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Development of 80- and 100- Mile Work Day Cycles Representative of Commercial Pickup and Delivery Operation

Adam Duran National Renewable Energy Laboratory

Ke Li and John kresse Cummins Inc

Kenneth Kelly National Renewable Energy Laboratory

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Abstract

When developing and designing new technology for integrated vehicle systems deployment, standard cycles have long existed for chassis dynamometer testing and tuning of the powertrain. However, to this day with recent developments and advancements in plug-in hybrid and battery electric vehicle technology, no true "work day" cycles exist with which to tune and measure energy storage control and thermal management systems. To address these issues and in support of development of a range-extended pickup and delivery Class 6 commercial vehicle, researchers at the National Renewable Energy Laboratory in collaboration with Cummins analyzed 78,000 days of operational data captured from more than 260 vehicles operating across the United States to characterize the typical daily performance requirements associated with Class 6 commercial pickup and delivery operation. In total, over 2.5 million miles of real-world vehicle operation were condensed into a pair of duty cycles, an 80-mile cycle and a 100-mile cycle representative of the daily operation of U.S. class 3-6 commercial pickup and delivery trucks. Using novel machine learning clustering methods combined with mileage-based weighting, these composite representative cycles correspond to 90th and 95th percentiles for daily vehicle miles traveled by the vehicles observed. In addition to including vehicle speed vs time drive cycles, in an effort to better represent the environmental factors encountered by pickup and delivery vehicles operating across the United States, a nationally representative grade profile and key status information were also appended to the speed vs. time profiles to produce a "work day" cycle that captures the effects of vehicle dynamics, geography, and driver behavior which can be used for future design, development, and validation of technology.

Introduction

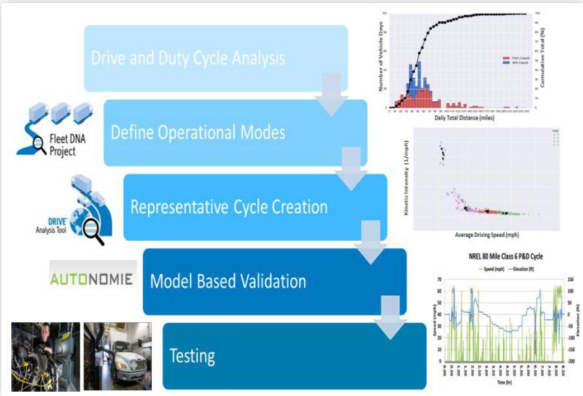
Under DOE-FOA-0001349 FY15 Award for Medium- and Heavy-Duty Vehicle Powertrain Electrification, Cummins and PACCAR jointly proposed the development of a range-extending plug-in hybrid electric Class 6 pickup and delivery truck. The goal of this project is to demonstrate an electrified vehicle that would deliver a minimum of 50% reduction in fuel consumption across a range of representative drive cycles. In addition to achieving the 50% fuel reduction target, the vehicle also needs to demonstrate as good or better drivability and performance while still meeting emissions requirements when compared to existing conventionally fueled baseline vehicles.

Most existing duty cycles used to test conventional internal combustion powered vehicles are of a limited time duration. For example, the Hybrid Truck Utility Forum Class 6 Pickup and Delivery cycle is slightly more than one hour. When testing a system using only fuel as its energy source, this is acceptable; a one- hour duty cycle can be used to represent the vehicle operation for the entire work day (e.g., fuel consumption in the middle of the day is very similar to fuel consumption at the end of the day). However, with plug-in electric vehicles, the system (battery characteristics and thermal management systems) may operate differently throughout the work day (especially near the end of the day). For example, the available battery energy may be completely spent prior to the completion of the route. A short duty cycle cannot simply be extrapolated.

Evaluating the vehicle over the entire work day also provides the ability to interject appropriate stops that are typical of the Class 6-7 pickup and delivery application. These stops can range from several minutes to much longer and can have significant thermal effect on the vehicle and powertrain systems. These stops may also have a large impact on overall duty cycle mileage (and other duty cycle characteristics such as average speed) as the stops may account for roughly half of the work day.

As part of the research and development team, the National Renewable Energy Laboratory (NREL) was been

FIGURE 1 Overview of NREL's data-driven design approach



tasked with leveraging its unique capabilities in commercial fleet data acquisition and analysis to lead the development of representative "work day" cycles that would be used to both size powertrain components, as well as serve as initial inputs with which to tune the control systems for the hybrid system as shown in Figure 1.

This work required analyzing the data currently stored in NREL's Fleet DNA database of commercial vehicle drive/duty cycles, as well as application of NREL's Drive-Cycle Rapid Investigation, Visualization, and Evaluation (DRIVE) tool for the generation of representative drive cycles. Additionally, as there was a need for a "work day" cycle, DRIVE's capabilities were expanded to include the ability to generate representative synthetic road grade profiles using the U.S. national highway road grade distribution and a gradeability curve input. A Markov-Chain Monte Carlo method was also developed to append key status information to the resulting speed-time and elevation-time traces to form a complete work day cycle. Once the cycles had been developed, they were externally validated using powertrain and driver models developed by Cummins Inc.

Developing Work Day Cycles

As an initial step in the development of the work day cycle, NREL researchers first had to develop benchmark targets for both cycle duration and distance traveled. To accomplish this task, NREL looked to both external as well as internal sources of data that could be used as inputs. Externally, NREL sourced operational information from the U.S. Environmental Protection Agency (EPA), California Air Resources Board (CARB), as well as the U.S. Department of Energy's (DOE's) own Alternative Fuels Data Center. Internally, NREL analyzed the data stored in its Fleet DNA database as shown for Class 6 pickup and delivery vehicles:

- 77,261 total days of operating data, of which 735 were conventional
- 261 total vehicles, of which 52 conventional
- Over 2.5 million miles of real-world vehicle operation.

Analyzing NREL's Fleet DNA Database

Fleet DNA data were analyzed to characterize, and document typical daily vehicle miles traveled (VMT) and operational duration. For this project, both a full sampling of all Class 6 pickup and delivery vehicles and a subsample of just Class 6 delivery straight trucks were examined and used as a foundation for developing the representative work day cycles used to size and tune the final powertrain system.

Determining Operating Time Targets As shown in Figure 2, results of Fleet DNA analysis demonstrated a median operating day duration of 4 hours with 95% of days operating for 8 hours or less, where operation is defined as time where the ignition key is in the "on" position.

Daily Vehicle Miles Traveled Targets For this analysis, the complete Class 6 pickup and delivery data set was compared to the Class 6 pickup and delivery straight trucks, and a separate analysis was performed on existing Class 6 pickup and delivery electric vehicles to compare their respective daily operating range requirements. Figure 3 shows

FIGURE 2 Distribution of daily work day duration results for all Class 6 pickup and delivery vehicles sampled from Fleet DNA

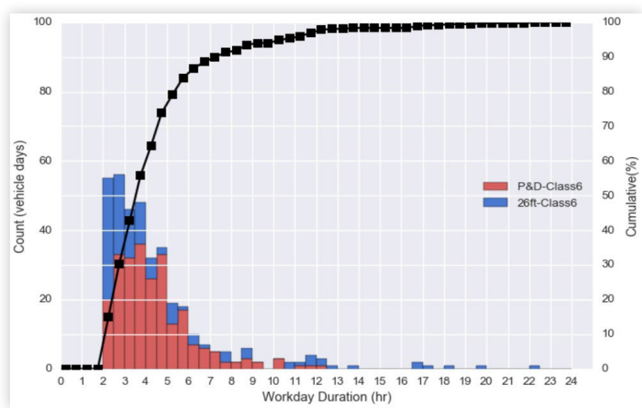


FIGURE 3 Daily VMT distribution for all Fleet DNA Class 6 pickup and delivery vehicles

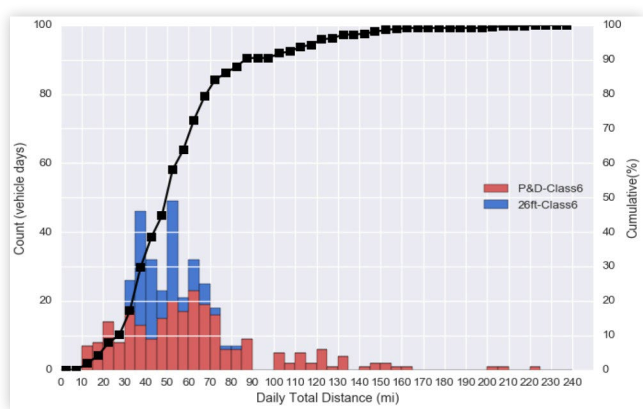
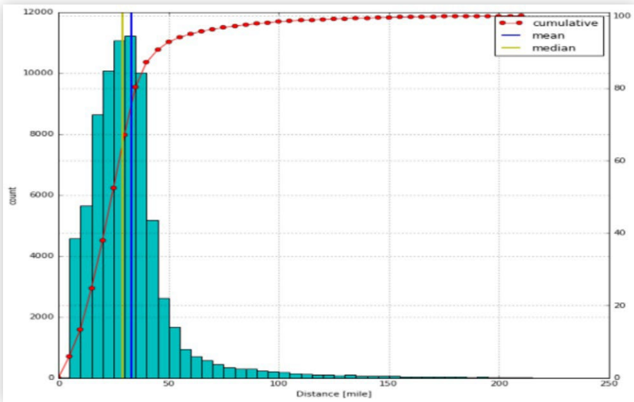


FIGURE 4 Daily VMT distribution for Fleet DNA Class 6 electric vehicles



the results of the daily VMT analysis performed on the Fleet DNA data set. The median daily VMT for the Class 6 vehicles examined is roughly 55 miles, while the 90th and 95th percentiles for distance correspond to 80 and 100 miles. Based on these results, 80- and 100-mile representative cycle durations were selected as desired targets for the project.

Examining a more detailed subset of Class 6 electric pickup and delivery trucks as shown in Figure 4, on average the daily VMT observed is significantly lower than that of conventional counterparts at 40 miles per day. The median daily VMT is also lower at approximately 35 miles per day. Ninety-five percent of all vehicles examined in this subset traveled less than 100 miles a day, further supporting the decision of 80- and 100-mile daily VMT targets for representative cycle generation [1].

Exploring Alternative Publicly Available Data Sets

As mentioned previously, in addition to analyzing data stored within NREL's Fleet DNA database, NREL researchers also examined other publicly available data sets and reports to document the potential operating range variability within the Class 6 pickup and delivery vocational space. Results from real-world fleet estimate studies, the 2002 U.S. Census Vehicle Inventory and Use Survey [2], EPA's MOVES model [3], and CARB's 2011 California Hybrid, Efficient and Advanced Truck (CalHEAT) report were all collected [4], and the compiled results are as follows:

- NREL data sets show ~50-60 miles daily.
- Ninety-five percent of trips are less than 120 miles.
- CalHEAT study estimates 125-175 miles per day.
- 2002 Vehicle Inventory and Use Survey estimates ~116.25 miles per day.
- Fleet estimates for PepsiCo ~110 miles per day.

The range of daily VMT reported by the individual studies fluctuated between 50 miles per day on the low side for the NREL Fleet DNA data (95% of daily operating VMT less than 120 miles), and up to 175 miles per day according to the CalHEAT study. Most results were in the range of 110-120 miles per day of daily operation as shown in Tables 1 through 3 and Figure 5.

Generating Drive Cycles with NREL's DRIVE Tool Upon determining appropriate cycle durations and distance targets for the final representative work day cycle,

TABLE 1 2002 Vehicle Inventory and Use Survey Annual Mileage by Vehicle Age [3]

Age	Model Year	Single Unit Trucks			Combination Trucks	
		Refuse (51)	Short-Haul (52)	Long-Houl (53)	Short-Haul (61)	Long-Haul (62)
0	2002	26,703	21,926	40,538	119,867	109,418
1	2001	32,391	22,755	28,168	114,983	128,287
2	2000	31,210	24,446	30,139	110,099	117,945
3	1999	31,444	23,874	49,428	105,215	110,713
4	1998	31,815	21,074	33,206	100,331	99,925
5	1997	28,450	21,444	23,784	95,447	94,326
6	1996	25,462	10,901	21,238	90,563	85,225
7	1995	30,182	15,453	27,562	95,679	85,406
8	1994	20,722	13,930	21,052	80,795	71,834
9	1993	25,199	13,303	11,273	75,911	71,160
10	1992	23,366	11,749	18,599	71,026	67,700
11	1991	18,818	13,675	15,140	66,142	80,207
12	1990	12,533	11,332	13,311	61,258	48,562
13	1989	15,891	9,795	9,796	56,374	64,473
14	1988	19,018	9,309	12,067	51,490	48,242
15	1987	12,480	9,379	16,606	46,606	58,95 1
16	1986	12,577	4,830	8,941	41,722	35,897
0-3	**1999-2002 Average**	**30,437**	**23,250**	**37,069**	**61,2411**	**116,591**

TABLE 2 CalHEAT Average Annual VMT for Truck Categories [4]

Vehicle Category	Annual Average VMT (Single Truck)
Tractors-OTR	85,000
Tractors-Short Haul/Regional	55,000
Class 3-8 Work-Urban	25,000
Class 3-8 Work-Rural/Intracity	35,000
Class 3-8 Work-Work Site	13,000
Class 2b/3 Vans/Pickups	21,000
Unknown	8,192

NREL researchers then applied NREL's DRIVE tool to generate a pair of composite custom drive cycles (one 80-mile and one 100-mile cycle). These cycles were developed using only conventional vehicle data as an input, as conventional diesel-fueled pickup and delivery trucks are the baseline vehicles' performance marker that the new hybrid powertrain is to be compared against. Once the speed-time cycles had been generated using DRIVE, additional gradeability and performance constraints were supplied by PACCAR and Cummins, which were used to develop a synthetic elevation-time profile representative of the national road network. Finally, once the dynamic components of the cycle were developed, the final stage in the work day cycle generation process was completed, and a key status cycle component was included along with the speed-time and elevation-time information to form the final work day cycles. These work day cycles were then used by researchers at Cummins to tune control strategies, size components (e.g., electrical energy storage capacity, assuming access only to overnight charging), and simulate fuel economy savings of the proposed electrified vehicle architecture. Additional details on the specific stages of cycle generation will be presented in the following sections.

Developing the Drive Cycle The first stage in developing the representative 80-mile and 100-mile drive cycles was to first perform statistical analysis on all the daily operating drive cycle data to evaluate the presence of unique clusters of behavior within the broader population. To do this, NREL researchers applied multivariate k-means clustering to the full Class 6 conventional pickup and delivery vehicle data set contained within the Fleet DNA database as shown in Table 4.

Metrics such as average driving speed, stops per mile, kinetic intensity, and others were used to identify unique operating modes within the data that could then be used to form a final composite cycle. As shown in Figure 6, the results

FIGURE 5 DOE's Alternative Fuels Data Center 2015 VMT estimates by vehicle type [6]

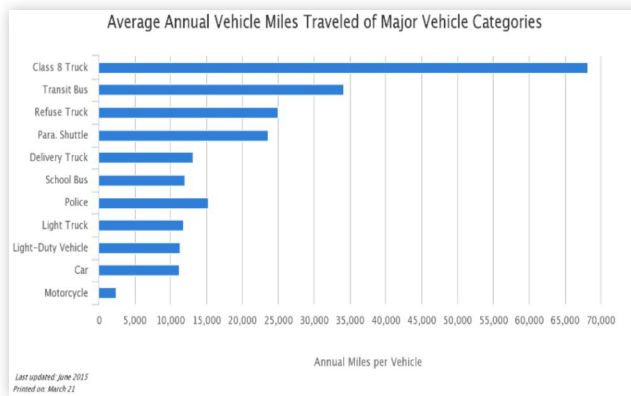


TABLE 3 USCUSA 2015 Real-World Fleet VMT Estimates [5]

Pepsi	#	Fuel Type	Average Annual VMT	Average Fuel Economy	Fuel Usage
Bulk Tractor-Trailer	1,969	Diesel	200,000	6.2 nnpg	64.2 M gals
Bulk Tractor-Trailer	140	H_2 + Diesel	200,000	7.1 mpg	4.0 M gals
Bay Tractor-Trailer	4,259	Diesel	20,099	5.8 mpg	14.8 M gals
Bon Truck	4,545	Diesel	25,087	5.7 nnpg	10.3 M gals
Bon Truck (Hybrid)	300	Diesel	25,087	13.1 mpg	0.4 M gals
Sprinter Var	500	Diesel	17,697	17.0 rnpg	0.3 M gals
Cargo Van	1,600	Gasoline	17,697	11.0 nnpg	2.6 M gals
Cargo Van (XL Hybrid)	100	Gasoline	17,697	13.2 mpg	0.1 M gals

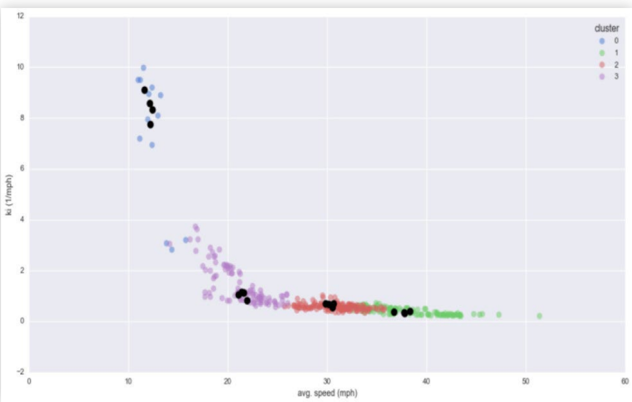
Frito-Lay	#	Fuel Type	Average Annual VMT	Average Fuel Economy	Fuel Usage
OTR Tracior-Trailer	832	Diesel	78,264	6.0 mpg	10.8 M gals
OTR Tracior-Traile-r	208	3600-psi CNG	78,264	1.5 mpg	*10.8 M gals
Box Truck	2,653	Diesel	22,037	5.7 mpg	6.0 M gals
Box Truck (Hybrid)	67	Diesel	22,087	12.1 nnpg	0.1 M gals
Box Truck (Electric}	280	Electricity	14,423	2.0 mi/kWh	2.0 GWn
Sprinter Var	3,000	Diesel	17,697	17 0 rnpg	3.1 M gals
Cargo Van	12,761	Gasoline	17,697	11.0 mpg	20.5 M gals

* This is the compressed volume of natural gas used on the truck. This is equivalent to the energy of 1.4 billion cubic feet of natural gas.

TABLE 4 Summary of Drive Cycle Data Used for Representative Cycle Development

Metric	All Class 6 Pickup and Delivery	Class 6 Pickup and Delivery Straight Trucks
Total Number of Vehicles	36	26
Total Number of Operating Days	636	390
Total Mileage (mi)	32,880	23,084
Average Daily Driving Distance (mi)	51.7	59.2
Average Maximum Driving Speed (mph)	60.9	60.5
Average Stops per Mile	2.5	3.5
Average Duration (hr)	3.6	3.88
Average Kinetic Intensity (1/mile)	1.7	2.3

FIGURE 6 Drive cycle mode identification using K-means clustering



of the clustering analysis identified four unique operational clusters within the data.

Once identified, statistics for each individual cluster were computed, and each of the clusters was run through DRIVE to develop a cluster representative mileage-weighted composite component. To illustrate what this means, consider a two-cluster case. If cluster 1 has a 2-to-1 mileage weighting over cluster 2, then the final cycle mileage will be weighted as follows: 2 parts component 1, 1 part component 2.

Once the composite cycles were generated, statistics were computed for each of the cycles and compared to existing standard chassis dynamometer test cycles as shown in Tables 5 and 6.

Looking at the results in Tables 5 and 6 and comparing the NREL 80- and 100-mile representative cycles to the Hybrid Truck Utility Forum Class 6 Pickup and Delivery Cycle, the NREL representative cycles are much longer in duration, achieve a much greater maximum driving speed, and have significantly higher acceleration/deceleration rates and fluctuations in driving speed. However, when compared to the CARB Heavy Heavy-Duty Diesel Truck Cycle, the NREL 80- and 100-mile cycles have lower maximum speed and

TABLE 5 Comparison of NREL 80- and 100-Mile Cycles

	NREL_80	NREL_100
absolute time duration (hrs)	8.56	10.77
maximum driving speed (mph)	65.09	64.73
average driving speed (speed > 0, mph)	31.86	30.34
standard deviation of speed (mph)	18.68	18.40
maximum acceleration (ft/s/s)	7.18	8.73
maximum deceleration (ft/s/s)	-7.56	-10.22
average acceleration (ft/s/s)	1.07	1.06
average deceleration (ft/s/s)	-1.14	-1.08
acceleration events per mile	5.10	6.29
deceleration events per mile	5.10	6.29
number of stops per mile	1.45	1.34
characteristic acceleration (ft/s/s)	0.41	0.40
aerodynamic speed (ft/s)	73.13	72.82
kinetic intensity (1/mile)	0.41	0.40

TABLE 6 Comparison of Standard Chassis Dynamometer Cycles

Metric	NYC COMP	HTUF Class 6 PDDS	CSHVC (CSC)	CARB HHDDT
absolute time duration (hrs)	0.29	1.09	0.47	1.00
maximum driving speed (mph)	36.00	56.60	43.80	59.30
average driving speed (speed > 0, mph)	13.11	21.95	18.44	35.59
standard deviation of speed (mph)	9.47	13.39	13.06	24.48
maximum acceleration (ft/s/s)	6.79	2.93	3.81	4.25
maximum deceleration (ft/s/s)	-6.42	-4.99	-5.87	-4.06
average acceleration (ft/s/s)	1.51	1.64	1.31	0.52
average deceleration (ft/s/s)	-1.71	-2.06	-1.58	-0.58
acceleration events per mile	57.88	11.01	20.06	6.53
deceleration events per mile	54.68	13.21	20.06	6.83
number of stops per mile	7.98	2.57	1.95	0.50
characteristic acceleration (ft/s/s)	0.75	0.58	0.56	0.18
aerodynamic speed (ft/s)	30.40	44.28	40.66	74.36
kinetic intensity (1/mile)	4.30	1.55	1.79	0.17

variability and similar acceleration/deceleration rates. This means the new cycles are somewhere in the middle of the aggressiveness spectrum when compared to portfolio of existing test cycles, with the major difference being overall duration.

Appending Nationally Representative Road Grade

Having generated a pair of 80- and 100-mile speed-time drive cycles using NREL's DRIVE tool, the next step in developing the final work day cycles used in this project was to append an elevation-time profile to each of the speed-time cycles. To accomplish this task, NREL researchers expanded the DRIVE tool to include the capability to generate representative net zero elevation profiles using gradeability and road grade distributions data. In this case, Cummins provided the gradeability curve shown in Figure 7, which describes the maximum grade achievable over a range of specified driving speeds.

FIGURE 7 Gradeability constraint used to develop cycle elevation profiles

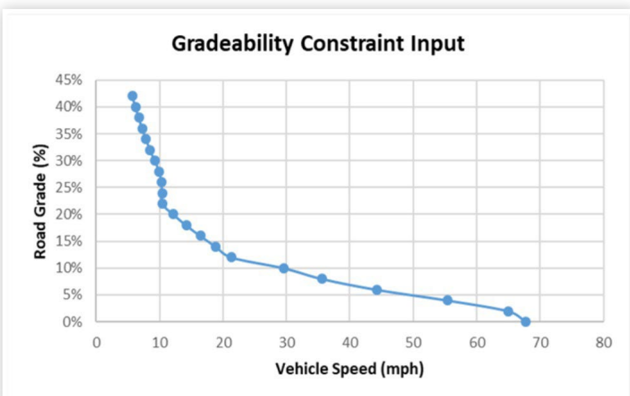


FIGURE 8 Final NREL 80-mile Class 6 pickup and delivery drive cycle with elevation

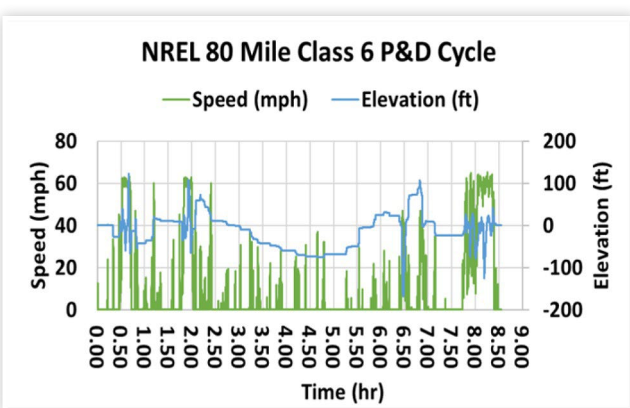
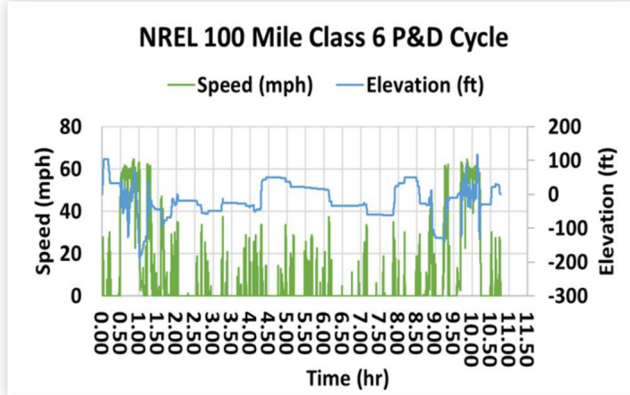


FIGURE 9 Final NREL 100-mile Class 6 pickup and delivery drive cycle with elevation



This curve was used as an additional constraint when developing the final elevation vs. time profile for the 80-mile representative cycle shown in Figure 8, as well as the elevation vs. time profile for the similar 100-mile representative cycle shown in Figure 9.

The underlying road grade information used to develop the profiles (distributions, number of climbs/descents per mile, approximate elevation change per event, etc.) was drawn from a sample of the U.S. national road network and fed into DRIVE as an input [7].

Adding Statistically Representative Key Status Information

Having completed the two major tasks of developing representative speed vs. time and elevation vs. time traces to prescribe appropriate vehicle dynamics, the final stage in the development of the representative work day cycle required the creation of representative key status cycles that could be appended to the dynamics components. The key status information was necessary to help develop key energy storage, and thermal management strategies and controls. The first step in developing the final representative key-off cycle components started with an analysis of the durations, frequency, and relative temporal positions of the key-off events within the full Fleet DNA data set. The results of these analyses are shown in Figures 10 through 13.

Examining the results shown in Figure 10, the majority of days examined demonstrated key-off frequency on the order of approximately once per hour.

Examining the results shown in Figure 11, one can see that typically the vehicles examined in the analysis demonstrated key offs every 20 minutes of operation.

Once the distributions were developed, regression models could be fit to the underlying data to predict key-off frequency and relative probability as shown in Figure 12. These data were then fed into a Markov-Chain Monte Carlo system that selected at random real key-off segments and used them to develop a statistically representative key status cycle component.

FIGURE 10 Distribution of key off frequency for all Class 6 pickup and delivery trucks in Fleet DNA

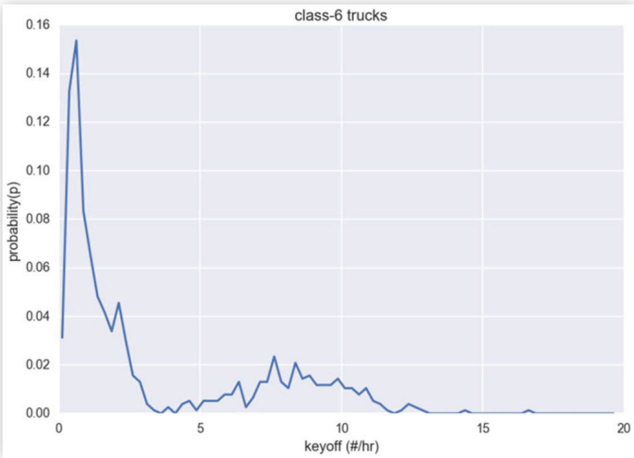


FIGURE 11 Distribution of key-off frequency for all Class 6 pickup and delivery trucks in Fleet DNA

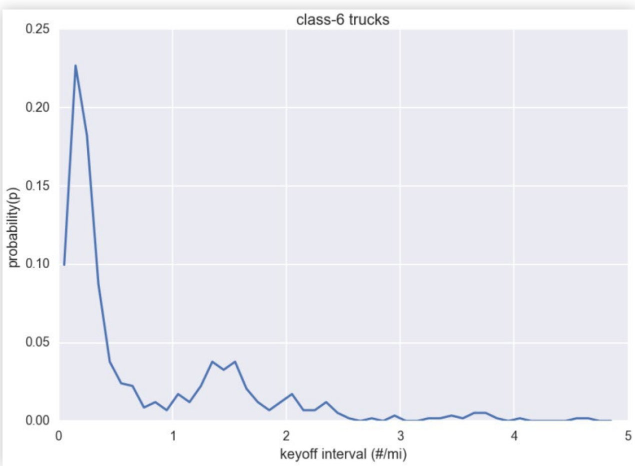


FIGURE 12 Distribution of key-off durations for all Class 6 pickup and delivery trucks in Fleet DNA

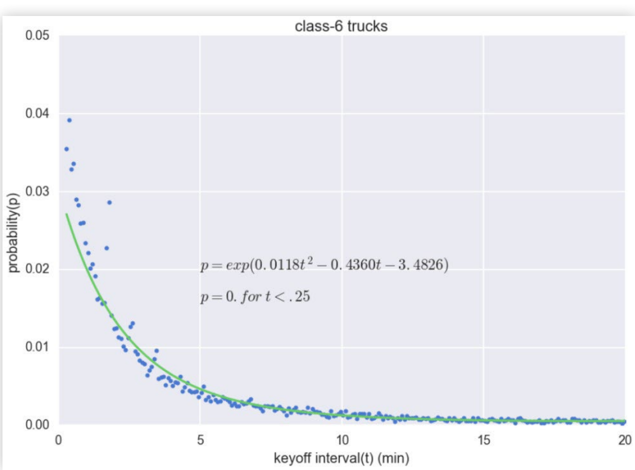


FIGURE 13 Distribution of key-off durations by time of day for all Class 6 pickup and delivery trucks in Fleet DNA

The results in Figure 13 were used to sequence the key-on/off components to match the relative order shown in the underlying data sets. In this case, what was done is that longer key-off times were sequenced to occur at the beginning and end of the cycle as identified in the distributions, while shorter key-off segments were ordered to occur in the middle.

Validation

The proposed duty cycles were validated by a dynamic vehicle simulation tool developed by Cummins. The simulation tool features a forward-looking model of the Class 6 plug-in hybrid truck that includes dynamics of the following components: route condition, driver, engine, battery, generator, traction motor, automatic transmission, rear axle, accessories, vehicle, and system controls. Specifically, the elevation and key status were imposed on the driver's model to follow the vehicle speed profile of the cycles. The driver's demand will go through the system controls and henceforth reflect on the powertrain and vehicle dynamics.

The parameters of the vehicle model were configured to match a Class 6 pickup and delivery truck. The cycles were

FIGURE 14 Simulated vehicle speed vs. target vehicle speed, NREL 80-mile cycle

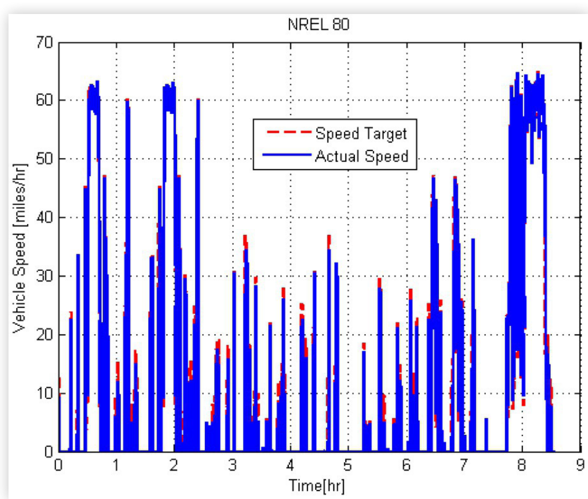


FIGURE 15 Simulated vehicle speed vs. target vehicle speed, NREL 100-mile cycle

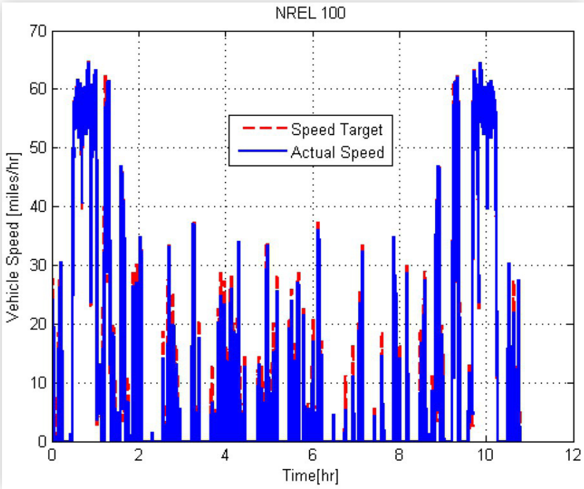


FIGURE 16 Zoomed-in simulated vehicle speed vs. target vehicle speed, NREL 80-mile cycle

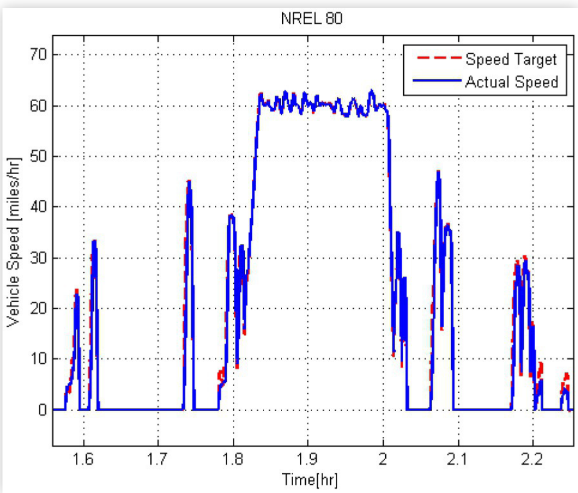


FIGURE 17 Zoomed-in simulated vehicle speed vs. target vehicle speed, NREL 100-mile cycle

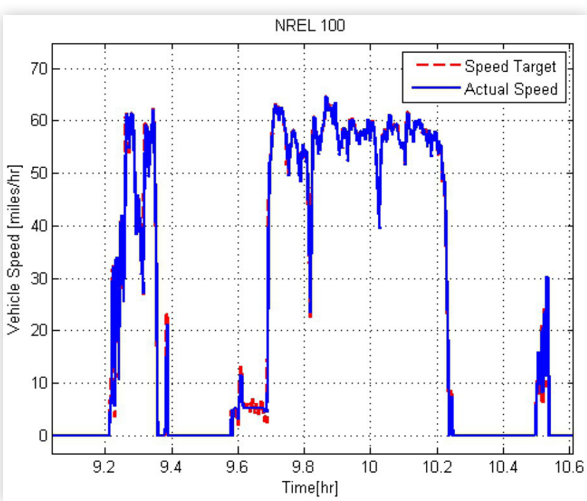


TABLE 7 Simulation Validation Summary

	NREL 80		NREL 100	
	Target	Simulation	Target	Simulation
Distance (miles)	79.5	79.2	96.9	96.5
Average Speed (mph)	31.4	31	30	29.5
Max Speed (mph)	65	64.8	64.7	64.6

validated around a half payload of the Class 6 vehicle. A few iterations were made in which the infeasible portions of the tested cycles were modified. Figure 14 and Figure 15 show the overall speed target vs. the simulated vehicle speed of the 80- and 100-mile cycles, respectively. The driver's model was able to follow both proposed cycles very closely, as shown in the zoom-in plots (Figure 16 and Figure 17). A cycle statistical summary is also provided in Table 7, in which the distance covered, average speed, and maximum speed of the target and simulation were compared. The close match further validates the feasibility of the proposed duty cycles.

The validation results show a close match between the target and simulated route metrics, which demonstrates the NREL 80 and NREL 100 cycles were designed to match the capability of a Class 6 vehicle.

Summary/Conclusions

This study has demonstrated the value of data-driven design and big data analytics as a path towards future powertrain development and optimization within the commercial vehicle sector. Future research opportunities include exploring and developing standardized work day cycles for additional vocations and weight classes, as well as documenting the results of this design process through prototype development and on-road testing.

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Contact Information

Adam Duran is a senior research engineer working with the Transportation and Hydrogen Systems Center at the National Renewable Energy Laboratory. Adam's work focuses primarily in the areas of transportation data science, drive cycle analysis and characterization, custom drive cycle development, and medium/heavy-duty fleet evaluations. He may be reached at Adam.Duran@nrel.gov.

Ke Li is a senior controls research engineer in the Research and Technology Department of Cummins in Columbus, Indiana. Ke's research interests are in the area of system integration and controls of the electrification for medium and heavy duty commercial vehicles. He may be reached at k.li@cummins.com

John Kresse is a technical leader for commercial electrified vehicles in the Research and Technology Department at Cummins in Columbus, Indiana. Currently, he is the principal investigator for the DOE-sponsored Electric Truck with Range Extending Engine (ETREE) program. John aims to develop practical solutions for applying electric vehicle technology to medium- and heavy-duty commercial vehicles. He may be reached at john.kresse@cummins.com.

Ken Kelly currently manages NREL's Commercial Vehicle Technologies team partnering with government and industry to develop advanced vehicle technologies for medium- and heavy-duty applications. While at NREL, Ken has managed and conducted research in a wide array of advanced vehicle and transportation technologies including medium- and heavy-duty vehicle technologies; alternative fuel vehicles; hybrid electric vehicle systems; advanced heat transfer technologies; computer aided engineering and robust design methods. He holds M.S. and B.S. degrees in Mechanical Engineering from Ohio University. He may be reached at Kenneth.kelly@nrel.gov.

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Definitions/Abbreviations

CalHEAT - California Hybrid, Efficient and Advanced Truck

CARB - California Air Resources Board

DOE - U.S. Department of Energy

EPA - U.S. Environmental Protection Agency

NREL - National Renewable Energy Laboratory

VMT - vehicle miles traveled

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