy required to run resistive heaters in each vehicle cab. It is also posited that there are additional viscous losses attributed to the powertrain as a result of colder temperatures. The observed trend holds across both the Navistar and Smith vehicles, but appears to have a greater nomalized impact on the Navistar vehicles. As a result, further analysis comparing external operating temperature to energy consumption rate was required.

In an attempt to further explore the relationship between external operating temperature and energy consumption rate and validate the team's hypothesis, a temporal energy consumption analysis was performed using the Navistar vehicle data collected at three different geographic locations. The locations of data collection selected ranged from the North Eastern United States (NY and IL) to the South West (CA). These locations were identified due to their differing climates and temperature ranges. Fig. 14 shows the relationship between average minimum ambient temperature and energy cosumption by location.

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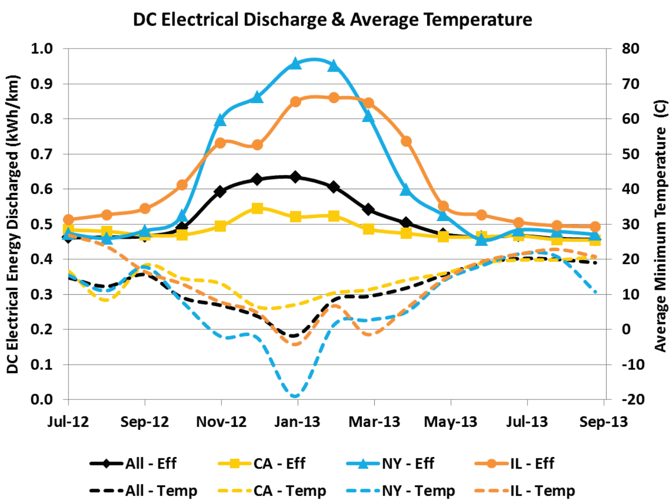

Fig. 14. Navistar eStar average battery DC electrical discharge and average minimum ambient temperature.

The trend shows that colder temperatures result in an increase in vehicle energy consumption per kilometer traveled. The locations with the coldest minimum temperatures displayed the highest energy cosumption (NY and IL), while the warmer locations consumed significantly less energy (CA). This trend supports the hypothesis, however additional analysis for each dataset comparing the amount of time in which the on-board heaters were active with overall energy consumption will further validate/reject this assumption.

As a follow up to analyzing the effects of geography and seasonality on overall energy consumption, researchers analyzed driving and charging times at the same three Navistar vehicle locations to explore whether or not there were geographic/fleet influences on operating behavior. Fig. 15 illustrates the results of this analysis.

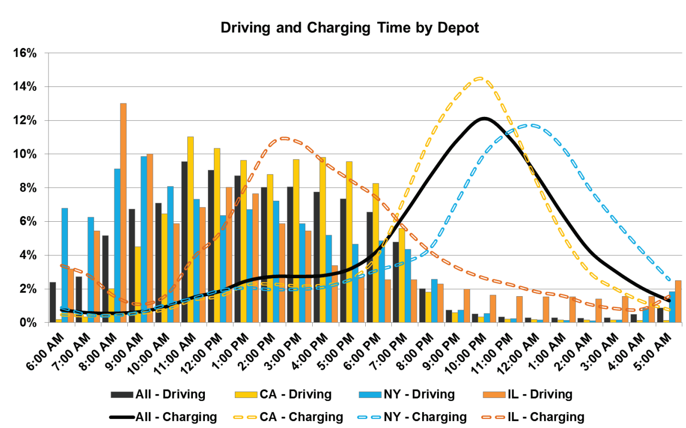

Fig. 15. Illustration of geographic and depot specific charging behavior influences.

Examining the results, it is apparent that while all three locations exhibit typical "day time" operating trends, it can be seen that charging behavior is highly dependent on each fleet/location. For example, the depot located in Illinois charges much earlier in the day than either the California or New York locations. This may be the result of different charging strategies or fleet operating characteristics.

IV. Summary and Conclusions

While this paper has provided the foundation for an initial understanding of medium-duty EV driving and charging behavior, further work is required to fully examine the effects weather, seasonality, and geography have on medium-duty EV driving and charging behavior. Additional in-depth studies are planned to further explore these areas, as well as to examine the trends within specific individual make/model combinations. There is also opportunity to explore vehicle chassis/platform optimization through the application of the data presented in this paper, particularly through large scale vehicle modeling and simulation efforts. In addition, with the release of second-generation Smith Newton vehicles it will be interesting to analyze the differences in energy efficiency and storage capacity between the two vehicle models, and observe the results that technology enhancements have on vehicle operating behavior.

Beyond providing a greater understanding of EV operation in the areas of medium-duty commercial vehicles, this paper also demonstrates the value of large scale data collection and the potential for application of "Big Data" principals to the area of transportation analysis. Having access to the rich database of vehicle operation data stored within NREL's Fleet DNA database, coupled with the requisite infrastructure, geography, and climate records provided the opportunity for the expanded analyses contained within this paper.

Acknowledgment

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