NREL/CP-7A40-59136. Posted with permission.
Presented at the SAE 2005 World Congress &
Exhibition, 11-14 April 2005, Detroit, Michigan.

2005-01-1165

Development of Refuse Vehicle Driving and Duty Cycles

Nicholas Dembski, Giorgio Rizzoni and Ahmed Soliman
Center for Automotive Research
The Ohio State University

Jim Fravert
Oshkosh Truck Corporation

Kenneth Kelly
National Renewable Energy Laboratory

ABSTRACT

Research has been conducted to develop a methodology for the generation of driving and duty cycles for refuse vehicles in conjunction with a larger effort in the design of a hybrid-electric refuse vehicle. This methodology includes the definition of real-world data that was collected, as well as a data analysis procedure based on sequencing of the collected data into micro-trips and hydraulic cycles. The methodology then applies multi-variate statistical analysis techniques to the sequences for classification. Finally, driving and duty cycles are generated based on matching the statistical metrics and distributions of the generated cycles to the collected database. Simulated vehicle fuel economy for these cycles is also compared to measured values.

INTRODUCTION

The U.S. Department of Energy's FreedomCAR and Vehicle Technologies Program has initiated a cost-shared research and development project for advanced, next-generation heavy hybrid propulsion systems. This activity is known as the Advanced Heavy Hybrid Propulsion System (AHHPS) project. The goals of this project are the following:

- Increase the fuel economy of heavy trucks and buses (Class 3-8) by up to 100% (2x) while meeting the EPA's 2007-2010 emission standards.
- Maintain the commercial viability of the vehicles

One of the vehicles being developed under the AHHPS project is an advanced hybrid electric refuse hauler. A critical element of the vehicle development process is the use of accurate vehicle systems analysis models. These models are being used to help guide design decisions, optimize components and sub-systems, and to evaluate the requirements for achieving 2x fuel economy. The models require representative drive cycles to simulate the system performance in "real-world" conditions. Although a number of chassis dynamometer drive cycles exist for heavy duty vehicles [1, 2, 3], these do not include a modeling of the hydraulic loading mechanisms based on field data. For instance, the William H. Martin Cycle [2] specifies a constant compaction cycle time. Theoretically, this is how the refuse hauler body is designed to perform. However, the field data collected for this project shows a large amount of variability in the hydraulic loading of the vehicle, especially during manual operations by the driver. For this reason, a systematic methodology for generating representative heavy vehicle duty cycles that include vehicle speed, mass, grade, and hydraulic loads from field data has been developed.

The methodology described in this paper has been adopted from previous work in the area of passenger vehicles [4, 5] and expanded to include the hydraulic duty cycles of a typical refuse vehicle, as well as an estimation of road grade over the course of a daily shift. Another key parameter in the methodology is the increasing vehicle mass over the course of the duty cycle. This increase has a great influence on the vehicle's performance, and must be accounted for in any duty cycles. Throughout the rest of this paper, the data collection and analysis methodology used for the generation of refuse vehicle driving and duty cycles will be described with one example of the resultant cycles.

REFUSE VEHICLE DATA COLLECTION

MEASUREMENT SIGNAL AND SENSOR SELECTION

The first step in the process of developing refuse vehicle drive and duty cycles was to determine the data required. The set of required data could be broken down into two categories: road load variables and hydraulic component variables. In order to develop drive cycles based on road loads, the vehicle speed, grade, and mass as a function of time are all required. Also, the engine loading can be measured as a check of the road load measurements assuming that component efficiency information for the vehicle powertrain between the engine and wheels is known. The required engine loading variables to be measured include engine speed and torque. Finally, in order to model the hydraulic system properly, the power required to lift, pack, and dump the refuse hauled by the truck was needed. This hydraulic power was determined by measuring the hydraulic pressure provided by the pump and the pump inlet shaft speed, and using the pump manufacturer's efficiency maps to determine the flow rates at each pump speed.

The next step was to determine how to measure these quantities with minimal sensor installation and alteration of the conventional vehicle. For the road load variables, a Garmin GPS sensor was utilized to measure vehicle speed, location, and elevation. The antenna model (model 16A) used has FAA WAAS differential GPS capabilities that allows resolution up to 3 meters. The road grade was estimated from the change in elevation and the vehicle speed measurement. In terms of the vehicle mass, it was determined that the measurement of the truck mass before and after each dump was sufficient for modeling purposes since the cost of instrumentation for continuous body mass measurements was too high for the scope of this project.

The engine data was available through the J1708 standard heavy-duty vehicle data bus. A Nexiq parallel-port MagicKey data module was purchased to collect this data directly from the vehicle engine data bus, without any additional sensors. For the hydraulic measurements, four pressure transducers rated at 207 bar (3000 psi) (the rated maximum pressure of the hydraulic system) were needed. On a typical refuse vehicle, the pump is run on a direct drive shaft from the engine. Hence, with the engine speed already being measured, the pump inlet shaft speed is also known. Table 1 lists the key measurements taken during the project and the sensors involved.

TEST VEHICLE

Once the sensors and data acquisition equipment were acquired, a truck had to be selected for installation. In consultation with Waste Management and Oshkosh Truck personnel, it was determined that the most severe usage of a refuse vehicle in terms of physical harm to the vehicle is in residential settings, specifically for side-loading trucks. This is due to large amount of high accelerations and decelerations between each house on the route combined with the driver's need to collect as much garbage as quickly as possible due to route design in some areas and due to pickup time constraints by city ordinances in other areas. McNeilus Companies provided a demo residential side-loading vehicle to perform the data collection. The vehicle specifications are listed in Table 2.

Table 1: Refuse Vehicle Measurements

Variable	Units	Sensor
Side Arm Pressure at Pump Outlet	bar (psi)	Honeywell Transducer
Packing Pressure at Load	bar (psi)	Honeywell Transducer
Side Arm Pressure at Load	bar (psi)	Honeywell Transducer
Packing Pressure at Pump Outlet	bar (psi)	Honeywell Transducer
Engine Speed/Pump Inlet Shaft Speed	rpm	MagicKey Data Bus Module
Percent Engine Load	%	MagicKey Data Bus Module
Vehicle Latitude	Deg. Min.	Garmin GPS
Vehicle Longitude	Deg. Min.	Garmin GPS
Sensor Elevation above sea level	m	Garmin GPS
Vehicle Road Speed	knots	Garmin GPS
Vehicle Mass	kg [lbs]	Scales at Refuse Dump Locations (hand collected)

TESTING CITIES

The determination of cities to collect refuse vehicle data relied on several key parameters. First, cities that did not use side-loading trucks on residential routes were eliminated. Next, the remaining locations were grouped based on any extreme climatic or geographic conditions, such as locations in Florida and Texas for heat and Minnesota for cold. Finally, through consultation with Waste Management, 5 main sites were chosen where the test vehicle could most easily be substituted into the normal route schedule. Blaine, MN, a northern suburb of Minneapolis was the first site chosen since the data collection began in January, and extreme cold temperature usage data was desired. The next three sites, Ft. Walton Beach, FL, Ft. Worth, TX, and Chandler, AZ were chosen for extreme heat and/or humid weather conditions. Finally, Ogden, Utah was chosen for extreme grade conditions.

Table 2: Test Vehicle Specifications

Chassis	2003 Autocar WXR64 with 215" Wheelbase and 110" Axle to Frame
Engine	Cummins ISM 239 kW (320 HP), 2100 RPM, 1559 N-m (1150 lb-ft) @ 1200 RPM
Body	Residential Side-Loader McNeilus Body Parker Pump Model P350 Dual Output Body: 94.1 mL (5.74 in^3) displacement Arm: 83.6 mL (5.10 in^3) displacement
Transmission	Allison HD4560 5-Speed Transmission Gear Ratios: 1st: 4.70 2nd: 2.21 3rd: 1.53 4th: 1.00 5th: 0.76
Differentials	Ratio: 5.02

DATA COLLECTION PROCEDURE

In each of the cities listed above, the test vehicle was placed into revenue service for one week. The daily data collection procedure required shadowing of the test vehicle along its route during 10 to 12 hour shifts. As mentioned previously, the vehicle mass was measured before and after each dump, and the amount of diesel fuel needed to fill the tank at the end of the shift was measured in order to provide a fuel consumption metric. Several other important observations include the number of houses that had multiple bins and/or additional refuse not contained in a bin, the number of times that the driver left the cab for any reason at a house, and the number times the driver made a reverse maneuver during the shift. The houses with multiple bins required additional time at a house, especially the ones with extra refuse outside of a bin. This required the driver to exit the truck, and resulted in spending up to five minutes at some houses. Also, the driver would often have to back up to maneuver the vehicle in neighborhood cul-de-sacs and dead-end alleys, resulting in longer times between houses. All of these instances were noted during each shift.

REFUSE VEHICLE DATA ANALYSIS

BASIC CALCULATIONS

The initial post-processing stages of data analysis included the conversion of the GPS location measurements to decimated variables, the conversion of percent engine load to engine torque based on the torque-speed map of the engine, the calculation of hydraulic flow rates and power consumed based on pump efficiency maps, and the estimation of road grade using the GPS measurements for elevation and vehicle speed. The grade was corrected using the National Elevation Dataset available at the US Geological Survey website [6] to eliminate errors in the GPS elevation measurement due to vehicle inertial pitch during acceleration, deceleration, and side-arm movements.

STATISTICAL ANALYSIS

Database Statistics

The next step of the data analysis was to develop and calculate statistical metrics for each data set, and data sub-set. A typical set of daily cycles is shown in Figure 1, where all of the areas with active hydraulic power are the route segments, and the rest of the areas are non-route segments. The daily data sets were broken down into these non-route and route segments. The non-route segments were broken down further into approach, return, dumps, and trips to and from the dump. This allows differentiation between the fully loaded vehicle body conditions (trip to dump segments) and the empty vehicle body conditions (all other non-route segments). Relevant statistical metrics for velocity, acceleration, distance, grade, and hydraulic usage were calculated for each segment and tabulated to determine daily statistics and in turn the weekly average statistics along with standard deviations for each metric. The statistical metrics are listed in Table 6 in the Appendix.

Database Joint Distributions

In addition to the database statistical metrics, several weekly distributions have been calculated for each of the segments, specifically the velocity-acceleration joint distribution, the velocity-acceleration-grade joint distribution, and several distributions for the hydraulic loadings. These distributions are used to determine how closely the developed cycles match the overall database.

Velocity-Acceleration Joint Distribution

The velocity-acceleration joint distribution is a two-dimensional probability distribution that helps to describe the kinematic behavior of the vehicle over a specific segment. An example of this distribution for non-route segments is shown as a surface plot in Figure 2.

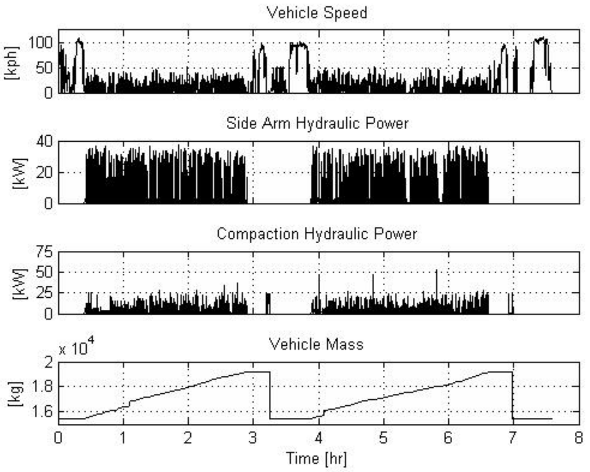

Figure 1: Typical Daily Refuse Vehicle Cycles

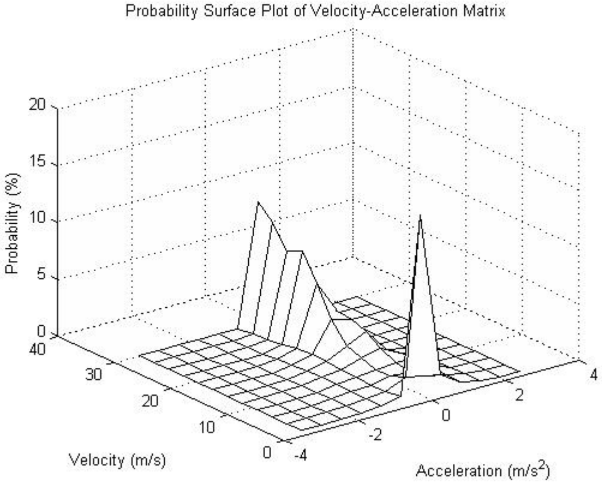

Figure 2: Velocity-Acceleration Joint Distribution for Non-Route Segments

Velocity-Acceleration-Grade Joint Distribution

The velocity-acceleration-grade joint distribution is a three-dimensional probability distribution that helps to correlate the road grades encountered with specific kinematic behaviors of the vehicle over a specific segment. Since this is a three-dimensional matrix of probabilities, there is no sufficient form of visualization. The grade also adds randomness to the probabilities since it is function of geographical conditions, not just a function of vehicle capability and performance.

Hydraulic Distributions

Distributions for peak power level, mean power level, and overall energy consumed are determined for the pickup (arm), packing (body), and dumping of the refuse along a given route. Examples of these distributions for pickups are shown as histograms in Figures 3 through 5.

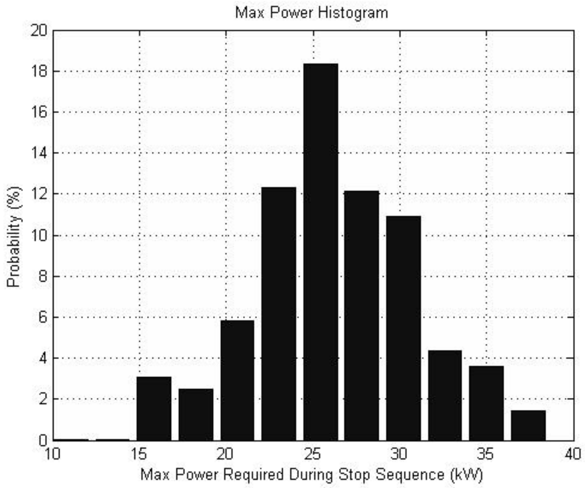

Figure 3: Distribution for Maximum Hydraulic Power Required for Refuse Pickup during Route Segments

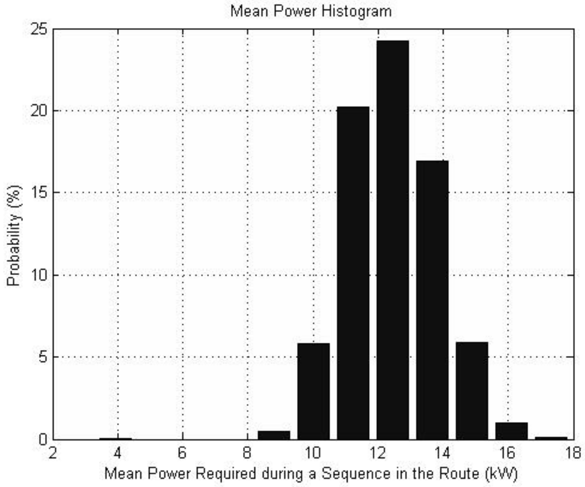

Figure 4: Distribution for Mean Power Required for Refuse Pickup during Route Segments

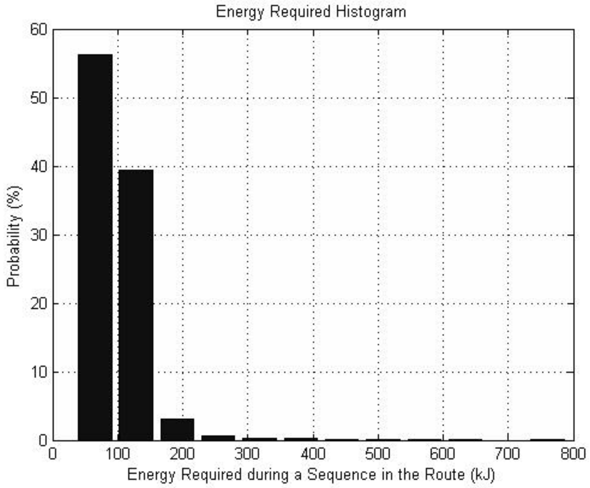

Figure 5: Distribution for Energy Required for Refuse Pickup during Route Segments

SEQUENCING

In order to further analyze the refuse vehicle data using multi-variate statistical analysis techniques, the data must first be broken-down into micro-trips and hydraulic cycles. The following sections describe this process and show examples of these sequences.

Kinematic Sequences

Non-Route Sequences

The development of kinematic sequences for the approach, return, and trips to and from dumps was based on breaking down the vehicle speed data into micro-trips from one vehicle house to the next. A corresponding grade sequence was also developed based on the same points of separation. This allows the development of grade cycles that do not have grades associated with impossible vehicle speeds or accelerations. An example of a kinematic sequence for these non-route sequences is shown in Figure 6, and the corresponding grade sequence is shown in Figure 7.

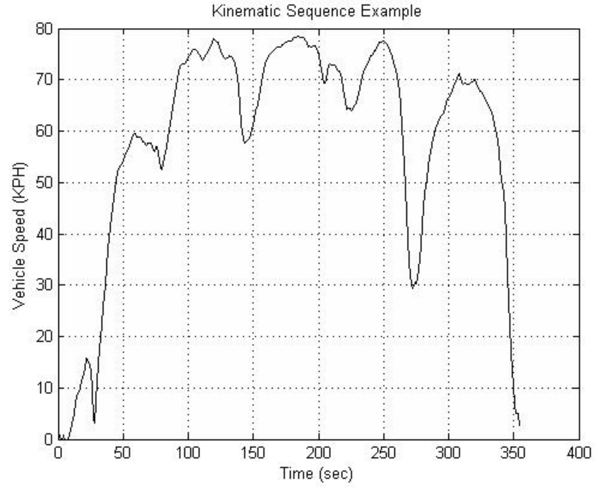

Figure 6: Non-Route Kinematic Sequence Example

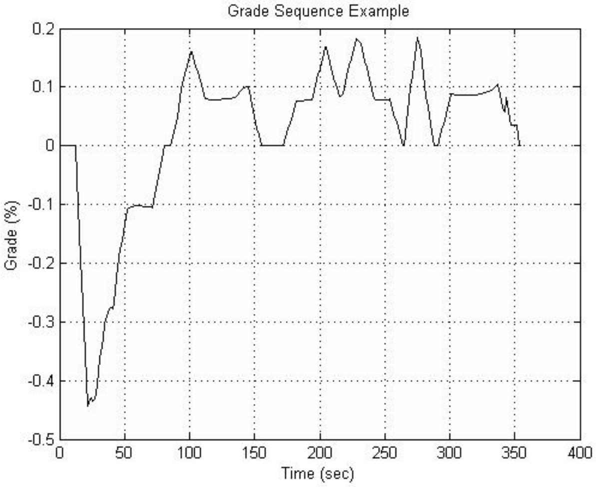

Figure 7: Grade Sequence Example

Route Sequences

For the route segments, the kinematic sequences were reversed with a vehicle moving period followed by a vehicle stopped period. The reasoning behind this reversal is that pickup of the refuse occurs during the vehicle stopped period, and sometimes the driver begins to operate the side arm mechanism while the vehicle is still slowing down to a stop. Hence, the vehicle moving period should occur prior to the vehicle stopped period to properly sequence the data as individual houses. An example of this reversed kinematic sequence is shown in Figure 8.

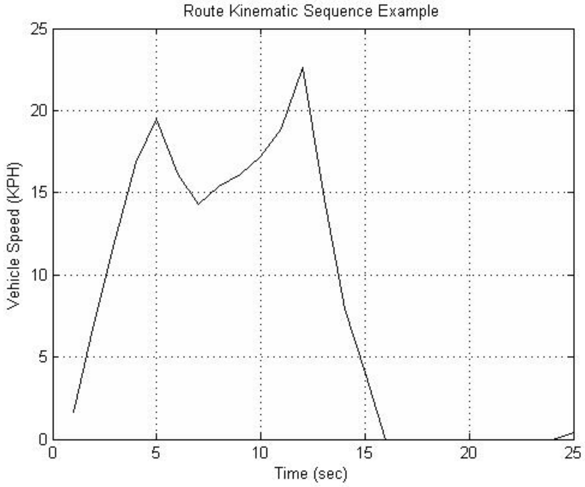

Figure 8: Route Kinematic Sequence Example

Hydraulic Sequences

Dump Sequences

These sequences consist of the body hydraulic power from the moment when the body is lifted and the tailgate is opened to the point where the tailgate is closed and the body is lowered. An example of a dump hydraulic pressure sequence is shown in Figure 9. The corresponding vehicle kinematic and grade sequences are also incorporated, even though the vehicle rarely moves once the body is lifted.

Route House Sequences

Another key data analysis constraint was the definition of a customer house, also known as a pickup location during the route. To identify a pickup event, a house was classified as any kinematic sequence during the route sections with the arm pressure above a certain threshold for a minimum of 5 seconds. The individual arm cycles could not be identified because they consisted of a varying number of pressure spikes during each cycle corresponding to each joystick maneuver by the operator. Since the number of spikes was random depending on several variables including the number of bins at each house and operator consistency, the arm cycle determination could not be automated. Examples of hydraulic pressure levels for several house sequences are shown in Figure 10.

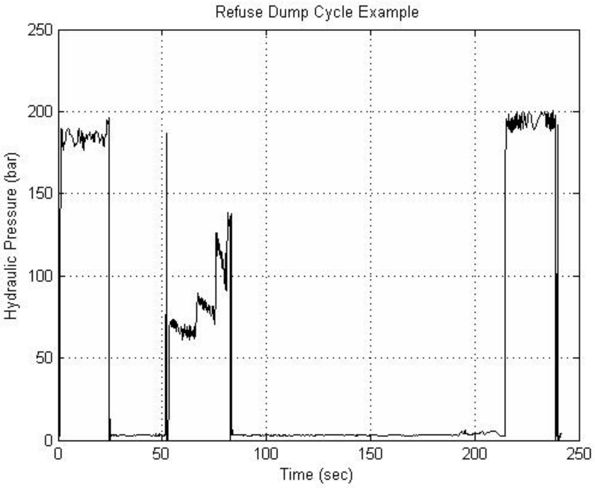

Figure 9: Dump Pressure Cycle Example

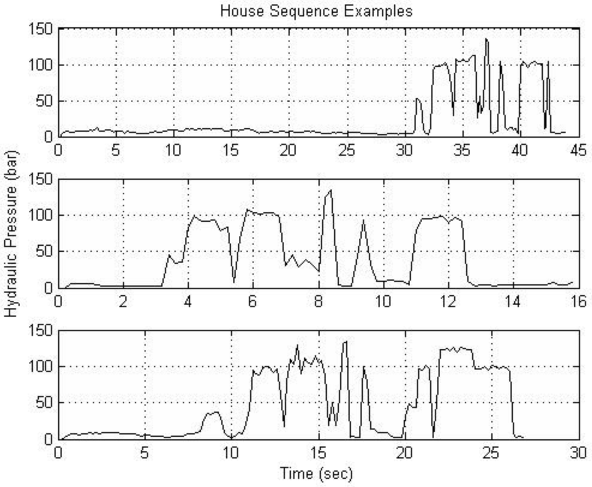

Figure 10: House Hydraulic Sequence Examples

Route Pack Sequences

Unlike the arm cycles, the individual packing cycles could be identified since each cycle consisted of one plateau period of operation. Each plateau was located using a minimum pressure on threshold of 13.8 bar (200 psi), as well as the derivative of the pressure to isolate the on/off points. The packing cycle sequences consisted of the time between cycles followed by a cycle. Examples of hydraulic pressure levels for several packing sequences are shown in Figure 11.

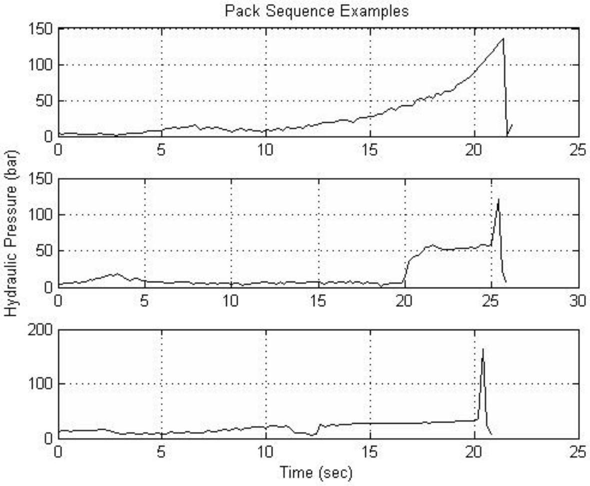

Figure 11: Packing Hydraulic Sequence Examples

PRINCIPAL COMPONENT ANALYSIS

For each set of segment sequences, statistical metrics were calculated for to determine the major statistical metrics using principal component analysis, and to classify the sequences using cluster analysis. Principal Component Analysis (PCA) is based on the matrix of correlations between variables [4]. This analysis determines linear combinations of the original set of variables that represent the original data along new optimal axes. The set of axes is optimal in the sense that the data is best projected onto the first component or the first few components. These principal components are orthogonal to each other; so there is no redundant information in the data, which often occurs with the original set of variables. The entire set of principal components is as large as the original set of variables. However, the first few principal components often represent over 80 percent of the variance of the data set, thus reducing the number of variables required to analyze the data set.

For this study, kinematic and hydraulic sequence statistical metrics comprised the data set to be analyzed. The statistical metrics used for each type of sequence are listed in Table 7 in the Appendix. Since, the metrics had different units, the data set had to be normalized using the standard deviation of each metric prior to the analysis.

CLUSTER ANALYSIS

With each set of sequence statistical metrics re-calculated along its principal components, K-means clustering was utilized to classify the sequences. K-means clustering creates a single-level of clusters based on the actual observations of the data in the database. The traditional hierarchal clustering technique bases the groupings of the data on a hierarchal tree structure. The “K”-value refers to a preset number of clusters that the data is split into. Each cluster in the partition is defined by its member objects and by its centroid, or center. The centroid for each cluster is the point to which the sum of distances from all objects in that cluster is minimized. K-means clustering uses an iterative algorithm that minimizes the sum of distances from each object to its cluster centroid, over all clusters. This algorithm moves objects between clusters until this sum cannot be decreased further. The result is a set of clusters that are as compact and well separated as possible. Since this process is iterative, the clustering results vary from trial to trial, even when using the same clustering parameters. These differences often mean that k-means clustering is more suitable for clustering large amounts of data, thus making it the proper technique for analysis of kinematic and hydraulic sequences based on a large number of statistical metrics.

Kinematic Sequence Clusters

The cluster analysis of the non-route segment kinematic sequences resulted in 4 distinct clusters. Figure 12 shows the four distinct clusters of kinematic sequences, while Figure 13 shows the corresponding clusters of grade sequences. The first kinematic sequence cluster has a majority of the sequences that are composed of intermediate speeds and durations, a combination of urban and highway driving. The second cluster shows the most extreme highway-driving sequences, and has a majority of the non-route sequences. The third cluster consists of several short-duration, intermediate-speed sequences, and the fourth cluster has the low-speed urban sequences that are more rarely seen in the non-route conditions where the driver is trying to get back and forth from the daily route segments as quickly as possible.

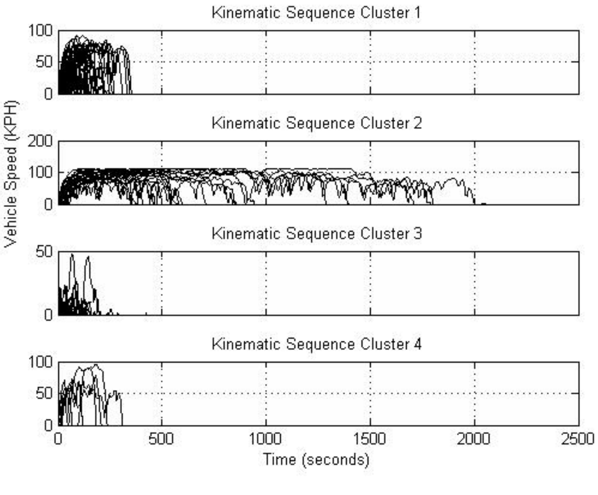

Figure 12: Non-Route Kinematic Sequence Clusters

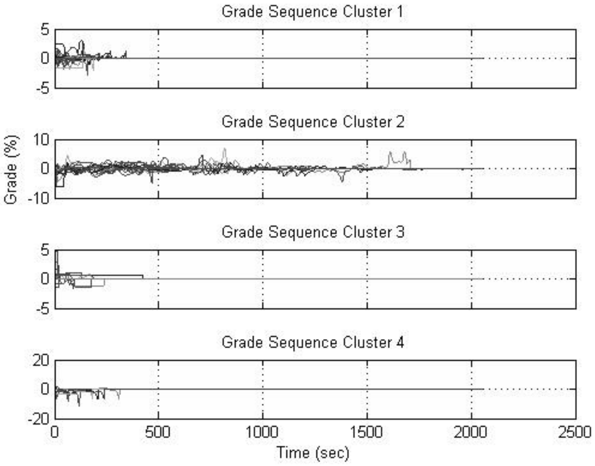

Figure 13: Non-Route Grade Sequence Clusters

Hydraulic Sequence Clusters

For the hydraulic cycle sequences, the hydraulic loading is also included along with the kinematic variables (speed and grade). Figures 14 through 16 show the six distinct clusters for the route house sequences. Cluster 6 consists mostly of non-house sequences. Cluster 2 consists of the extreme house sequences, with extra-long sequences and higher speeds between houses. Cluster 5 consists of the low-speed houses. Clusters 1, 3, and 5 are similar kinematically, but vary in the amount of hydraulic power required.

CYCLE DEVELOPMENT

With all of the statistical metrics of the database calculated as well as the classification of the kinematic and hydraulic sequences complete, the next step is to develop driving and load cycles for each segment representative of each segment's statistical metrics and distributions. The main goals were to 1. minimize the difference between the developed cycle distributions and the overall database distributions and 2. match as many cycle segment statistical metrics within ± 1 standard deviation of the weekly statistical metrics. However, for several segments in some of the city data sets where there was a limited amount of data, the differences could not be minimized as well as in the other cites with better data sets.

Non-Route Segments

For the non-route segments where the hydraulics were neglected, the kinematic sequences were randomly selected using each cluster's frequency of occurrence. The sequences were then placed together until as many of the developed cycle segment metrics (listed in Table 3) matched within ± 1 standard deviation of the weekly statistical metrics. The difference between cycle and database distribution for velocity-acceleration and velocity-acceleration-grade was also minimized.

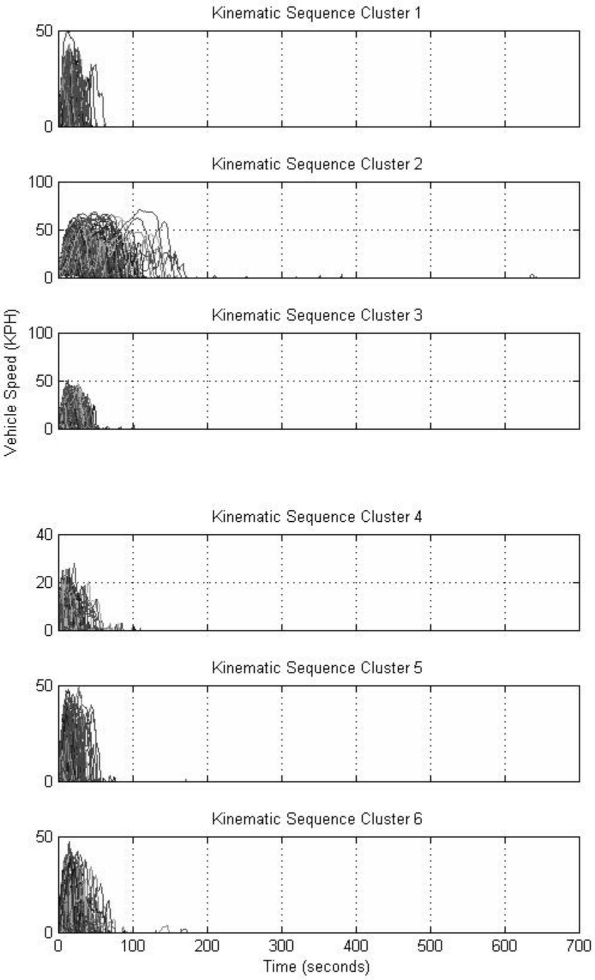

Figure 14: Route Kinematic Sequence Clusters

Dump Segments

Since there were so few dump segments per city, one of the dump segments was randomly chosen until as many as possible of the developed cycle segment metrics matched within ± 1 standard deviation of the weekly statistical metrics listed in Table 4. The mass dumped for this chosen dump segment was used to determine the number of houses needed in each route segment of the generated cycle.

Route Segments

The route segments are determined in two phases. First, a set of house sequences is developed based on the amount of mass picked up for a chosen dump segment. Then, the packing cycle sequences are picked to match the house sequences, based on the mass currently in the truck, and the amount of time between houses. Again, the developed cycle segment metrics are checked to be within ± 1 standard deviation of the weekly statistical metrics listed in Table 5, along with the minimization of the velocity-acceleration, velocity-acceleration-grade, and hydraulic distributions.

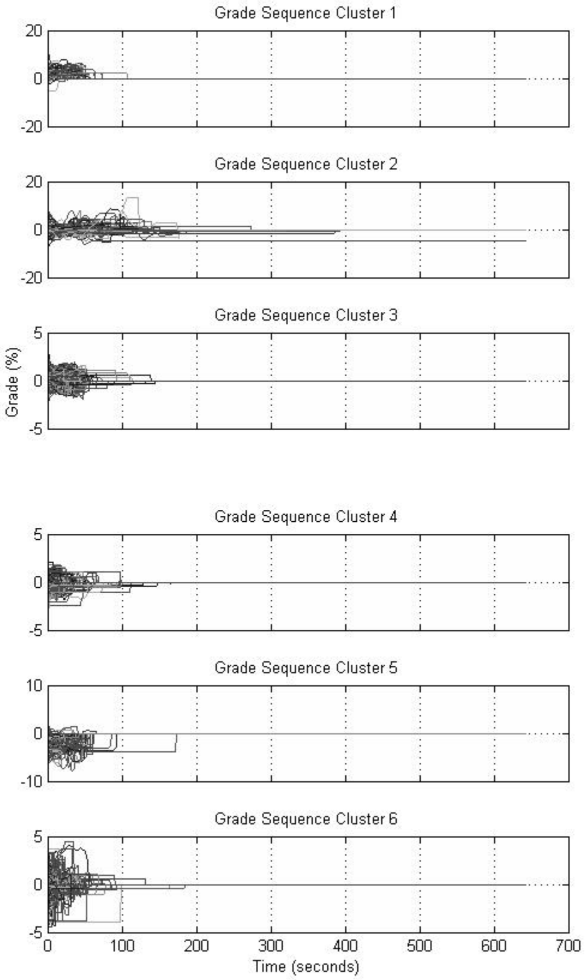

Figure 15: Route Grade Sequence Clusters

Table 3: Statistical Metrics Checked for Non-Route Segments

Segment Time	Mean Deceleration	Max Grade Descent
Segment Distance	Pct Time Accelerating	Mean Grade Descent
Pct Time Vehicle Stopped	Pct Time Decelerating	Mean Grade Overall
Max Velocity	Pct Time Cruising	Pct Time Grade Climb
Mean Velocity	Pct Distance Accelerating	Pct Time Grade Descent
Mean Run Velocity	Pct Distance Decelerating	Pct Time Grade Level
Peak Acceleration	Pct Distance Cruising	Pct Distance Grade Climb
Mean Acceleration	Max Grade Climb	Pct Distance Grade Descent
Peak Deceleration	Mean Grade Climb	Pct Distance Grade Level

Table 4: Statistical Metrics Checked for Dump Segments

Mass Dumped	Hydraulic Energy Required
Max Hydraulic Power	Mean Hydraulic Power

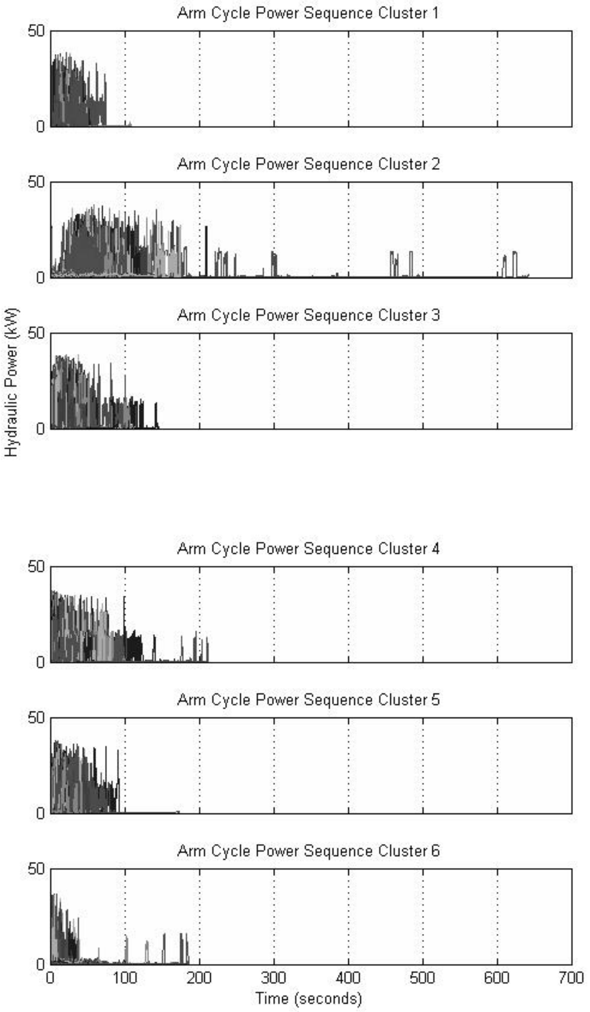

Figure 16: Route House Hydraulic Sequence Clusters

Overall Driving and Duty Cycles

The final overall driving and load cycles were developed by combining each cycle segment into either a single-dump per day cycle, a two-dump per day cycle, or a three-dump per day cycle. This was based on the average number of dumps per day for the specific city data set. The mass cycle was also developed based on the average amount of mass of refuse picked up at each house during the route segment.

GENERATED CYCLE EXAMPLE

Due to the variety and randomness of the daily routes in each city, it was determined that a separate set of driving and duty cycles had to be generated for each testing city. An example of the generated refuse vehicle driving and duty cycle for the data collected in Ft. Walton Beach, FL is shown in this section. Since the average shift required two route segments with refuse being dumped at a landfill or transfer station twice-a-day, the generated cycle for Ft. Walton Beach is a two-dump cycle. Examples of each phase of the driving and duty cycle are shown in Figures 17 through 21.

Table 5: Statistical Metrics Checked for Route Segments

Segment Time	Mean Deceleration	Max Grade Descent
Segment Distance	Pct Time Accelerating	Mean Grade Descent
Pct Time Vehicle Stopped	Pct Time Decelerating	Mean Grade Overall
Max Velocity	Pct Time Cruising	Pct Time Grade Climb
Mean Velocity	Pct Distance Accelerating	Pct Time Grade Descent
Mean Run Velocity	Pct Distance Decelerating	Pct Time Grade Level
Peak Acceleration	Pct Distance Cruising	Pct Distance Grade Climb
Mean Acceleration	Max Grade Climb	Pct Distance Grade Descent
Peak Deceleration	Mean Grade Climb	Pct Distance Grade Level
Pct Time Vehicle Stopped with Arm Activated	Pct Time Vehicle Stopped with Body Activated	Pct Time with Arm Activated
Pct Time with Body Activated	Houses per Route	Packs per Route
Avg. Hydraulic Energy Required per House	Avg. Max Hydraulic Power per House	Avg. Mean Hydraulic Power per House
Avg. Hydraulic Energy Required per Pack	Avg. Max Hydraulic Power per Pack	Avg. Mean Hydraulic Power per Pack

Kinematic Cycle

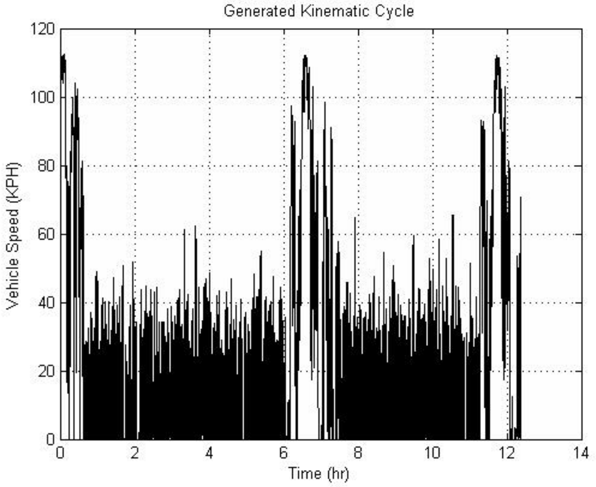

Figure 17: Generated Kinematic Cycle

Grade Cycle

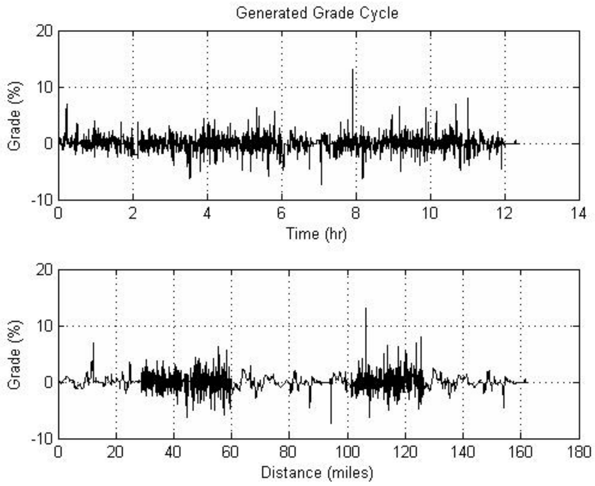

Figure 18: Generated Grade Cycle

Mass Cycle

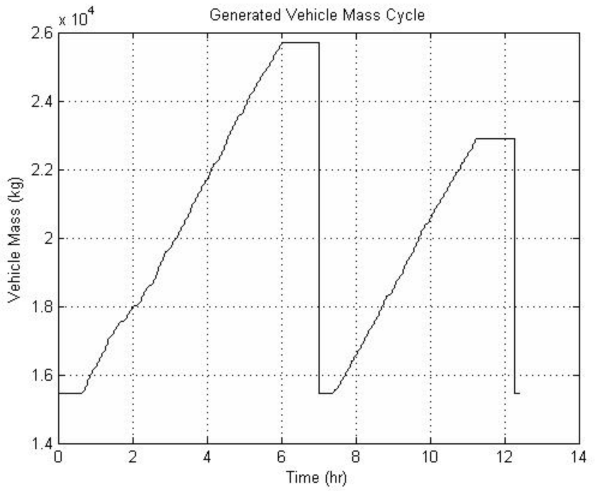

Figure 19: Generated Mass Cycle

Lifting Hydraulic Cycle

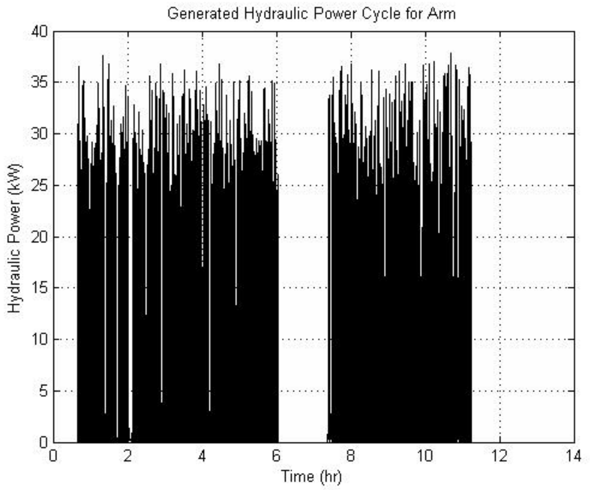

Figure 20: Generated Lifting Hydraulic Power Cycle

Packing/Dumping Hydraulic Cycle

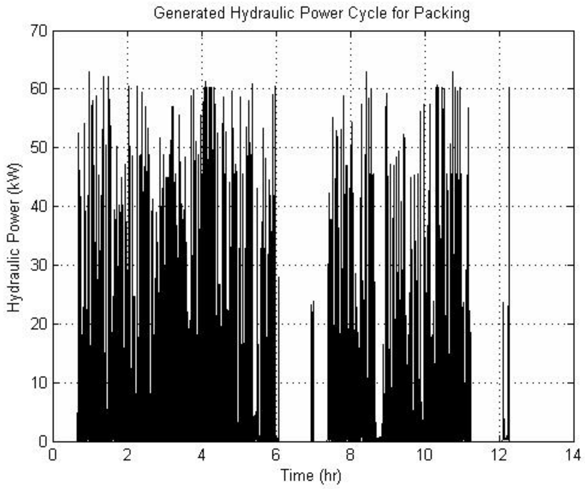

Figure 21: Generated Packing/Dumping Hydraulic Power Cycle

Fuel Economy Comparisons

With DOE's emphasis on an improvement in vehicle fuel economy, the ability to correctly model the vehicle's performance is inherently critical to the driving cycle. As a final comparison of the generated cycles to the collected database, each generated cycle has been run through a conventional refuse vehicle simulator based in the Simulink programming language to estimate a fuel economy over the generated cycles. Figure 22 shows a comparison of the generated cycle fuel economy estimate to the average measured daily fuel economy for each testing city as well as the 95% confidence interval for each average measured value. The confidence intervals were calculated based on the number of data points per week and the variance between these points. This figure shows that generated cycles fall within the confidence interval for each test city indicating that the generated cities are representative of typical vehicle performance for each weekly data set. Another key observation is the large confidence interval for the data collected in Minnesota and Arizona, which was caused by the fact the data was not consistent due to loss of data and driver switches during the week of collection in those locations.

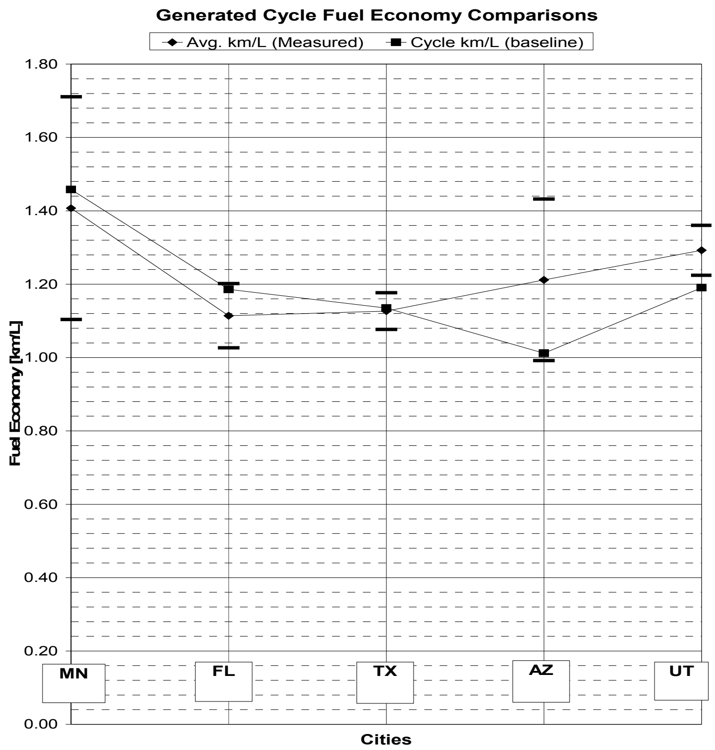

Figure 22: Generated Cycles Fuel Economy Comparison to Measured Database

CONCLUSION

This paper has described a systematic methodology for developing representative refuse vehicle driving and duty cycles that include not only the standard cycle information of vehicle speed, but also mass, grade, and hydraulic loads from field data. This data has not been combined into a set of driving and duty cycles before. These driving and duty cycles are representative of a weekly set of refuse vehicle data collected in five unique testing locations, match the statistical characteristics of each separate data set as closely as possible, and correctly estimate vehicle performance through simulation. These cycles will be utilized in the development and computer simulation of future refuse vehicle designs, specifically energy-saving hybrid-electric vehicles. A smaller drive cycle, comprised of sections from the generated full driving cycles, will be developed for vehicle emissions testing due to the need to minimize vehicle testing time.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Department of Energy for their funding of the entire AHHPS project, as well as Susan Rodgers and Terry Hendricks for their contributions to the project.

The authors would also like to acknowledge Chris Yakes at Oshkosh Truck Corporation for his tireless work as project manager.

The authors would also like to acknowledge Bob Pfeffer, Jason Weinandt, and Bob Post of McNeilus Companies for their assistance in the instrumentation of the test vehicle and the logistics of the data collection.

The authors would also like to acknowledge Mike Ehrenhaft of Waste Management for all of his input to the project.

Finally, the authors would like to acknowledge all of the route managers and drivers that accommodated the data collection effort in each city. Without their efforts, this project never would have been completed.

REFERENCES

1. Clark, Nigel, et al. "Application of the new city-suburban heavy vehicle route (CSHVR) to truck emissions characterization". SAE Paper # 1999-01-1467, SAE International Spring Fuels and Lubricants Meeting and Exposition, Dearborn, MI, May, 1999.
2. Heavy Vehicle Projects at NREL – Emissions Test Cycles. http://www.ctts.nrel.gov/heavy_vehicle/emissions_test_cycles.html
3. Clark, N.N., and Lyons, D.W. "Emissions from CNG and Diesel Refuse Haulers Using Six Engine Types in New York City". Seventh CRC On-Road Vehicle Emissions Workshop, San Diego, April 1997, pp. 5-49 to 5-64.
4. Dembski, N., Guezennec, Y., and Soliman, A. "Analysis and Experimental Refinement of Real-World Driving Cycles". SAE Paper # 2002-01-0069, SAE International Congress and Exposition, Detroit, MI, March, 2002.
5. Andre, Michel, et al. "Driving Cycles for Emission Measurements under European Conditions". SAE Paper #950926, SAE International Congress and Exposition, Detroit, MI, March, 1995.
6. United States Geological Survey website, http://www.usgs.gov.

CONTACT

Nicholas Dembski
Research Engineer
Center for Automotive Research
The Ohio State University
930 Kinnear Rd
Columbus, OH 43212
Phone: (614) 292-7855
Fax: (614) 688-4111
E-mail: dembski.5@osu.edu

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AHHPS: Advanced Heavy Hybrid Propulsion System
FAA: Federal Aviation Administration
GPS: Global Positioning System

House: A single refuse pick-up customer along a residential route, which could include multiple arm lifts
Non-Route: Any section of a refuse vehicle duty cycle where refuse is not being picked up
PCA: Principal Component Analysis
Route: The section of a refuse vehicle duty cycle where refuse is being picked up
WAAS: Wide Area Augmentation System

APPENDIX

Table 6: Database and Segment Statistical Metrics

Statistical Metric	Description
Duration	Time Spent During Segment
Pct Time Vehicle Stopped	Percent of Time During Segment Vehicle is Stopped
Pct Time Vehicle Stopped Arm On	Percent of Time During Segment Vehicle is Stopped with Arm Activated
Pct Time Vehicle Stopped Body On	Percent of Time During Segment Vehicle is Stopped with Body Activated
Pct Time Arm On	Percent of Time During Segment with Arm Activated
Pct Time Body On	Percent of Time During Segment with Body Activated
Pct Time Acc	Percent of Time During Segment while Accelerating
Pct Time Dec	Percent of Time During Segment while Decelerating
Pct Time Cruise	Percent of Time During Segment while Cruising
Pct Time Grade Climb	Percent of Time During Segment while Traveling over a Positive Grade
Pct Time Grade Descent	Percent of Time During Segment while Traveling over a Negative Grade
Pct Time Grade Level	Percent of Time During Segment while Traveling over a Level Grade
Max Velocity	Maximum Speed During Segment
Mean Velocity	Average Speed During Segment
Mean Run Velocity	Average Speed During Segment while Moving
Peak Acceleration	Maximum Positive Acceleration During Segment
Mean Acceleration	Average Positive Acceleration During Segment
Peak Deceleration	Maximum Negative Acceleration During Segment
Mean Deceleration	Average Negative Acceleration During Segment
Distance	Distance Traveled During Segment
Pct Distance Arm On	Percent of Distance Traveled During Segment with Arm Activated
Pct Distance Body On	Percent of Distance Traveled During Segment with Body Activated
Pct Distance Acc	Percent of Distance Traveled During Segment while Accelerating
Pct Distance Dec	Percent of Distance Traveled During Segment while Decelerating
Pct Distance Cruise	Percent of Distance Traveled During Segment while Cruising
Pct Distance Grade Climb	Percent of Distance Traveled During Segment while Traveling over a Positive Grade
Pct Distance Grade Descent	Percent of Distance Traveled During Segment while Traveling over a Negative Grade
Pct Distance Grade Level	Percent of Distance Traveled During Segment while Traveling over a Level Grade
Grade Max Climb	Maximum Positive Grade During Segment
Grade Mean Climb	Average Positive Grade During Segment
Grade Max Descent	Maximum Negative Grade During Segment
Grade Mean Descent	Average Negative Grade During Segment
Grade Mean Overall	Average Grade During Segment
Avg Max Power Req Per House/Cycle	Average Maximum Power Required per house or packing cycle during each route or dump segment
Avg Mean Power Req Per House/Cycle	Average Mean Power Required per house or packing cycle during each route or dump segment
Avg Energy Req Per House/Cycle	Average Energy Required per house or packing cycle during each route or dump segment
n houses	Number of houses per route segment or shift
n pack cycles	Number of pack cycles per route segment of shift
houses per min	Number of houses per minutes during each route segment or shift
avg houses per pack	Average Number of Houses per Pack during each route segment or shift
Mass Collected	Mass Collected per dump or shift
Mass Avg	Average Mass per house during each route segment or shift
Time avg house	Average Time Spent at each House during each route segment and shift
avg dist between houses	Average Distance between each House

Statistical Metric	Description
n back	Number of Backing Maneuvers per shift
n houses left cab	Number of Houses where the Driver Left the Cab per shift
fuel cons	Amount of Diesel fuel consumed during shift
fuel mpg	Daily Fuel Economy in Miles per Gallon
fuel gph	Daily Fuel Economy in Gallons per Hour
fuel tons mpg	Daily Fuel Economy in Tons Hauled - Miles per Gallon
n dumps	Number of Dumps per shift
n backs	Number of Backing Maneuvers per shift
n houses left cab	Number Houses where Driver Left Cab per Shift
temp hi	Daily High Temperature
temp lo	Daily Lo Temperature

Table 7: Statistical Metrics Used for PCA

Approach, Trip to Dump, Trip from Dump, and Return Kinematic Sequences	Dump Sequences	Route House Sequences	Route Pack Sequences
Max Velocity	Sequence Time	Max Velocity	Sequence Time
Mean Velocity	Mass Dumped	Mean Velocity	Mass Packed
Mean Run Velocity	Hyd. Energy Required	Mean Run Velocity	Hyd. Energy Required
Peak Acceleration	Max Hyd. Power	Peak Acceleration	Max Hyd. Power
Mean Acceleration	Mean Hyd. Power	Mean Acceleration	Mean Hyd. Power
Peak Deceleration		Peak Deceleration	Time with Body Activated
Mean Deceleration		Mean Deceleration	Houses per Pack
Distance Traveled		Distance Traveled	
Max Grade Climb		Max Grade Climb	
Mean Grade Climb		Mean Grade Climb	
Max Grade Descent		Max Grade Descent	
Mean Grade Descent		Mean Grade Descent	
Mean Grade Overall		Mean Grade Overall	
Sequence Time		Sequence Time	
Time Vehicle Moving		Time Vehicle Moving	
Time Vehicle Stopped		Time Vehicle Stopped	
		Time with Arm Activated	
		Mass per House	
		Hyd. Energy Required	
		Max Hyd. Power	
		Mean Hyd. Power	
		House Indicator	